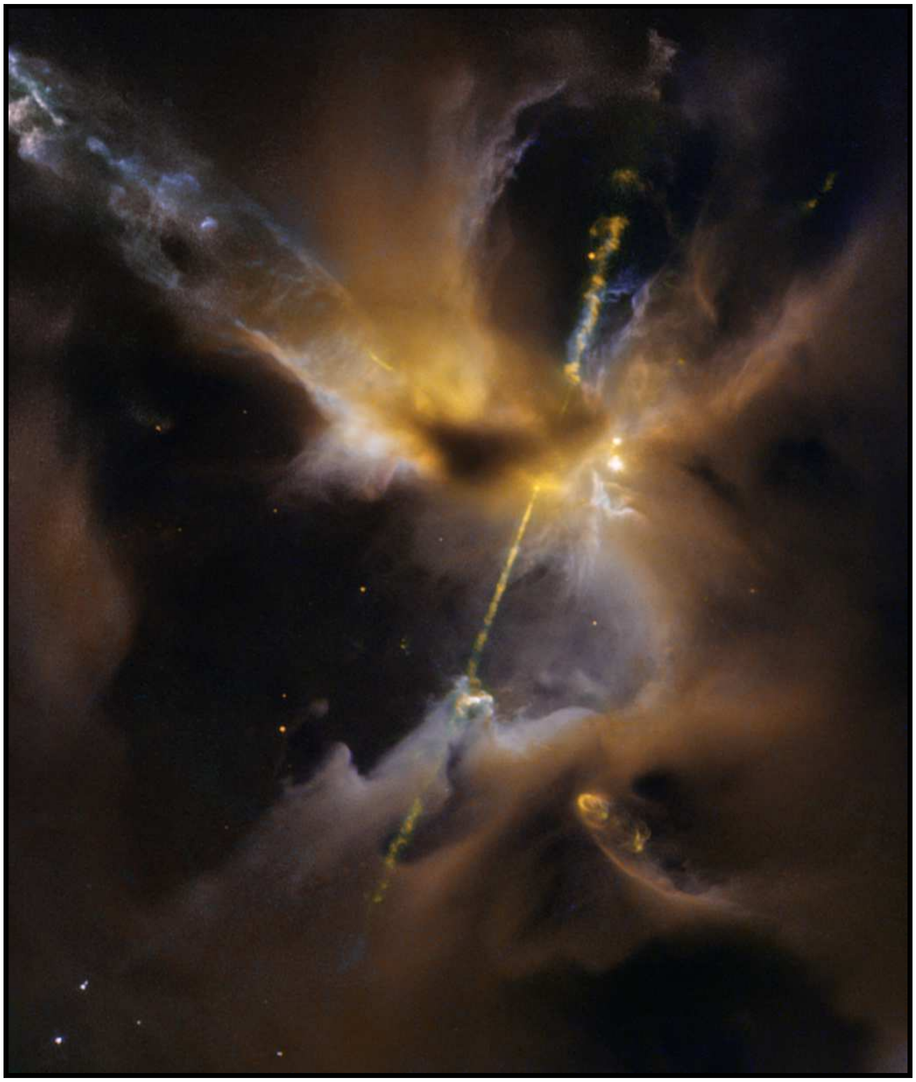
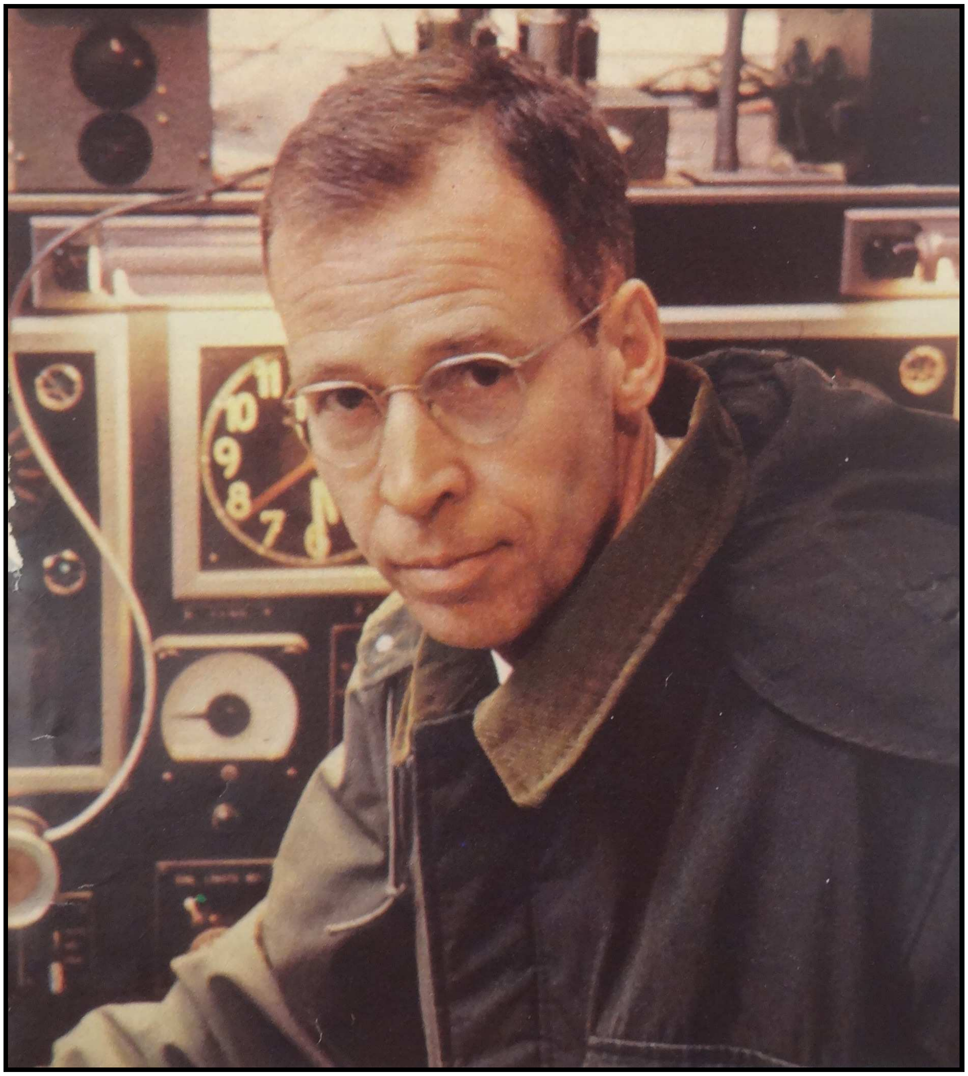
George Herbig
and Early Stellar Evolution



Bo Reipurth

Institute for Astronomy Special Publications No. 1



George Herbig in 1960

George Herbig
and Early Stellar Evolution

Bo Reipurth

Institute for Astronomy
University of Hawaii at Manoa
640 North Aohoku Place
Hilo, HI 96720
USA

.

Dedicated to Hannelore Herbig

Version 1.0 – April 19, 2016

Cover Image: *The HH 24 complex in the Lynds 1630 cloud in Orion was discovered by Herbig and Kuhi in 1963. This near-infrared HST image shows several collimated Herbig-Haro jets emanating from an embedded multiple system of T Tauri stars. Courtesy Space Telescope Science Institute.*

This book can be referenced as follows:
Reipurth, B. 2016, http://ifa.hawaii.edu/SP1

FOREWORD

I first learned about George Herbig's work when I was a teenager. I grew up in Denmark in the 1950s, a time when Europe was healing the wounds after the ravages of the Second World War. Already at the age of 7 I had fallen in love with astronomy, but information was very hard to come by in those days, so I scraped together what I could, mainly relying on the local library. At some point I was introduced to the magazine Sky and Telescope, and soon invested my pocket money in a subscription. Every month I would sit at our dining room table with a dictionary and work my way through the latest issue. In one issue I read about Herbig-Haro objects, and I was completely mesmerized that these objects could be signposts of the formation of stars, and I dreamt about some day being able to contribute to this field of study. As fate would have it, Herbig-Haro objects did become my main focus after I became a professional astronomer. But it was not until I was 40 that I got to meet and talk to George Herbig in person, when he attended a conference I was organizing at ESO in Germany. Afterwards we had occasional correspondence.

After Herbig retired from the University of California in 1987, he moved to Honolulu and took up a professorship at the Institute for Astronomy at the University of Hawaii in order to focus exclusively on his research. Later, in 2001, I also moved to the University of Hawaii, and soon we developed strong scientific and personal ties, meeting frequently for lunch or dinner to talk about the latest results in star formation.

During the last year of his life, when Herbig's health started to decline, he asked me to act as his scientific executor and to take care of his voluminous writings, documents, notes, letters, and data. Herbig was a highly organized and disciplined person, and his archives are full of meticulous notes on his numerous projects, both completed and unfinished, from his entire career. Of special interest is his carefully kept collection of thousands of letters exchanged with essentially all of the leading astronomers of the 20th century.

Herbig never wrote a full length memoir, but he left extensive notes and comments about his work and times. And sometime in his mid-seventies, he decided to put together a brief account of his scientific endeavours up to that time, notes meant only for his family. But shortly before his death, he gave me a copy of these autobiographical sketches. With the permission of his wife, Hannelore Herbig, I will throughout the present book cite from this material, as well as from many other documents, letters, and extensive notes found among Herbig's archives. In doing so, I hope to give voice to Herbig on many of the epochal events and scientific results throughout his life. Written by hand on the cover of his autobiographical notes, Herbig added *"... perhaps it may* *prove useful to that hapless soul who has to write my obituary."* Indeed I have found it very useful, and quotes from Herbig's various writings will appear in italics throughout this book. The autobiographical notes are introduced thus:

> *"For reasons not entirely clear, I have thought it worthwhile to try to put down a kind of inventory or outline of the various astronomical activities that I have pursued, and how my involvement in each of them came about – to the extent that I can remember or reconstruct reasons and motives at this late date (January 1993). The scornful phrase 'jack of all trades, master of none' has more than once come to my mind, for I recall old-timers speaking with contempt of colleagues who frittered away their energies on a host of activities, rather than spending their lives bearing down hard in a single area. Probably my uneasiness about the checkered nature of my own career arises from recollection of such scornful remarks by conservatives, Paul Merrill and Joseph Moore in particular, who I heard on such matters in my early days. Obviously, I did not hew closely to their examples or their admonitions."*

From this brief quote, two of Herbig's characteristics are evident: his complete lack of awe over his many and major contributions to science, and his unique mastery of the written word.

This book attempts to give an overview of the scientific life of George Herbig. Little will be said about Herbig's personal life, mainly because scientists generally live dynamic lives in their minds, while living unremarkable daily lives. Herbig was no exception, he enjoyed a quiet life, was happily married to his wife Hannelore, and spent all of his time doing great intellectual voyages. In the course of these journeys, he nearly singlehandedly built the foundation for the observational study of infant stars. Almost all papers published today on young stars rest in some way on the results established by Herbig.

The Danish philosopher Søren Kirkegård said "We live life forwards, but understand it backwards". When new ideas are developed and refined over time, what in hindsight appears as a gradual but ordered evolution of a subject towards a correct answer in reality was often a chaotic process, with much groping in darkness for answers, and with many explorations of blind alleys. While Herbig ultimately succeeded in establishing the foundations for the modern view of early stellar evolution, also he from time to time embraced ideas that he later realized were inconsistent with observations, his own or others. This self-correcting process is at the heart of scientific progress. To the extent that such forks in the road are reflected in the literature, I have attempted to describe the wrong turns.

It should be emphasized that this book is not a general history of how star formation studies have unfolded over time, and no attempt has been made to mention all important papers in the history of the field. The focus here is on Herbig's pioneering work, and other studies are discussed only as context for the development of his ideas, or to show how a subject has later evolved. Herbig tended to open up a new field, work on it only long enough to establish the foundation and the key facts, and then move on to new ideas and endeavors, often leaving it to others to polish the details.

While efforts have been made to write this book so it is also understandable for a more general readership, the audience that the book targets is drawn from researchers and advanced students, who know the terminology of the field of star formation, and who understand the underlying scientific issues. Other readers who may wish to first get an overview of the field of star formation can read the popular-level book by Bally & Reipurth '*The Birth of Stars and Planets'* from Cambridge University Press.

Many people have contributed to the present book, for a full list see the Acknowledgements, and I am grateful to all. First and foremost I wish to thank Hannelore Herbig, who has been indefatigable in answering my many questions, in finding photos, and in facilitating my work with Herbig's major collections of documents.

Bo Reipurth

CONTENTS

1 THE BUDDING ASTRONOMER

1.1 Early Years

George Howard Herbig was born on Wheeling Island in West Virginia on January 2, 1920. His father, George Albert Herbig, was born in 1873 in Dirschau, West Prussia (now Tczew, Poland), and emigrated in 1885 with his parents and siblings to the United States. Here he met Glenna Howard, who was born in 1884 in Ohio, and they married in 1906 (Figure 1). Herbig was a single child, and grew up in comfortable although modest circumstances. His father was a tailor, as were all his uncles and his grandfather, and the father operated a tailor shop in an upper floor of an office building on the main street of Wheeling. Apparently the prosperity of this enterprise rose and fell with that of the coal-mining industry that dominated the region, and which supported many of his customers. But in 1926 disaster befell the little family when Herbig's father got appendicitis, the appendix ruptured, peritonitis followed and he died. Herbig writes:

> *"After his death, my mother tried to run the tailor shop herself, with the help of some woman who had worked for my father. I remember afternoons there after school: a big table (where I was told my father used to work, sitting cross-legged), tea with milk and toast made on an electric hot plate; playing with different colors of tailors' chalk. I don't know what tailoring experience my mother had: probably only what she had learned helping my father. But after 2 or 3 years she gave up, disposed of the shop, and with the money left from his life insurance, we went to California."*[1]

Herbig and his mother lived in California for several years (Figure 2), but after the 1929 Wall Street crash occurred, times became hard for everybody. They moved frequently, searching for work, both on the East and West Coast, until finally settling in Los Angeles, where Herbig was enrolled in the Polytechnic High School. At that time, he had discovered the public libraries and had developed an intense interest in astronomy.

> *"I read Jeans' popular books with some comprehension, Eddington with very little, one of Baker's textbooks, and especially a book by Kelvin McKready ('Field Book of the Stars' or something like that, I think), which I can still open with a thrill of delight."*[1]

Meanwhile, at high school, he was

> *"... compiling a highly undistinguished record. I don't know whether I was basically stupid, or uninterested, or too occupied with my hobby, or lazy – probably a combination of all these – but my grades were poor. Considering*

Figure 1: *George Herbig's parents in Wheeling, West Virginia around 1910.*

Figure 2: *George Herbig in 1930 at age 10 yr while he and his mother stayed at Long Beach, California.*

my ultimate profession, it is amusing that I found geometry and physics especially opaque, and was awarded rousing D's and F's as a consequence. [...] My only two academic interests in High School were chemistry, in which I majored, and photography, [and I learned] a lot about the photographic techniques of that era, which I found very useful in subsequent years. [...] I did rather well in chemistry. My mother wanted me to become a chemist because it allegedly paid well [...] and didn't encourage my dreams about becoming an astronomer."[1]

As so many teenage amateur astronomers, Herbig longed to have his own telescope, but commercial telescopes were far too expensive, and it became clear that he would have to build one himself. At that point, he joined the Los Angeles Astronomical Society.

"The 'Society', which was to become my utter absorption for about 4 or 5 years, was located in some rough garage-like rooms behind a residence [...] Its guiding spirit was an elderly, lantern-jawed man named Archie M. Newton, a printer by trade, whose hobby was telescope making, and who was perennial president of the organization. He lived in the front house and was usually on hand in the club rooms, which contained a 6-inch lathe, a drill press, equipment for cutting and grinding glass, etc. etc., all stained red from optical rouge or crystalline grey from carborundum mud. [...] For those years, while I was in High School, I spent every free minute at the Society: afternoons, Thursday evenings when the old-timers gathered, and all day Saturdays and Sundays. My mother was angry at my complete involvement in telescope making and astronomy, but I didn't care. The dues were $6 per year, which I managed to find. I loved every minute of it, and every corner of the club rooms. I remember I was there one afternoon when word came of the outbreak of World War II in Poland. It was here, in my first months of membership, that I made an 8 1/2-inch plateglass mirror, the 45° flat for it, managed to pay for a 3/4-inch Ramsden eyepiece, built an atrocious yoke mounting of black-painted redwood, with floor flanges for bearings. I was an utter dub at matters mechanical: I could never have done this without the patient help of men like Newton, a real estate agent named George Bartlett, a policeman named Russell Booker, and a gravel-voiced professional optician named Jimmy Herron. [...] Due to utter devotion and unlimited time, I gradually became a fixture at the Society. [...] In time, I became Secretary of the Society, and my reports of the meetings and excursions appeared in fine print in the back pages of Popular Astronomy."[1]

With his new telescope, Herbig explored the sky, made drawings of the planets, drew meticulous maps of star fields, projected sunspots on a screen. But eventually he found his passion in variable stars, which he observed with ded-

Figure 3: *Herbig (left) as a teenager with members of the Los Angeles Amateur Astronomical Society at Lake Elsinore, California in the winter 1938-39.*

Figure 4: *Herbig at a telescope built by Jimmy Herron (optics) and Lynn Hildom (mechanics), both from the Los Angeles Amateur Astronomical Society. Photo by Lynn Hildom. From the LAAS 50th Anniversary Bulletin.*

ication and enthusiasm, to the point where Leon Campbell (then the AAVSO Recorder) gently had to tell him that it was unnecessary to observe R Andromeda *every* night; once every ten days would suffice.

Then fate intervened once again in Herbig's life. His mother had for some time been in failing health, probably exacerbated by the hardships she had suffered while trying to keep them afloat financially, and in September 1938 she died from cardiac arrest. Herbig, then a lad of 18 just out of high school, suddenly was on his own, utterly unprepared to fend for himself. But then, as sometimes happens in the middle of a desperate situation, a savior appears, in this case in the form of a well-to-do business man, Charles "Jack" Preston. He and Herbig had met at the Astronomical Society, where Herbig apparently had impressed him with his obvious abilities. Jack Preston now stepped in and invited the young man to spend time and get on his feet at a vacation home in the mountains near Lake Elsinore, to which Preston's father, also an amateur astronomer, had retired (Figures 3,4). For four months, until he could start in college, Herbig stayed with the elder Preston,[2] was well fed, observed under clearer skies than he had known before, and prepared himself for the new life that was awaiting him at the University of California at Los Angeles, where he had been accepted for the spring 1939 semester. In February 1939, the Prestons brought Herbig back to Los Angeles, where he had located a place with room-and-board near UCLA.

1.2 UCLA and Griffith Observatory

During the first term at UCLA, Herbig worked as a clerical assistant to Frederick C. Leonard, who was chairman of the Department of Astronomy, which he had founded and ruled with an iron hand. He had a *"frosty, opinionated, and off-putting exterior"*, but as Herbig was to find out, behind it was a kind and warm-hearted man.[3] Herbig's salary was $20 per month, which was just barely enough to keep him alive (he later said that during that time he lived on French bread and butter milk, and shared a single room in a boarding house with one, sometimes two, students). In the beginning he did not do very well academically, but he must have done well enough that Leonard at the end of the first semester recommended him for a part time student job at Griffith Observatory, the planetarium and public observatory in the foothills above Los Angeles (Figures 5,6). He and other college students

> *"... gave explanations of the exhibits, ran the telescope, and assisted around the place during several afternoon-evenings per week. The salary was $50 per month, which was a princely sum indeed in my world. I kept this job until graduating from UCLA in October 1943. [...] In many ways, Griffith was a wonderful place: a lot of kidding around, a lot of eyeing pretty visitors, a lot*

Figure 5: *Griffith Observatory above Los Angeles.*

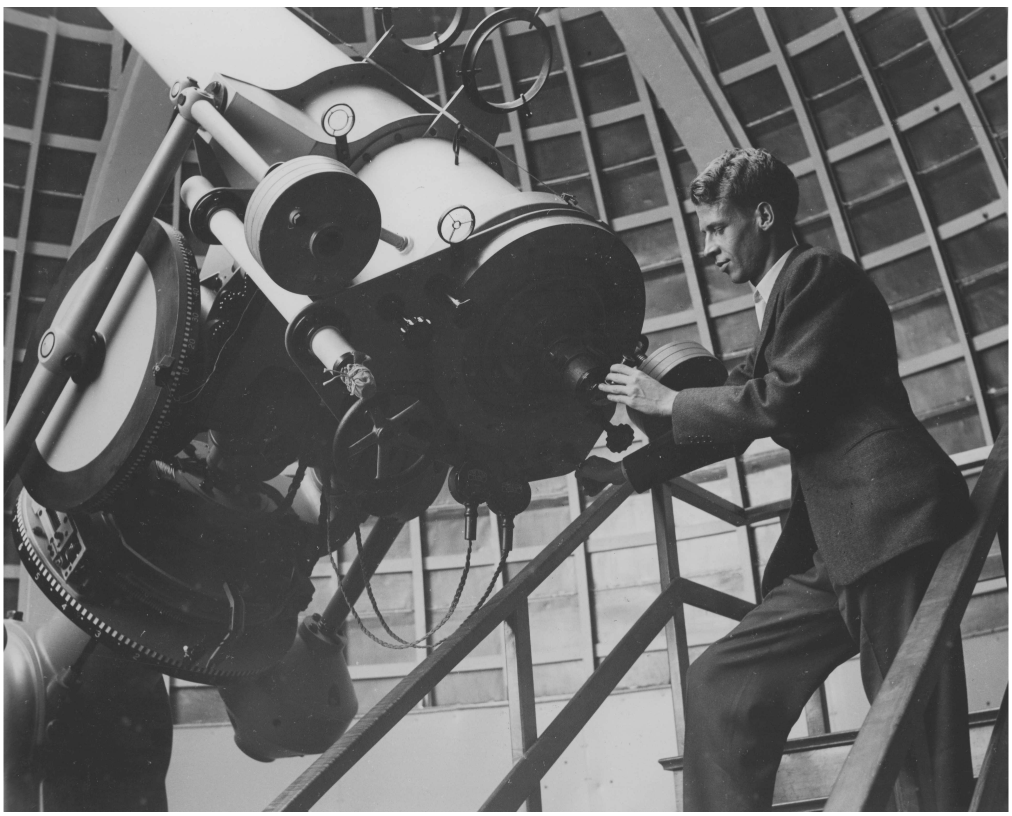


Figure 6: *During his undergraduate studies in the early 1940s, Herbig worked as an assistant at Griffith Observatory showing the sky and the exhibits to the public.*

of sitting in the library during slack hours. My experience with photography in high school, and a certain neatness in lettering, proved useful here: an increasing fraction of my time went into taking photos for the Observatory guide book and magazine, and making drawings of one kind or another. I had a little empire of my own in the photographic darkroom, where I loafed many an hour away, [...] Often I slept on the concrete darkroom floor on nights when it was too late to catch the last bus back"[1] (Figure 7).

Figure 7: *Herbig in the Griffith Observatory darkroom, where he reigned during the early 1940s.*

During the years 1939-1943 at UCLA and Griffith, Herbig started to take

"... a somewhat more serious attitude toward my studies, and my grades improved, although I never crowded anyone for Phi Beta Kappa recognition. I think in my senior year I was elected to Pi Mu Epsilon, the mathematics honor society; this was a mild surprise since I never considered myself even remotely competent as a mathematician. I won something called the Houghton Key, given to a member of Sigma Xi (the science honorary) considered superior in some fashion. I graduated with honors in astronomy. So, my undergraduate years wound up in a moderately commendable style on the academic side, although they began with every promise of disaster."[1]

USA entered the war in 1941, and it soon had an impact on the college. Celestial navigation became an important offering of the Astronomy Department.

Many of Herbig's friends were sent overseas, although he himself was exempted on account of a lifelong weak back. Upon graduating from UCLA and as part of the war effort, Herbig took up an unspecified physicist position to do classified work at the Radiation Laboratory in Berkeley. Much later he learned that it was

> *"... the Berkeley project for developing technology for the separation of uranium isotopes with mass spectrographs, a process which was later put into full-scale production at Oak Ridge. I was just a callow graduating senior in astronomy at UCLA in October 1943, with no prospects for further education because all the graduate schools were then effectively closed down, and with no prospects for other employment except in war industries."*[1]

The work turned out to involve climbing around in a large steel tank and doing unexplained things with mysterious mechanisms, a very unsatisfactory situation for a young person deeply interested in understanding things.

1.3 Assistantship at Lick Observatory

On a day off, Herbig went to Lick Observatory on Mt. Hamilton to visit Frederick Leonard, who spent half a year there on a sabbatical. Herbig was fascinated with the observatory, and since many of the astronomers were away on war work, they were under-staffed and in great need of assistants. Apparently Leonard had a conversation with the then Director of the observatory, J.H. Moore, and an offer for an assistantship[4] was made to Herbig, who gladly accepted. Herbig had recently married[5], so towards the end of 1943 the young couple moved into a small apartment in the Old Dormitory on top of Mt. Hamilton.

> *"Thus began my long association with the Lick Observatory. There were a few visitors on hand: Leonard and Julie Vinter Hansen I remember especially, but the old gentlemen of the staff did not press the telescopes very hard, while I was in my element. I had every opportunity to use the 36-inch refractor* [Figures 8,9a]*, but didn't find out how even to open the Crossley dome until Lawrence Aller, then in the Theoretical Division at the Radiation Laboratory, came up on a weekend to observe and showed me how* [Figure 9b]*. My Observatory duties were to take double-star plates with Jeffers' automatic camera at the 36-inch, to work on the measurement and reduction of comet plates in Jeffers' program, and to take care of the clock corrections. None of this occupied very much of my time (especially the first, which languished from the start), and I photographed planets at the 36-inch*[6]*, comets at the Crossley, learned the spectrographic ropes at the 36-inch. Doctor Moore encouraged me to read A.B. Wyse's paper on the*

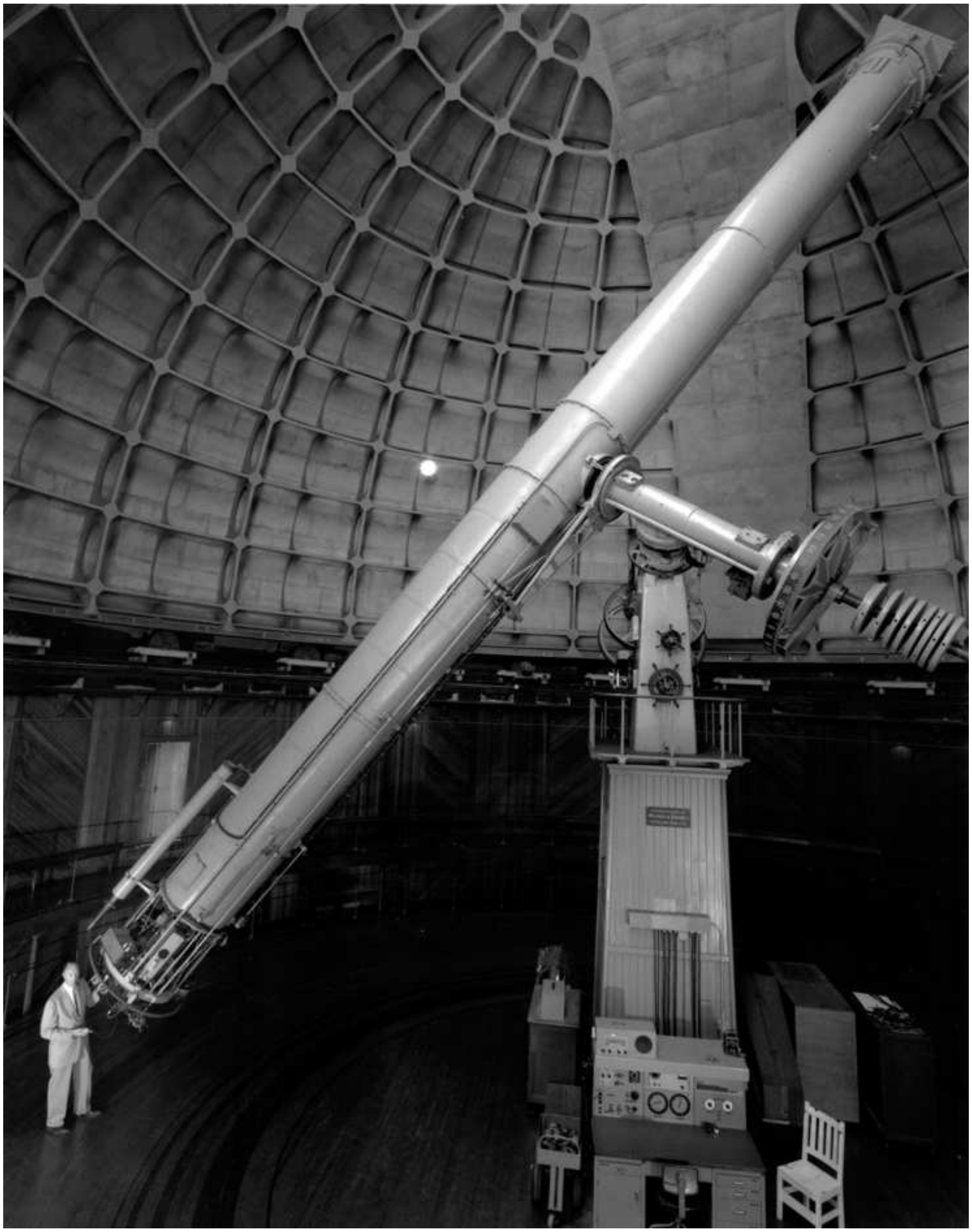


Figure 8: *The Lick 36-inch refractor, which Herbig used extensively from 1943 until 1959, when the Lick 120-inch reflector went into operation.*

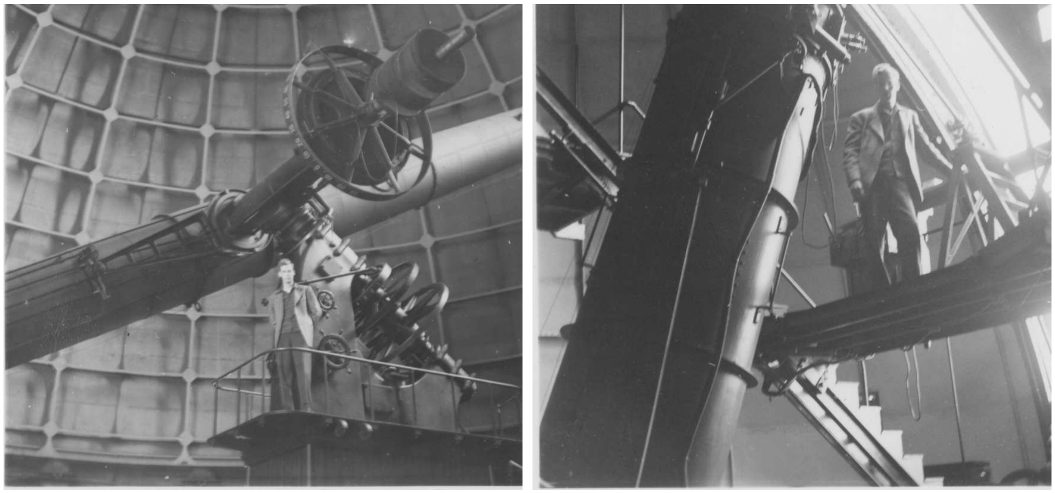


Figure 9: *Herbig at the 36-inch refractor (left) and the 36-inch Crossley reflector (right) soon after starting his assistantship at Lick Observatory.*

spectra of eclipsing binaries in the Lick Bulletins, and suggested that I observe and work up some of the systems that Wyse had just begun. This was the origin of my paper on ZZ Cep and UY Vir, that ultimately appeared in the Ap.J. Among my other duties was the disposition of the effects of Wyse, the very promising Lick astronomer who was killed in a blimp accident in 1941. In the process of all this, I became familiar with the Lick work on novae, and as a consequence eagerly observed the spectra of T Pyx in 1944, Nova Aql 1945, and T CrB in 1946. I doubt if science profited very much from my published reports on these observations, but I learned a great deal. I ground out two Lick Bulletins *filled with comet and asteroid positions, and in general worked in all directions on all kind of projects with my breathless, semi-amateurish enthusiasm. In time, I became Jack-of-all-trades at the Observatory. I knew how to assemble all kinds of unconventional spectroscopic combinations, where forgotten apparatus was hidden, how some mysterious machine worked (the Ross photometer, the Schraffierkasette, the Crossley nebular spectrograph and the Wright quartz spectrographs, and so forth), where old records were to be found. I soaked up ancient Lick lore from Moore and Wright and Neubauer, all of whom loved to spin tales of the old days. [...] Moore was a kindly old man, a little stiff and stern at times, who filled me with his stories of Lick eclipse expeditions, of the Chile station, of long-gone great names in astronomy, of why thus-and-so was necessary to eke the ultimate efficiency out of a prism spectrograph. Wright was the former Director, who had been called back to the Observatory from retirement when the younger staff left for war work (these were Jeffers,* *Wyse, Kron, and Mayall). Wright was a slow and deliberate old man, tall but a little stooped, with a long face, a petrifying stare, and a cold Olympian air that utterly awed me. But he was a very, very sharp man despite his age: he really knew whereof he spoke, and on optics, mechanisms, the old-style spectroscopy, telescopes, his depth of knowledge was devastating to an astronomical stripling like me."*[1]

1.4 Alfred Joy

At this point, we must go back in time to introduce a person who had a deep and lasting influence on Herbig's career. Through his membership in the Los Angeles Astronomical Society, Herbig had from time to time the opportunity to listen to popular lectures by some of the great names in astronomy at that time. Among these was Alfred Joy, an astronomer at Mt. Wilson Observatory, which at that time housed the largest telescope in the world, the 100-inch Hooker telescope. More or less accidentally, Herbig was introduced to Joy, who at the time needed someone to do tests on photographic emulsions, and so started an association that had a profound impact on the young Herbig.

"I got to know Joy very well, and spent many a fascinated hour with him in his little office at the end of the cross corridor on the second floor at Santa Barbara Street. I remember on one of my first visits being shown the drawings for his big paper on the velocity curves of Cepheids, and how he talked gravely and patiently with this eager, but oh-so-ignorant 18-year old. Sometimes when I am impatient with some too-ebullient amateur, I try to subdue myself and think of gentle, white-haired "Doctor Joy", with his fine clear features, and soft voice, and great kindness."[1]

When Joy died in 1973 at the age of 90, Herbig wrote his obituary, and there included the recollection of when Joy invited him for his first night at Mt. Wilson Observatory:

"I remember well the first time that I saw a star in a large telescope: on a chill autumn evening in 1938, Joy showed an awed teenager the boiling red disk of Mira on the slit of the 100-in. coudé spectrograph, and how to press the control buttons that persuaded the leaping foaming mass of light to remain where it should. And later, in the darkroom, he carefully showed me how to hold the dripping spectrogram, and patiently pointed out the intricate structure in Hγ and Hδ. It was an experience one does not forget."

Joy was a spectroscopist interested in a wide variety of stars, and at the time Herbig met him he was working on M and Me dwarfs. In 1942 Joy was studying the variable late-type star UZ Tau, but quickly realized that this object was different from the Me stars. Additional similar variables were found, and this culminated in Joy's famous paper on the "T Tauri Variables" from 1945, in which the characteristics of the T Tauri stars were defined.

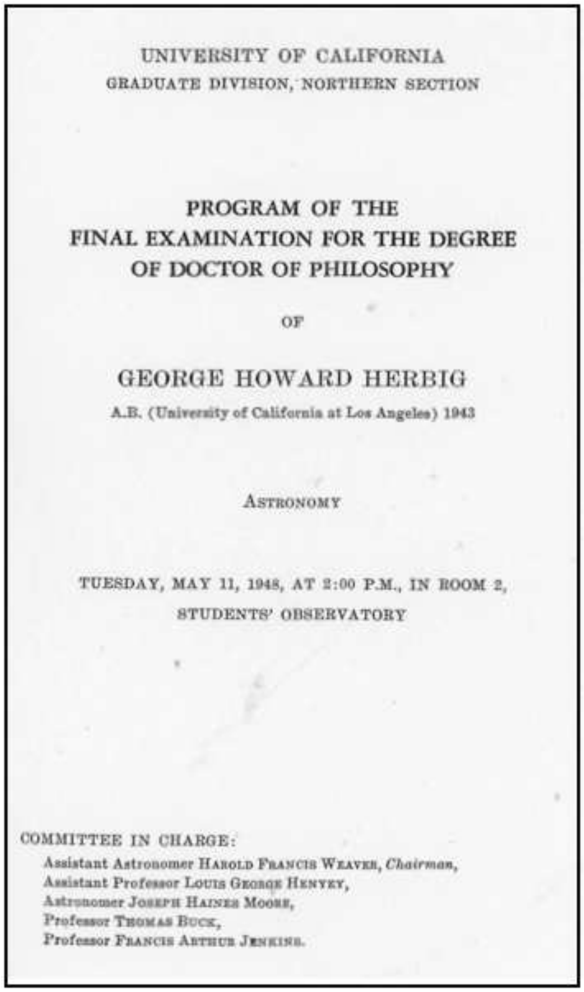
Joy had talked to Herbig about this new category of stars, and it must have planted a seed, because eventually this became the topic of Herbig's PhD thesis. Joy was thus an important mentor for the young man. As we shall see shortly, two more men, Baade and Struve, were also to have a lasting impact on Herbig.

1.5 PhD at Berkeley

During 1944-45 Herbig was engaged, with seemingly boundless energy, in the operation of Lick Observatory at Mt. Hamilton. The older astronomers must have been impressed with his dedication and skills, and realized that the young man was cut out for more than a position as a telescope assistant. Herbig notes:

> *"Sometime during this period I was encouraged to think that the wartime availability of the telescopes might be turned to my future advantage if I took the opportunity to collect material for an eventual Ph.D. thesis. It was probably Leonard with Moore's approval who broached the idea, and it led to the spectrophotometry of RW Aur and WW Vul and my ultimate deep involvement with the T Tauri stars. It was while working away on this plan (before ever stepping into the Berkeley Department of Astronomy!) that I explained the fluorescent Fe I lines in T Tauri stars, stumbled across V380 Ori, discovered the Hα emission in T Ori, and noted on Crossley direct plates centered on NGC 1999 the peculiar little luminous "clots" (as I called them) of nebulosity that were the first Herbig-Haro Objects. I don't know how I decided to do a thesis in this particular subject; certainly my early talks with Joy had filled me with ideas on the matter, and I sought his advice in 1945-47 when at work on these stars. But the precise point of commitment I cannot reconstruct. I regard it as a tribute to Moore that he let me, an untutored kid, go ahead on this problem of which neither he or anyone else at Lick or in Berkeley knew a thing. When C.D. Shane came to Mount Hamilton just after the war as the new Director – it must have been in late 1945 – I explained my work to him, and how I intended to move to Berkeley in the fall of 1946. He raised no objection, and went along with Moore's practice of allowing me to count the thesis activity as part of my assistantship duties."*[1]

In the early fall of 1946, Herbig and his wife left Mt. Hamilton and moved to Berkeley. Shane had told Herbig that if he did well in Berkeley, it was the intention to give him a position as staff astronomer at Lick Observatory after he graduated[7]. This was a remarkable offer, and ensured that Herbig worked with


UNIVERSITY OF CALIFORNIA
GRADUATE DIVISION, NORTHERN SECTION

PROGRAM OF THE
FINAL EXAMINATION FOR THE DEGREE
OF DOCTOR OF PHILOSOPHY

OF

GEORGE HOWARD HERBIG
A.B. (University of California at Los Angeles) 1943

ASTRONOMY

TUESDAY, MAY 11, 1948, AT 2:00 P.M., IN ROOM 2,
STUDENTS' OBSERVATORY

COMMITTEE IN CHARGE:
Assistant Astronomer HAROLD FRANCIS WEAVER, *Chairman*,
Assistant Professor LOUIS GEORGE HENYEY,
Astronomer JOSEPH HAINES MOORE,
Professor THOMAS BUCK,
Professor FRANCIS ARTHUR JENKINS.

Figure 10: *At the age of 28, Herbig defended his PhD dissertation at the University of California, Berkeley.*

great focus towards his PhD. He had also received a Martin Kellogg Fellowship (about $1500 per year), which allowed him to focus exclusively on his studies without having to worry about investing time as a teaching assistant. Even more importantly, during the previous two years, Herbig had accumulated a wealth of observations, some of them already analyzed and published, which would form the core of his thesis.

> *"I was driven through graduate school by the hideous fear of getting anything short of straight A's in all subjects. I slipped only once: a B in the second semester of partial differential equations. I cannot say that I was any more intelligent than at UCLA, six years before, but now I had a maturity, a*

feeling for how to go about learning a subject, and immense incentive: a staff position at Lick at the end of the line."[1]

Shane kept his promise and on November 4, 1947 he requested to the president of the University of California that a position as Junior Astronomer be made ready for Herbig. In the letter one can read: "Mr. Herbig while in the Lick Observatory proved himself to be an outstanding and most energetic observer. His work is well planned and carried out with accuracy and intelligence. He has, moreover, shown excellent ability and judgment in interpreting his observations. He has acquired a fine command of the literature of his subject. He reads and absorbs practically everything in his field and can carry the results of his reading in his mind to such an extent that members of the staff of Lick Observatory found it most useful to consult him in many matters pertaining to astronomical literature."

On Tuesday May 11, 1948, Herbig successfully defended his thesis (Figure 10), and a new life began for him.

Figure 11: *Herbig with Katherine Kron from Lick Observatory, Walter Baade from Mt. Wilson Observatory (middle), and Harold Weaver (right) from University of California Berkeley, later to become chairman of Herbig's dissertation committee. Image taken in June 1946 during the Astronomical Society of the Pacific meeting in Reno, Nevada.*

1.6 Pasadena, Yerkes, McDonald Observatory

Harold Weaver was the chairman of Herbig's thesis committee (Figure 11), and he suggested that Herbig should take a year off to spend time at some other of the main astronomical centers of that time. Shane did offer Herbig the position as Junior Astronomer from July 1948, but agreed to allow him a year's leave of absence. Equipped with a National Research Council Fellowship, Herbig would then spend time first in Pasadena and at Mt. Wilson Observatory, and later at Yerkes Observatory and McDonald Observatory.

> *"That summer I spent at Santa Barbara Street trying to get estimates of the titanium isotope abundance from plates of M and S stars in the Mount Wilson files. I also did a little observing with the 100-inch coudé to the same end. Abundance ratios from eye-estimates of band strengths are not entitled to much respect, but I think it was shown that there are no gross deviations from the terrestrial ratios. Fascinating to me was the chance to go through the luncheon ritual every day with the regulars [including Bowen, Joy, Merrill, and Sanford] at a little restaurant on Euclid Avenue (since vanished). Of course I was in awe of these great men and tried not to be too obtrusive. [...] Walter Baade was not one of the lunch-time old guard. He ate alone in his office, where I talked to him as often as I could find an excuse, both during that summer as well as in the years before and after. [...] Baade delighted to talk with great animation about all aspects of astronomy and astronomical technique, and would illustrate his points with exquisite direct plates from the cabinet beside his desk. He was a marvelously jovial, hearty man of infinite generosity and wisdom. He got me started on the nebulae at T Tauri by stories of Burnham and Hubble, illustrated by his superb 100-inch direct plate of 1938. [...] He had a broad understanding of all aspects of stellar and extragalactic astronomy, and I think welcomed visitors into his office in the hope of filling them with such enthusiasm over some job that Baade felt should be done, that they would hurry away and tackle it themselves. He was utterly unselfish: he felt no proprietary interest so far as I could see in any of his ideas. The important thing was to get the work done: let's find out about this! [...] A wonderful astronomer indeed, but he published so little that one could appreciate him properly only through personal contact. I certainly am the better for knowing him."*[1]

The summer at Pasadena was a very stimulating time for Herbig, but it passed quickly. He must have been making a good impression, because not long after he was offered a staff position there by Bowen, and a few years later the offer was extended again by Horace Babcock. Herbig declined, feeling an affinity for Lick Observatory. But first he was going to Yerkes and McDonald.

In October 1948, Herbig bought his first car, and he and his wife Delia drove east to work at Yerkes Observatory in Wisconsin. Yerkes had been a powerhouse in astronomy since Otto Struve took over the direction in the late 1930's. Struve had hired some of the great astronomers of the 20th century, and when Herbig visited he met Chandrasekhar, Kuiper, Morgan, Bidelman, Münch and others. After Struve left, Yerkes started to quietly fade.

> *"But in 1948-49 it was the most lively astronomical organization I have ever seen: an exciting, stimulating place to work. I turned out in my 8-9 months there some respectable contributions: on the spectra of the Orion Nebula variables, on the close nebulosity at T Tauri, on the spectrum of R CrB at minimum. And I think that the atmosphere of the place was a real factor in getting those papers out. There were good people on every hand, working hard, doing good things – what more can one wish?"*[1]

Herbig also got the opportunity to observe with the 40-inch refractor:

> *"At Yerkes, my plan was to try to duplicate the early 40-inch direct plates of the Orion Nebula to obtain proper motions for the stars within. [...] I did obtain a couple of indifferent second-epoch plates with the parallax camera of the 40-inch, but went no further with the project because of other more interesting opportunities that arose that winter of 1948-49. It was taken up by Kaj Strand some years later, and carried through properly."*[1]

Herbig's real interest was in observing with the 82-inch telescope at McDonald Observatory, then the second-largest telescope in the world[8] (Figure 12). It was

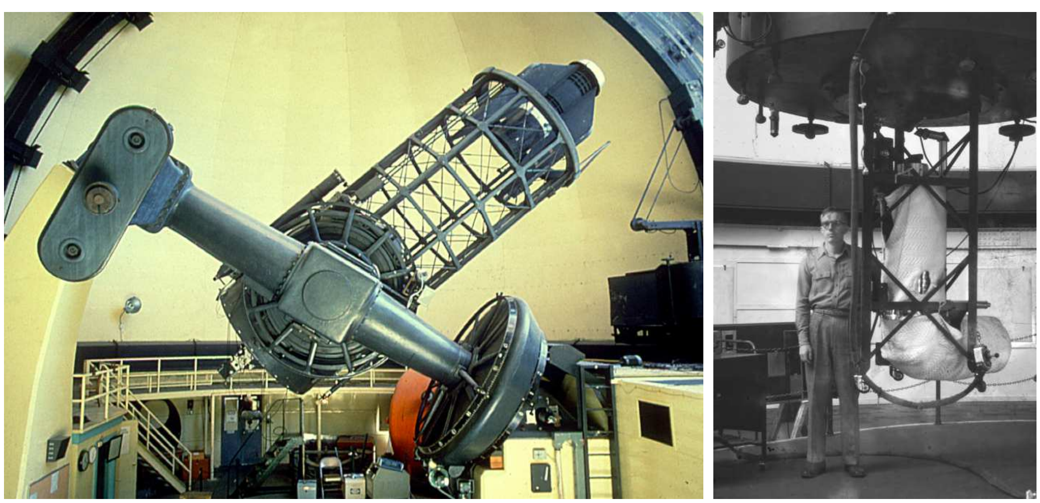


Figure 12: *(left) The 82-inch Otto Struve Telescope at McDonald Observatory. (right) Herbig at the Cassegrain focus of the 82-inch telescope during the winter 1948/49.*

at that time operated under contract by the University of Chicago, and Otto Struve was the director. During the 8-9 months of Herbig's stay at Yerkes, he had the opportunity to drive down to McDonald Observatory, where he met Struve, who left a powerful impression on the young man. After Struve died, Herbig edited a book about Struve's major contributions to spectroscopic astrophysics, and in his foreword, Herbig wrote:

> *"I found Otto Struve to be a very tired, but a kind and exceedingly generous man. He was an unfailing source of three commodities that at a certain stage in one's career are more precious than gold: support, encouragement, appreciation. Much of Struve's words and actions were due, I think, to the fact that he believed astronomy to be a terribly important matter, so important that it was entirely justifiable for one to wrap himself in it to the exclusion of almost everything else. With Struve, astronomy was no eight-to-five, Monday-through-Friday occupation, any more than was the act of breathing. It was his life, his* raison d'être*. There is a story at Yerkes that, following an evening staff meeting over which Struve presided, the faculty went home to bed while Struve went up to the 40-inch dome to observe for the rest of the night. To a young man, this energy and all-encompassing devotion that Struve poured into astronomy was an inspiration. Struve gave the impression that the sky was filled with marvelous and important things, free for joyful harvesting by anyone with perception and the opportunity. It was unforgivable in his eyes for anyone to fall short of full commitment: his harshest judgments descended upon those who through sloth, distraction, or weakness of will failed to take full advantage of their scientific opportunities. I found this a stern philosophy on bitter nights when sixty-mile-an-hour winds roared around the open dome, and snow blew down on the spectrograph, and the seeing disc exploded to the point of invisibility. Perhaps the basic reason for Struve's success is that he asked no more of anyone – on cold nights or otherwise – than he was prepared to give himself, and that he lived according to his own guideline: if astronomy is worth doing at all, it is worth everything that the individual astronomer can bring to it."*

In reading this laudatio to Struve, one wonders if Herbig here was really not also writing about himself: the words are a precise description of his own attitudes to the astronomical profession as they transpired in our numerous conversations during the last decade of his life. It seems that the young Herbig absorbed these attitudes during his time with Otto Struve.

During his stay at McDonald Observatory, Herbig got rich opportunities to observe with the 82-inch telescope, which he seized, resulting in a series of significant papers.

> *"It was interesting and exciting work. When night after night, T Tauri stars kept turning up in the Orion Nebula where I had supposed there were none. When R CrB slid down past mag. 10, and that weird emission-line spectrum came up – I could get the 82-inch to track at that far eastern hour angle only by hanging the heavy observing ladder on the back of the mirror cell for extra ballast. I got far more telescope time than I had expected because Struve spent half our nights downstairs in his office, dictating away to a recorder what later appeared as his book* Stellar Evolution*. On long guiding spells, he would bring the recorder up on the Cassegrain platform with him. And our joint run, originally scheduled for (I think) 1 1/2 months, went on for 3 months when our relief man (Kuiper) was held up in Williams Bay."*[6]

Herbig had developed a strong interest in faint stars towards the Orion Nebula Cluster:

> *"About the time I was born, Shapley had called attention to the large number of 'nebular' variables in the Orion Nebula. The Orion Trapezium Cluster of course had had a long history, going back to the first Otto Struve in the 1860s, Lord Rosse, one of the Bonds at Harvard, and other illustrious visual observers. But little was known of the spectra of the fainter stars in the Cluster, and so there was some interest on my part whether these stars were like the 'T Tauri variables' in the dark clouds of Taurus-Auriga, that Joy had described and named in his note of 1942 and his large paper of 1945. By the time I went to McDonald Joy was working on the fainter emission stars that had been picked up on the Mount Wilson objective-prism plates of the Taurus clouds. Joy did not go after the Orion Nebula stars, I suppose because of the bright background and their faintness. Struve and Greenstein had observed some of the brighter ones at McDonald, but had not gone faint enough to reach the TTS population. I was of course unaware that at about the same time, Haro in Mexico was at work on his objective-prism survey of Orion, which was to turn up hundreds of TTS, although not in the brightest part of the Nebula.*
>
> *Since I was planning to carry out the astrometry of the Orion Nebula Cluster at Yerkes (as already mentioned), the spectroscopy of these stars was a major item on my McDonald agenda. Spectrograms, of a quality that would be sneered at today, were obtained of about 19 stars in the Nebula. In those days, I was blissfully content with unwidened, underexposed low-dispersion photographic spectrograms and so was able to write a paper (1950) describing the spectra of these stars. There were indeed TTS among them (11 of the 19 had H and/or Ca II emission, some of them with veiled absorption lines), although none were found that had rich emission spectra like RW Aur and DG Tau. I have since that time wondered if this has something to do*

with the likelihood that circumstellar disks or envelopes around TTS in the Orion Nebula cluster have been scraped off by encounters with other cluster members.

I should mention that among the stars I observed at McDonald was XZ Tau, whose spectrum had already been described by Joy. While setting up, I noticed that there was another fainter star about 23″ away from XZ, so rotated the Cassegrain slit and took a spectrogram of the two together. I didn't make anything of this 'companion of XZ Tau' at the time, but of course it is now famous as HL Tau."[1]

In February 1949, Herbig returned to Yerkes, where he spent until June working on his new material. *"After this, we drove back westward, across South Dakota and Wyoming, and arrived at Mount Hamilton, broke and exhausted, in the first days of July 1949."*[1]

1.7 Lick Observatory

Herbig took up his position at Lick Observatory, and he lived up on Mt. Hamilton with his family, which eventually counted four children, in a house near the domes (Figure 13). Eventually, in 1966, all the astronomers moved down to the newly developed University of California campus at Santa Cruz. Upon formal retirement in 1987 from his position at Lick Observatory, Herbig and his second wife Hannelore, whom he had married in 1968, moved to Hawaii, where he became a professor at the University of Hawaii in Manoa. The body of research that Herbig made from the time of his PhD in 1948 until his death on October 12, 2013 is the subject of the following chapters.

Figure 13: *Lick Observatory as it appears today. The large 120-inch dome is in the background. The house where Herbig lived is in the foreground.*

2 THE T TAURI STARS

2.1 Joy's 1945 Paper

Alfred Joy was the first to identify the T Tauri stars as a distinct group of stars. The abstract of his famous 1945 paper commences as follows: "Eleven irregular variable stars have been observed whose physical characteristics seem much alike and yet are sufficiently different from other known classes of variables to warrant the recognition of a new type of variable stars whose prototype is T Tauri. The distinctive characteristics are: (1) irregular light-variations of about 3 mag., (2) spectral type F5-G5 with emission lines resembling the solar chromosphere, (3) low luminosity, and (4) association with dark or bright nebulosity. The stars included are RW Aur, UY Aur, R CrA, S CrA, RU Lup, R Mon, T Tau, RY Tau, UX Tau, UZ Tau, and XZ Tau." A modern image of the prototype T Tauri is shown in Figure 14.

Joy found that hydrogen lines were in emission in all eleven stars, and that the Ca II H and K lines were also in emission in all but one star (R CrA, which was later re-classified as a Herbig Ae/Be star). In all, he was able to identify 160 emission lines, and noted that many were found to be variable in intensity. He also noticed that for many of the stars the absorption lines generally used in classification were lacking, a first sign of the veiling of the photospheric spectrum that we now know is characteristic of young low-mass stars with high accretion rates. He was also fascinated by the fact that five of the eleven stars were visual binaries, a result that was published separately (Joy & van Biesbroeck 1944).

Joy named this new class of peculiar variables after T Tauri "because it is the best known, is among the brightest, and represents the group with respect to both emission and absorption spectra." As will be discussed further in Section 2.7, today's use of the term T Tauri star is much more relaxed, and many thousands of stars are now included in the category. It is ironic that T Tauri itself is no longer perceived as typical of the group, rather its characteristics of youth are now seen as especially advanced. This is also generally true for the other stars of the group identified by Joy, and it was thanks to their more extreme nature and their brightness that Joy took note of the stars. Today all of these eleven stars are among the best studied of their class.

Joy's intent with this paper was to characterize the T Tauri stars in as much detail as possible. He was satisfied to uncover the facts about the new stars, and did not make any speculations about the reason for their peculiarities. Neither he nor anyone else at that time had any idea that these were very young stars.

Figure 14: *T Tauri with its bright reflection nebula known as Hind's variable nebula. This variability is likely due to moving clouds near the star making a shadow play on the cloud surface. Courtesy Capella Observatory.*

Initially, Joy's work did not spawn any special interest within the community, and it was not until Herbig's major 1962 review that T Tauri stars became the focus of numerous studies. As a result, the young Herbig had the field fairly much to himself. About the germination of his interest in T Tauri stars, Herbig writes:

> *"I was turning to things that had stirred my interest since Joy had talked to me about the odd spectra of what he called 'T Tauri variables', that he had shown me in his office in Santa Barbara Street. The chapter on "Nebular Variables" in the Gaposchkins' book* Variable Stars *was another incentive, and I became seriously interested in what I called 'the interaction between stars and nebulosity', a phrase that I probably picked up from someone else. So I began observing stars of that ilk, encouraged even more by Moore's suggestion that since I intended to go on to Berkeley after the war, here was a chance to collect material for a future Ph.D. thesis. What an extraordinary opportunity! And really, what an extrapolation of my professional promise on Moore's part!"*[1]

2.2 RW Aur and V380 Ori

Herbig's first two studies of what we today recognize as young stars dealt with two stars that later were to become famous targets in the study of early stellar evolution.

RW Aur, an already known variable star, was listed as one of the original eleven T Tauri stars by Joy (1945). It was also discovered very early that RW Aur is a binary (Joy & van Biesbroeck 1944), thus beginning the study of young binaries, which has grown into a mature and very exciting field of study today.

Herbig got interested in the many Fe I lines often appearing in T Tauri spectra, and in particular in RW Aur. With his ample access to telescope time in 1943-46 as an assistant at Lick Observatory, Herbig took spectra of T Tauri stars and one result

> *"... was the recognition that a peculiar selectivity in the Fe I spectra of T Tauri stars was due to fluorescent excitation via a near-coincidence with the H line of Ca II. Fascinated by this process, I was later to pursue the same idea, first with Billy Bidelman on a note* [Bidelman & Herbig 1958] *on the excitation of Mn I 5341 in long-period variables by a coincidence involving Mg II 2795. Even later on* [Herbig 1968c] *I made a more complete examination of Mn I fluorescence, and came up with an explanation of some unidentified emission lines that I had discovered on coudé plates of long-period variables: they turned out to be forbidden lines of Mn I."*[1]

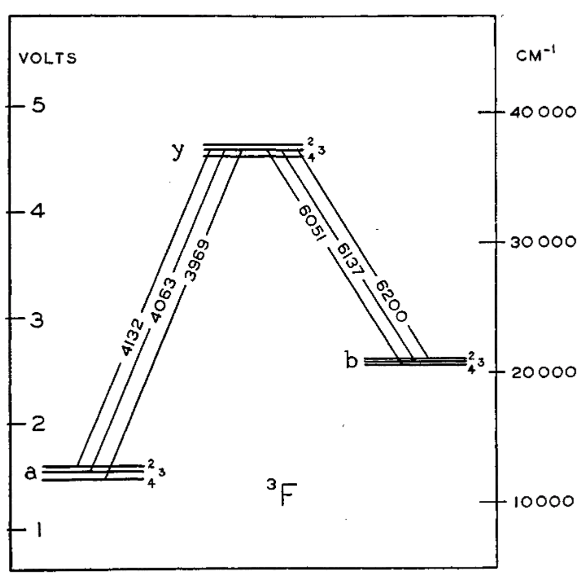


Figure 15: *A partial Grotrian diagram of three ^3F levels of Fe I for RW Aur. The energy scales are referred to the ground state a^5D_4. From Herbig (1945a).*

This result appeared as a paper discussing the Fe I lines in RW Aur (Herbig 1945a, see also Figure 15). It is noteworthy that Herbig already at this very early stage of his work is abandoning the classical astronomy so favored at Lick Observatory at that time, and dives into astrophysics, driven by a desire not only to report the facts as observed, but also to understand them.

Herbig's second paper on young stars (Herbig 1946) dealt with the discovery of V380 Ori, then known as BD -6°1253, a star that would later become one of the classical Herbig Ae/Be stars, but at the time that was still in the future. This discovery was simultaneous with the independent recognition of V380 Ori by Morgan & Sharpless (1946). Today we know the nearby star forming regions so well, and especially the Orion clouds that harbor V380 Ori have been scrutinized at all wavelengths and is recognized as *the* star forming region par excellence. Hence it can be difficult to fully grasp now how Herbig was groping in darkness as he set out to find more faint stars embedded in nebulosity. He writes:

> *"I had spent much time with hand magnifier going over the Franklin-Adams charts and the Ross Atlas photographs of obscured regions (of course this was long before the Palomar Atlas), and had observed spectroscopically some of the nebulous stars that I came across in that way. The first jackpot was BD -6° 1253, a star south of the Orion Nebula with an oddly shaped image on the Ross prints, a result of it being imbedded in the reflection nebula NGC 1999. Spectra at the 36-inch showed a T-Tauri-like emission spectrum (although on an A-type absorption spectrum, an oddity that remains unexplained to this day), and in 1946 I published a carefully-hedged note on it and its variability, the latter established by a series of visual estimates that I made with the 12-inch refractor."*[1]

Today we know that V380 Ori is a multiple system with at least 4 components, driving a giant Herbig-Haro flow HH 222 (Reipurth et al. 2013).

2.3 Thesis

In 1948, Herbig defended his PhD thesis on 'A Study of Variable Stars in Nebulosity' in front of a committee consisting of Harold Weaver (chair), Louis Henyey, Joseph Moore, Thomas Buck, and Francis Jenkins.

Weaver was then a young faculty member at Berkeley Astronomy Department, and through his work on the interstellar medium, he was a natural choice as chair. Henyey was a theoretician, who in the late 1930's had published a series of studies of reflection nebulae, so he was highly qualified to evaluate the theoretical part of Herbig's thesis on stars in nebulosity. He later would become famous for his calculations of radiative stellar evolutionary tracks for young stars moving towards the main sequence, the socalled Henyey tracks (Henyey et al. 1955) and for his innovative numerical method for evolving stellar models[9]. Moore had recently retired as director of Lick Observatory, and represented the expertise on the Lick instruments and telescopes. Buck was a senior professor of mathematics, specializing in mathematical astronomy, and Jenkins was a molecular spectroscopist.

Herbig's dissertation presented the first detailed observational study of the newly discovered variable stars in dark clouds illuminating reflection nebulae. The abstract states:

> *"Matter in our galaxy, at least near the sun, appears to be divided about equally between two forms: stars and diffuse, intrinsically non-luminous, interstellar material. Interaction may take place between these two forms of matter, particularly if the interstellar material is concentrated into localized clouds. Such interaction, as manifested by the variability of stars physically and optically associated with nebulosity, is the subject of this study which consists of (1) a detailed examination of two typical stars associated with nebulosity, and of (2) a general survey of variables in nebulosity.*
>
> *RW Aurigae, a variable star in physical contact with dark nebulosity, was observed both spectroscopically and spectrophotometrically. The observational technique developed for this latter type of observation removed completely the effects of reciprocity law failure. This refinement was essential because of the length of the exposure times necessary to record the faint variable. It was found that the energy distribution in the continuum and the intensity of the emission lines both varied, and that the emission line displacements also changed. A semi-quantitative interpretation of these observations has been proposed.*
>
> *WW Vulpeculae, an example of a star possibly obscured by moving nebulosity, was shown to be, probably, some type of intrinsic variable.*
>
> *In the general survey, examination has been made of the variables associated with the Orion Nebula, the dark nebula in Corona Australis, and a number of other objects."*

Herbig much later commented on this thesis work:

> *"I took as a thesis an investigation of several aspects of the problem that were appropriate to the opportunities at Mount Hamilton, and to my own somewhat immature interests at the time. I had become interested in photographic spectrophotometry, partly by reading MNRAS papers by Greaves, partly through my interest in the photographic process: H&D curves and their change with wavelength, reciprocity failure, etc. So the central effort*

was the measurement of the variation in the energy distribution (between about 3500 and 6800 Å) of the T Tauri star RW Aur (and its emission lines) as it varied in light, and the same for the A-type variable WW Vul, the latter of which I looked upon as an example of a star being screened by passing clouds in the foreground. The material was obtained with the 2-prism quartz slitless spectrograph at the Crossley.

As a check on the screening hypothesis, I took a number of Crossley directs of the field of WW Vul, to see if there was any concentration of faint variables in its vicinity; I found no obvious effect of that kind. As one would expect, RW Aur became redder when faint, and there was some discussion of changes in the strengths of its emission lines. In addition to all this, there were chapters on other stars on which I had managed to gather Lick material (-6 1253, R Mon, R CrA, TY CrA, etc.) Given the dim state of the subject in the mid-1940's, when the idea of star formation *from interstellar material had not really taken hold, perhaps this kind of a fuzzy, exploratory thesis was acceptable. For as I recall (and it is very difficult to reconstruct one's beliefs and state of mind at any such time in the remote past especially when those beliefs have changed so radically in the meantime), I was thinking in terms of* interaction *between already-formed stars and interstellar material as the explanation of all these phenomena, influenced I am sure by Hoyle's then-current ideas of how stars would accrete IS material as they passed through."*[1]

So at the time of Herbig's thesis defense, the notion that T Tauri stars are young had not taken hold yet, and as we shall see in the following, it would be a while before this became universally accepted.

2.4 Are T Tauri Stars Young?

We are so used to think of T Tauri stars as young objects that it is difficult to understand why, upon their discovery, this was not quickly realized. In fact, it took almost a decade for that view to be widely accepted. As noted by Elmegreen (2009): "The history of our understanding of star formation is an example, like many others in science, of an incredible resistance to new ideas during a transition time when old ideas, however absurd they appear to us now, could not be clearly disproved, and new ideas, however obvious they are to us now, could not be unambiguously demonstrated." The difficulty of making this paradigm shift was mainly due to two misconceptions.

First of all, while it was clear that stars obviously must have formed at some point, it was widely accepted that they had all formed at about the same time in a 'catastrophe' in the early Universe. Because of this acceptance, the possibility that stars could still be forming out of the interstellar medium was simply not being considered. Richard Larson has some interesting comments on the state of affairs at the time (Larson 2011):

"The first suggestion that stars may be forming now in the interstellar medium was credited by contemporary authors to a paper by Spitzer in 1941 in which he talks about the formation of interstellar condensations by radiation pressure, but then oddly says nothing about star formation. That may be because, as Spitzer later told me, when he first suggested very tentatively in a paper submitted to The Astrophysical Journal that stars might be forming now from interstellar matter, this was considered a radical idea and the referee said it was much too speculative and should be taken out of the paper. So Spitzer removed the speculation about star formation from the published version of his paper."

Lyman Spitzer was at that time a 26-year old with a newly minted PhD, unburdened by the traditions and prejudices of his elders, and so with a fresh mind he had taken a look at the effects of radiation on interstellar matter (Spitzer 1941, see also Elmegreen 2009 for the historical context). Fred Whipple soon elaborated in more detail on how stars could form, and speculated that stars might continuously be born in the Milky Way (Whipple 1946).

A second barrier to the idea that T Tauri stars could be young related to the then current ideas about how and where stars were born. Today it is taken for completely granted that stars are born in the deep interiors of dense cores within molecular clouds. But that was not the view in the 1940s and 50s. It was generally accepted that stars somehow would be the end result of progressive steps of concentration of matter from the diffuse interstellar medium through increasingly dense stages, as discussed by Spitzer and Whipple. But it was assumed that this happened in the open, with radiation as the principal force that condensed the gas. These theoretical ideas were supported by the identification of small dark globules in HII regions discovered by Bok & Reilly (1947), which were assumed to be intermediate steps towards the formation of stars. The large quiescent dark clouds, with which TTS were associated, were thus not the first place astronomers expected to find newborn stars.

In the late 1930s, Fred Hoyle and Raymond Lyttleton advanced the idea that stars passing through dark clouds would accrete matter, leading to variability of their brightness (Hoyle & Lyttleton 1939). While Joy was content to define the T Tauri class of variables without much speculation on their origin, others reasoned that the association of T Tauri stars with dark clouds would naturally occur if T Tauri stars were normal field stars that accidentally passed through such clouds, in the manner suggested by Hoyle and Lyttleton, and in the process got their spectral characteristics from interaction with the clouds (e.g., Greenstein 1948, 1950).

Today we understand the fallacy of this view, but with the limited observational data at hand at that time it was a perfectly sensible interpretation of the available observations. As already mentioned, T Tauri stars as interlopers in dark clouds was the framework in which Herbig's thesis was discussed.

It was the Armenian astronomer Victor Ambartsumian who first advocated that the T Tauri stars were young, based on their assembly in associations (a term coined by Ambartsumian) which were shown to be unstable under the influence of Galactic tides and hence recently formed (Ambartsumian 1947, 1949, 1950). However, most of the papers by Ambartsumian and colleagues like Kholopov, Parenago, and Mirzoyan were either written in Russian or published in places not easily accessible, so their ideas only slowly percolated to the West. Otto Struve, of Russian ancestry, was one of the few from the West who read the Russian literature, yet for a while he continued to adhere to the idea that passage through a cloud would induce the observed emission line characteristics of T Tauri stars (e.g., Struve & Rudkjøbing 1949).

Herbig was intrigued by the idea of Ambartsumian and co-workers that the T Tauri stars are young stars, and in a review in 1952 he examined the pro's and con's of this idea. Herbig drew attention to two important issues (Herbig 1952a). First, he had noticed that T Tauri stars are systematically too bright when compared to normal dwarfs, and increasingly so as their spectral types become later (see below), something Joy had already hinted at when comparing the components of visual T Tauri binaries. Second, high-resolution spectra showed that T Tauri stars have broader and more diffuse lines. Neither of these two facts seemed to fit in with the view that T Tauri stars are merely normal stars passing through clouds. Today we understand the former as a consequence of T Tauri stars lying above the main sequence as they approach it through contraction, but at the time evolutionary tracks had not yet been calculated. The latter is now understood as the combined result of the high rotation rates of T Tauri stars, their outflowing winds, and their lower gravity. Herbig was never one to jump to conclusions, so he cautioned that it could not be excluded that there might still be ways to reconcile these unusual behaviors of T Tauri stars with the initial idea that they are passing through clouds, and concluded that at that time *"... it is not possible to make a clearcut and entirely acceptable decision between the two opposing alternatives on the basis of observational evidence alone."*

In 1952, Adriaan Blaauw published the first of several studies showing expanding motions of the OB stars in the Per OB2 association (Blaauw 1952), thus proving their youth and confirming the theoretical arguments of Ambartsumian that such stars must be young. Clearly massive stars were forming today, but would that apply to lower-mass stars also? Shortly after, Herbig searched for and found T Tauri stars in IC 348, which participates in the expansion of the Per OB2 association, and he concluded that these members must therefore be young, but still warned that *"the present results do not by themselves imply that all T Tauri-like objects are of recent formation"* (Herbig 1954a).

On the theoretical side, Fred Hoyle wrote a very influential paper introducing the idea of a collapsing cloud undergoing a cascade of hierarchical fragmentation into smaller clouds (Hoyle 1953). This implied a strong association of newborn stars with dark cloud complexes.

The final shift in opinion occurred in the following few years, and is described by Herbig thus (Herbig 2002):

> *"Theorists began to appreciate that young stars could be recognized by their location in the HR-diagram. Salpeter was apparently the first clearly to say so, initially at a symposium in Michigan in 1953, then again in the 1954 Liège symposium* [Salpeter 1954]*, where he recommended an 'attempt to study whether the low luminosity part of the main sequence is actually missing in young star associations, to look for reddened stars to the right of the main sequence and to look for similar effects in gas and dust clouds where star formation is still suspected to go on'. The following year Henyey, Lelevier, & Levee (1955) actually calculated radiative tracks for masses between 0.65 and 2.291 $M_{\odot}$ and tabulated their contraction times."*

Unbeknownst to Salpeter, the deviation of the lowest mass stars from their expected location on the main sequence had already been observed. In his 1962 review, Herbig writes:

> *"It became apparent in 1945, when Joy's spectral types for double T Tauri stars were published, that the Δm's did not correspond to the difference in spectral types if both components were dwarfs. The best example was UX Tauri, type dG5, with a companion of dM2. The difference in apparent visual magnitudes (variable star near maximum) is about 3.0 mag., yet the spectral types correspond to a difference of 5.0 mag. This represents a general phenomenon, also observed in single stars, that appears in all subsequent work. Its sense is that if one fits the brighter T Tauri stars in the Taurus clouds to a main sequence with modulus of 6.0 mag., then the M1-M3 stars in the clouds are too bright by 2 to 3 mag. or more."*[1] (see Figure 16).

Perhaps the definite tipping point, if one exists, would be on Sept 1, 1955, when Herbig organized a one-day IAU symposium in Dublin on *Non-stable*

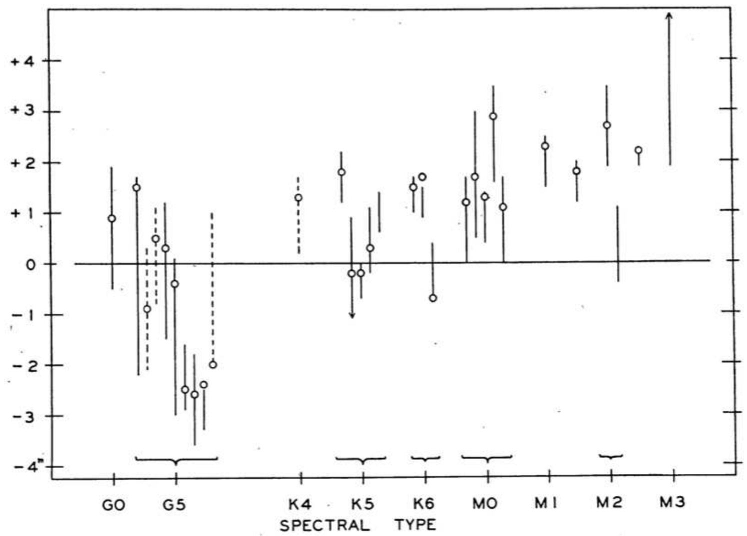


Figure 16: *Herbig noted that T Tauri stars become increasingly brighter than normal dwarf stars with increasing spectral type. The vertical lines indicate range of variability (Herbig 1952).*

Stars, attended by the leading researchers interested in T Tauri stars at that time (incl. Ambartsumian, Greenstein, Haro, Hoffmeister, Joy, Kholopov, Kukarkin, Struve, Walker), and here Herbig stated unequivocally

> *"I believe that the evidence now available favors the hypothesis that the TTS as a class are new objects, genetically associated with the clouds in which they are found"* (Herbig 1957a).

Of the many oddities of the T Tauri stars, the main one that for Herbig clinched the argument in favor of youth was the volume density of T Tauri stars in dark clouds relative to the solar neighborhood. Even with the limited capability to detect T Tauri stars in those early days, it was very clear that *"there are far more T Tauri stars in dense clouds – by one order of magnitude – than can be accounted for by the random encounter of field stars with the clouds"* (Herbig 1957a). The possible loophole that T Tauri stars could be slow-moving field stars trapped in clouds was closed, since Herbig showed that this would require dark clouds to survive for $\sim 10^{11}$ yr (Herbig 1962a).

These various arguments, individually and in combination, were universally accepted, and thus – finally – it was established that the attributes of T Tauri stars were due to their extreme youth.

Within this framework, Herbig set out to understand the properties, peculiarities, and statistics of the T Tauri phenomenon. In the following sections, Herbig's diverse efforts are discussed. Around 1960, Herbig felt that the time was ripe for a review of the knowledge gained up to then, and this resulted in his famous 1962-review, which will be frequently cited in the following (Herbig 1962a). The appearance of this review had a profound effect on the study of T Tauri stars. Up to that time, T Tauri stars had been mostly a curiosity pursued by a very small group of researchers. In the seventeen years between Joy's discovery paper in 1945 and Herbig's review in 1962, only 15 papers with 'T Tauri stars' in the title appeared in the refereed literature. In the seventeen years following the 1962-review, this number increased by almost a factor of 10. The review is remarkable in that it identifies nearly all the important characteristics of T Tauri stars that have been the focus of attention since then, as discussed in the following.

2.5 Objective-prism and Grism Surveys

In his 1945 paper, Joy had noted that the newly recognized T Tauri stars had a tendency to cluster in areas with dark clouds, and of the original 11 T Tauri stars, 7 were found in the Taurus-Auriga clouds. This led Joy to use the Mt. Wilson 10-inch photographic refractor with an objective prism to search for further stars with the Hα line in emission, and his survey in the Taurus clouds led to the discovery of 40 new Hα emission line stars (Joy 1949). Similarly, Haro (1949, 1953) had very successfully searched for stars with Hα in emission near the dark clouds in Ophiuchus and around the Orion Nebula using the Tonantzintla Schmidt telescope. These results inspired Herbig to conduct his own Hα emission surveys on an ambitious scale (Figure 17). He writes:

> *"Sometime after I returned to Lick in 1949, I became interested in carrying out my own searches for Hα emission stars, although there was no telescope at Lick that would perform in the red like the 10-inch survey camera at Mount Wilson, or the Tonantzintla Schmidt being used by Haro. I do not know whether I came to the concept on my own, or whether it emerged from talks with or suggestions by Nick Mayall and Harold Weaver, but I decided to build a slitless spectrograph at the Crossley around the zero-power corrector that had been designed by Frank Ross in the 1930's. This corrector had never been used seriously, I believe because telescope flexure made it difficult to keep in collimation. I drew up and had built in the Lick shop a new cell and spider for the lens, the first element repositioned to deliver a parallel Hα beam to a 4×6-inch transmission replica grating, the original of which had been ruled by R. W. Wood and was given to me (or to Lick) by James Baker, then a consultant at Lick on the 120-inch telescope project. This grating, mounted on a glass plate somewhat less than 1 inch thick, was followed by a thin prism to return the Hα beam to its original direction, following which*

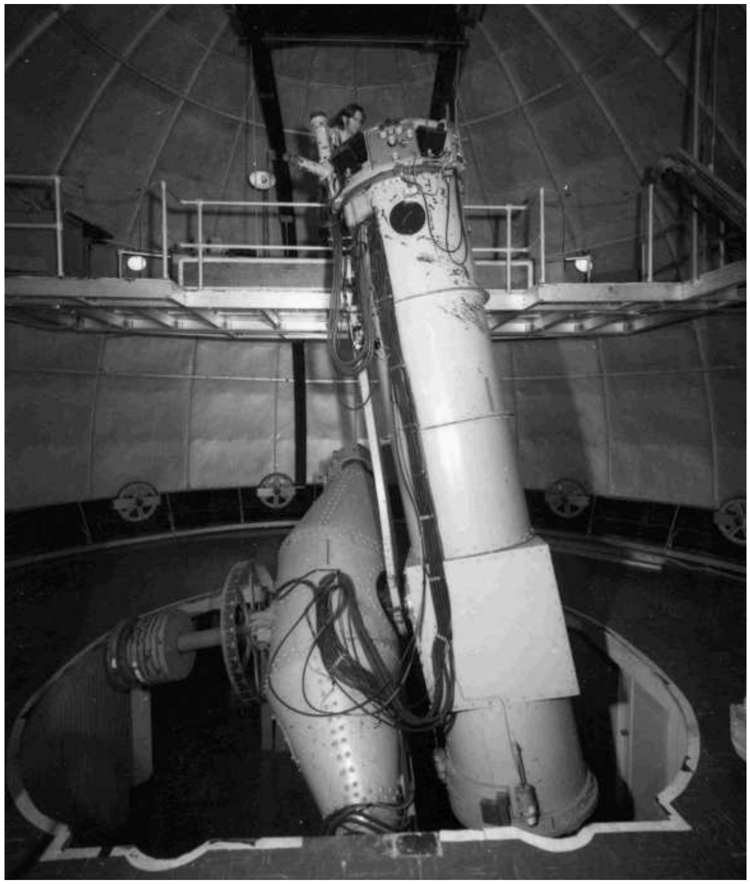


Figure 17: *The Lick 36-inch Crossley reflector.*

the beam was reconverged by the positive element of the corrector. A red filter isolated about 400 Å of the first-order Hα region. This was one of the first, if not the first, of what later became popular as 'grism' spectrographs.[10]

With this slitless system, in the following years I went after faint emission-Hα stars in clusters and obscured areas. It was very successful in relatively crowded fields such as NGC 2264 (1954), IC 348 (1954), M8 & M20 (1957b), NGC 7000 (1958), but the area covered (about 40×50 arcminutes) was too small for surveys of large dark clouds. About 350 of these discoveries have been published, while many more were found but never followed up. The necessary checkup of many of these detections with the Crossley nebular spectrograph took much time. I should mention that one of these confirmations by blue-violet slit spectroscopy turned out to be very important over a decade later: one of the emission-Hα stars in NGC 7000 flared up in 1970 and is now known famous as V1057 Cyg."[1]

Table 1

Regions	No. of stars	Line	Paper
IC 348	16	Hα	Herbig (1954a)
NGC 2264	84	Hα	Herbig (1954b)
M8, M20, Simeis 188	26	Hα	Herbig (1957b)
NGC 7000, IC 5070	68	Hα	Herbig (1958a)
IC 5146	22	Hα	Herbig (1960b)
NGC 2068	45	Hα	Herbig & Kuhi (1963)
Taurus-Auriga	19	Ca	Herbig, Vrba, Rydgren (1986)
IC 348	110	Hα	Herbig (1998)
NGC 6611	29	Hα	Herbig & Dahm (2001)
IC 5146	83	Hα	Herbig & Dahm (2002)
NGC 1579	36	Hα	Herbig, Andrews, Dahm (2004)
L988	64	Hα	Herbig & Dahm (2006)
IC 1274	87	Hα	Dahm, Herbig, Bowler (2012)

Table 1 lists the six papers that resulted from these surveys between 1954 and 1963. Many now famous T Tauri stars were discovered in these early efforts. The stars are numbered consecutively, numbers 1 - 100 in the first two papers were labeled as LHα (for Lick-Hα), but it was later realized that this designation was used in K.G. Henize's catalog of southern Hα discoveries, so subsequent papers used LkHα.

Herbig emphasized the importance of follow-up slit spectroscopy of an Hα emission star before one can conclude that it is a bona fide T Tauri star, as expressed for example in his large review (Herbig 1962a):

> *"The simple detection of a reddish star with Hα emission in an obscured area does not prove that this can be only a T Tauri star; a slit spectrogram of the blue region is required to rule out the possibility of a distant, reddened Be star. Thus objective-prism surveys must be supplemented by slit spectrograms if certain identification of T Tauri stars is to be made. In fields of extensive and heavy obscuration, however, there is a lesser chance of encountering background Be stars. Likewise, in regions along Gould's Belt at high galactic latitude, there are likely to be few distant emission objects. but in complex fields having great extension in depth, as in Cygnus and Cepheus, the chance of contamination by background is large."*

Since Hα emission in T Tauri stars mostly reflects accretion from circumstellar disks onto the stars, and disks gradually disappear as the stars evolve, it follows that in stars approaching the main sequence Hα emission should subside towards their chromospheric levels (Herbig 1985), making their detection with traditional Hα emission survey techniques difficult. Herbig was interested in identifying such "post-T Tauri" stars, but Hα emission would evidently not be a good tracer of such more evolved stars. Herbig had noted that some young stars could have prominent emission in the Ca II H- and K-lines at 3968 and 3934 Å while having very weak or absent Hα emission, and this led to a study using the Burrell Schmidt telescope at Kitt Peak equipped with the 4$''$ dense flint prism giving a dispersion of about 190 Å/mm at 3950 Å together with a 10-inch diameter interference filter with a 200 Å passband centered on the Ca II lines. In a Ca II H- and K-line survey of a large area of the Taurus-Auriga dark clouds, Herbig et al. (1986) were able to re-discover essentially all the known Hα-emitting T Tauri stars in the area (51 in all), as well as 18 other stars. These other stars, the LkCa stars, were found to be mixed with conventional T Tauri stars in an HR-diagram, and so could not be identified with post-T Tauri stars, and it was concluded that Hα emission does not decay with time in a simple, gradual manner. But the LkCa stars have attracted much attention in later years, especially LkCa 15 (Figure 18) which is surrounded by a transitional disk and is hosting several newborn planets (Kraus & Ireland 2012, Sallum et al. 2015).

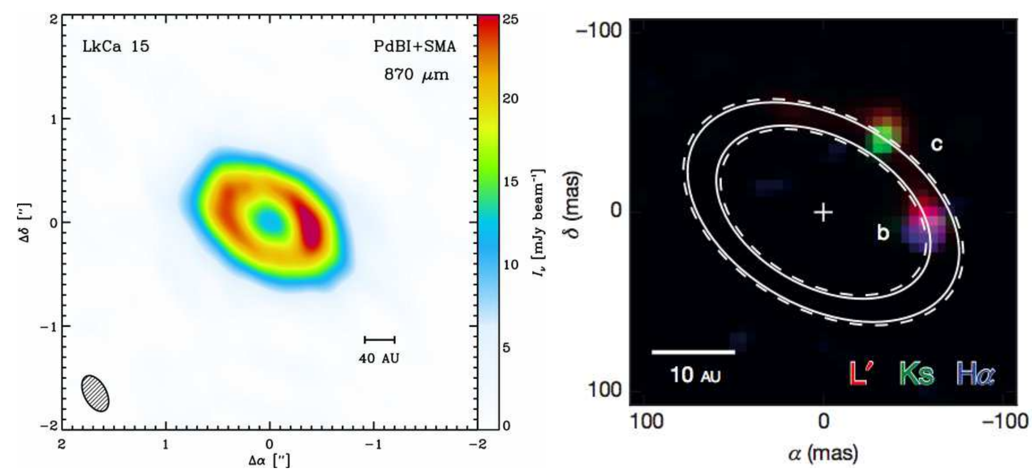


Figure 18: *(left) LkCa 15 is probably the most famous of the LkCa stars discovered by Herbig due to its circumstellar disk, identified much later, seen here in an aperture synthesis image of the 870 μm emission based on Plateau de Bure Interferometer and Sub-Millimeter Array data. The figure is 560 AU across at the distance of LkCa 15. From Andrews et al. (2011). (right) Inside the gap of the LkCa 15 transitional disk two candidates for accreting protoplanets in Keplerian orbits have been found. From Sallum et al. (2015).*

After these papers, Herbig left the subject to others, who subsequently did major and important surveys (e.g., Schwartz 1977b, Parsamian & Chavira

1982, Wiramihardja et al. 1989). But after his move to Hawaii in 1987 with access to a modern instrument, Herbig embarked on a large-scale Hα-emission survey of young clusters, soon in collaboration with his student Scott Dahm. The instrument used was the Wide Field Grism Spectrograph installed on the UH 88-inch telescope at Mauna Kea.

> *"A 420 line/mm grism blazed at 6400 Å plus a narrowband Hα filter isolated a region of the first-order spectra between 6300 and 6750 Å at a dispersion of 3.85 Å/pxl, imaging on the central 1024 $\times$ 1024 pixels of the 2048 $\times$ 2048 Tektronix CCD, yielding a 5.5$'$ $\times$ 5.5$'$ FOV. Depending on seeing conditions, the limiting measurable Hα equivalent width [W(Hα)] was approximately 2 Å. The continua of stars brighter than V = 21.0 were sufficiently well defined that W(Hα) was determinable"* (Herbig & Dahm 2006).

In this fashion, surveys were carried out of IC 348, NGC 6611, IC 5146, NGC 1579, L988, and IC 1274 (see Table 1). Several hundred young stars were found, labeled IHα (I is short for the Institute for Astronomy at the University of Hawaii). An example of the data used is shown in Figure 19.

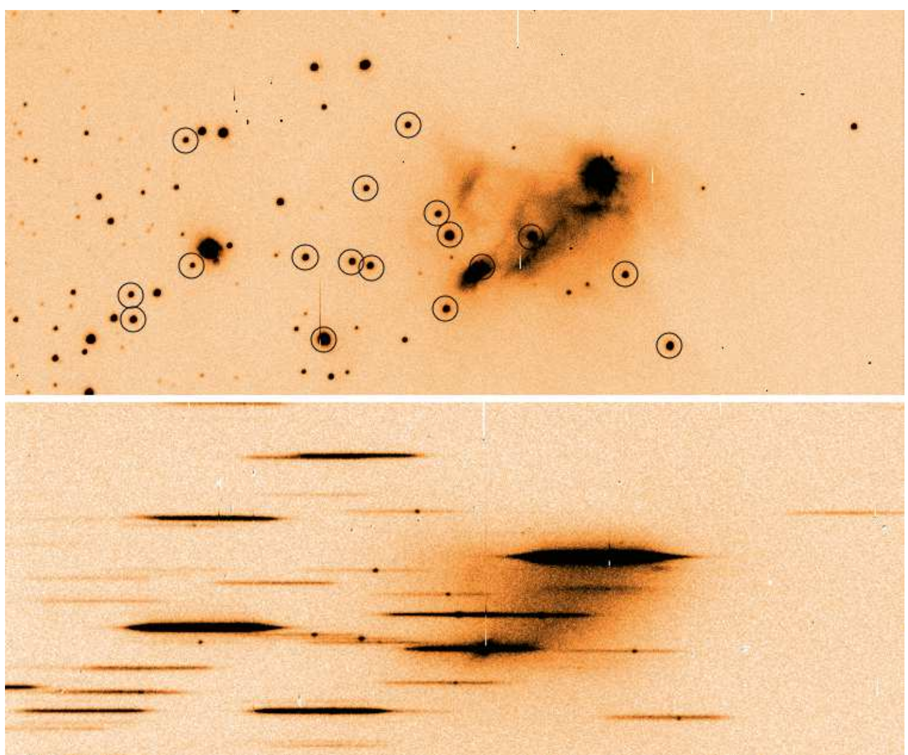


Figure 19: *Identification of Hα emission stars in the LkHα 324 cluster in L988, showing direct and grism images. Data from Herbig & Dahm (2006).*

Today deep Hα emission surveys have been made of most of the nearby star forming regions (e.g., Nikoghosyan et al. 2012, Szegedi-Elek et al. 2012, Pettersson et al. 2014), and the technique remains a powerful tool. Other techniques to uncover the young stellar populations in star forming regions have meanwhile emerged, especially surveys at near-infrared, mid-infrared, and far-infrared wavelengths (e.g., Gutermuth et al. 2008), and surveys by X-ray observatories like Chandra and XMM-Newton (e.g., Getman et al. 2005, Güdel et al. 2007), as well as variability studies (e.g., Cody et al. 2014). A question that interested Herbig greatly in the last years of his life was to what extent these various techniques overlap, and whether the techniques we use today enable us to find *all* young stars in a star forming region. How complete is our census of the nearest star forming regions?

2.6 The Herbig-Rao and Herbig-Bell Catalogs

Hα emission surveys are useful to develop a first census of young stellar populations and for statistical studies, if done systematically, but they do not provide insights into the characteristics and the physics of young stars. As a spectroscopist, Herbig was keenly aware of the need to obtain slit spectrograms of as many of the newfound Hα emission stars as possible, and he invested major efforts into collecting such spectra. With the low-sensitivity photographic plates and the relatively smaller telescopes used $\sim$60 years ago, this task was definitely non-trivial: *"With the 36-in. Crossley reflector at Lick Observatory and a dispersion of 430 Å/mm, about 2 hr is required to obtain an unwidened slit spectrogram of a magnitude 17 star."*[11] In his 1962 review, Herbig cataloged 126 young stars for which spectroscopy was available. Ten years later the accumulation of spectroscopic information by Herbig and others had grown to the extent that a much larger catalog was called for. At that time a young student from India, N. Kameswara Rao, had come to Lick for graduate studies, and his fascination with the new field of young stellar populations led to contact with Herbig and eventually to the 'Second Catalog of Emission-line Stars of the Orion Population' (Herbig & Rao 1972). Rao has provided the following reminiscences of the process:

"While I was studying in Santa Cruz, George at some point mentioned to me that people were asking him for lists of T Tauri stars, that a lot of new data had accumulated since his earlier catalog, and that it would be good to prepare an up-to-date catalog of stars for which slit spectra were available. He said this would give me an opportunity to get to know the literature and the characteristics of young stars etc. I started to look at the spectra of T Tauri stars in Herbig's collection. Most were unwidened Crossley prime focus photographic spectra with 430 Å/mm at Hγ, extending from below the

Balmer jump to Hβ. I was to compare the spectrum of a T Tauri star with spectral standards to classify it and note other particulars. The standards were usually well widened, well exposed, nice absorption spectra, whereas the T Tauri spectra were unwidened and some times not well exposed. Looking for faint absorption features of H & K, Ca I 4226 Å, maybe CH 4300 Å, Fe I 4045 Å, Sr II 4077 Å on small 1.5 inch plates was not always easy. I developed a great respect for the astronomers of that time who had to guide for hours to keep a star on the slit and somehow try to get a spectrum. We also wanted to include as much information as possible regarding the photometry. It was great fun for me going into the Science Library, where astronomy journals and observatory publications from all over the world were kept, hunting for photometric information. Most of my classifications and descriptions from Lick plates and the literature were checked by George. He knew every star that entered the catalog personally."

The Herbig-Rao catalog listed 323 young emission-line stars and became an important tool that stimulated much new research on many of both the more typical T Tauri stars and the more peculiar cases. For 15 years it stood as the most comprehensive compilation of information on individual young stars. But as more information and more young stars were found and studied, the need for an update became increasingly obvious. Katherine Robbins Bell was working on her masters thesis in 1987, and later did a theoretical PhD on FU Orionis stars with Doug Lin. She collaborated with Herbig on the new catalog, and remembers the process:

"George had been collecting data almost continuously since the Herbig-Rao catalog, and was ready to finish the new catalog as soon as he could. He had decided to not publish the catalog in a journal. This was long before AASTeX and electronically submitted documents. In those days, each number would have to be transcribed by someone at the journal, with many possibilities for error. George said that just checking the accuracy of the galley proofs would be way more work than he wanted to endure, and so he decided to publish it through the Lick Observatory Bulletins. He had boxes of index cards with coordinates, notes, references, and often little images for every 'interesting' object that had been studied since the HRC. George was adamant about keeping the HRC number for any object that had one, giving new numbers only to additional objects. My first task was to get improved coordinates for certain of these objects where George deemed that we could 'do better'. This was a very different task in those days than now, when online access to catalogs like 2MASS and USNO makes coordinate determination almost trivial. I had access to precious Lick Observatory archival glass plates. They were large, maybe 18 inches on a side, 1/4 inch thick. Only to be touched on the edges and as much as possible held vertically so their weight wouldn't cause them to crack. My job was to find the object first on a photograph of the region, often from descriptions in articles, then use a measuring machine controlled by a PDP 8, an ancient computer even then, with data stored on 4 inch reels of magnetic tape. After several hours, coordinates would finally be spit out. My second task was to program a code to format the catalog entries. Since we were not going to publish in a journal, we had to do all the formatting ourselves. Although George declared a cut off for introducing new objects, he would still come to me with 'special' cases, so the page breaks kept shifting and all page headers had to be re-programmed. The resulting Lick Observatory Bulletin #1111 ended up being one of the most commonly requested Lick publications of all time."

The 'Third Catalog of Emission-Line Stars of the Orion Population' (Herbig & Bell 1988) contains information on 742 pre-main sequence stars. It has been widely used, and I remember always keeping my copy on the console during observing runs. Today's electronic access to its content has made its use even more widespread. Since the appearance of the HBC, nobody has attempted the monumental task of preparing a fourth catalog, although Herbig for his own use kept notes on many new interesting objects. When I asked him about the possibility of updating the catalog, he lamented that after his retirement, he was no longer able to get the kind of important assistance he had received from Kameswara Rao and Katherine Bell.

2.7 Spectral Properties of T Tauri Stars

In 1962 Herbig put everything together that was known at that time about T Tauri stars in a major review article[12] (Herbig 1962a). In it he defined how to identify T Tauri stars:

> *"It is important to realize from the beginning that the unambiguous assignment of a star to the T Tauri class is entirely a spectroscopic matter. The primary spectroscopic criteria are as follows:*
>
> **1**. *The hydrogen lines and the H and K lines of Ca II are in emission;*
>
> **2**. *The fluorescent Fe I emission lines λλ4063, 4132 are present (they have been found only in T Tauri stars);*
>
> **3**. *The [S II] emission lines λλ4068, 4076 are usually but not always present. Probably [S II] λλ6717, 6731 and [O I] λλ6300, 6363 are also characteristic;*
>
> **4**. *Recent results [...] suggest that the presence of strong Li I λ6707 absorption, in those stars in which an absorption spectrum can be seen at all, may*

constitute another primary criterion."

Herbig went on to defend this restrictive definition of T Tauri stars. Half a century ago the only effective way to find young stars was to search for Hα emission stars using slitless spectra. But Herbig warned against classifying all reddish stars with Hα emission as T Tauri stars, and pointed out that such surveys, even if focused only on star forming regions, would pick up foreground Me dwarfs and background Be stars. To ascertain the T Tauri nature of a star, slit spectrograms of adequate dispersion should be secured.

Figure 20: *Herbig at his desk at Lick Observatory in 1964.*

However, today Herbig's four criteria are no longer applied, partly because they are overly restrictive, but primarily because we now have other techniques to efficiently identify young low-mass stars, such as surveys for infrared excess stars and X-ray surveys. The one definition among Herbig's original criteria that has remained is the presence of lithium (see Section 2.8), which has become the gold standard for asserting the youth of any low-mass star. Another difference is that 50+ years ago, only a few hundred stars were certified as young low-mass stars, and the focus was often on individual objects. Today more than a hundred thousand low-mass young stars are known, and focus has shifted towards statistical analysis of group properties as function of various parameters such as age or mass, in which the occasional contaminant is not significant.

Today, the term T Tauri star is widely used to describe any optically visible young low-mass star, while the term young stellar object (YSO), coined by Strom (1972), tends to be used to describe all pre-main sequence stellar objects, whether embedded or visible.

In the 1962 review, Herbig went on to note that

> *"the emission lines are usually superimposed upon a continuous spectrum which may range from a pure continuum, through one with only vague depressions at the positions of the strongest late-type features, to an approximately normal absorption spectrum of type late F, G, K, or early M. [...] This apparent masking of the absorption spectrum, which is usually more striking in the stars with the strongest emission-line spectra, has generally been ascribed to continuous emission."*

This veiling was first discovered by Joy and mentioned in his 1945 paper. Herbig further noted that *"On spectrograms, one sees what appears to be a continuous spectrum that begins in the λλ3700-3800 region and rises rapidly in intensity toward shorter wavelengths."* For reasons not entirely clear, Herbig in 1962 thought that this would be another continuum confined to the ultraviolet and separate from the blue veiling. This UV excess was studied in detail by Haro & Herbig (1955), who examined a variety of possible mechanisms, including hydrogen lines and continua, free-free emission, negative hydrogen ion emission, and 2-quantum emission. In the end they concluded that *"The explanation which seems to meet with the least difficulties is that of thermal radiation by a hot source of small size, located near the stellar surface."* It is today accepted that spectral veiling and UV excess is the same phenomenon and is caused by funnel flows from a circumstellar disk that accrete onto the stellar surface in 'hot spots'. An example of a modern decomposition of continuum and photospheric spectrum for a heavily veiled T Tauri star is seen in Figure 21.

Twentyfive years later, after the IUE satellite was launched, Herbig returned to the question of the UV excess in T Tauri stars. He and Bob Goodrich, then a student at UC Santa Cruz, acquired UV spectra (1200-3200 Å) of five K-type T Tauri stars and nearly simultaneously obtained UBVRI photometry of the same stars. They concluded that

> *"The ultraviolet excesses observed in the optical region of TTS extend into the ultraviolet at least to 1500 Å. While precise continuum levels are difficult to determine at low resolution due to the presence of emission lines, the effect is so large that there is a gross mismatch between the observed UV colors of TTS and those corresponding to their optical-region absorption line types. The dereddened ultraviolet colors do not show a large dispersion,*

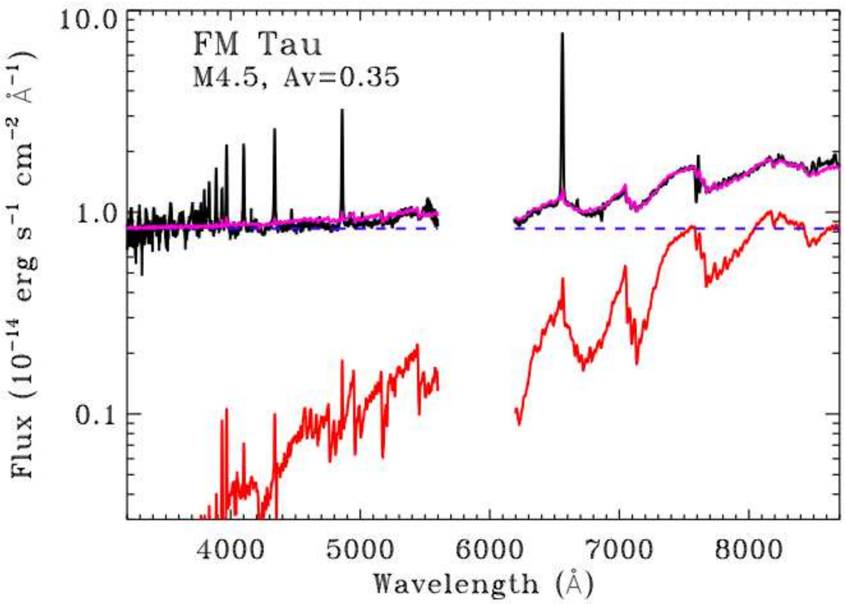


Figure 21: *Veiling is severely affecting the observed (extinction-corrected) spectrum of the T Tauri star FM Tau (black line). The red spectrum is a photospheric template, and the blue dashed line is a continuum. The purple line is the best fit to the observed spectrum. From Herczeg & Hillenbrand (2014).*

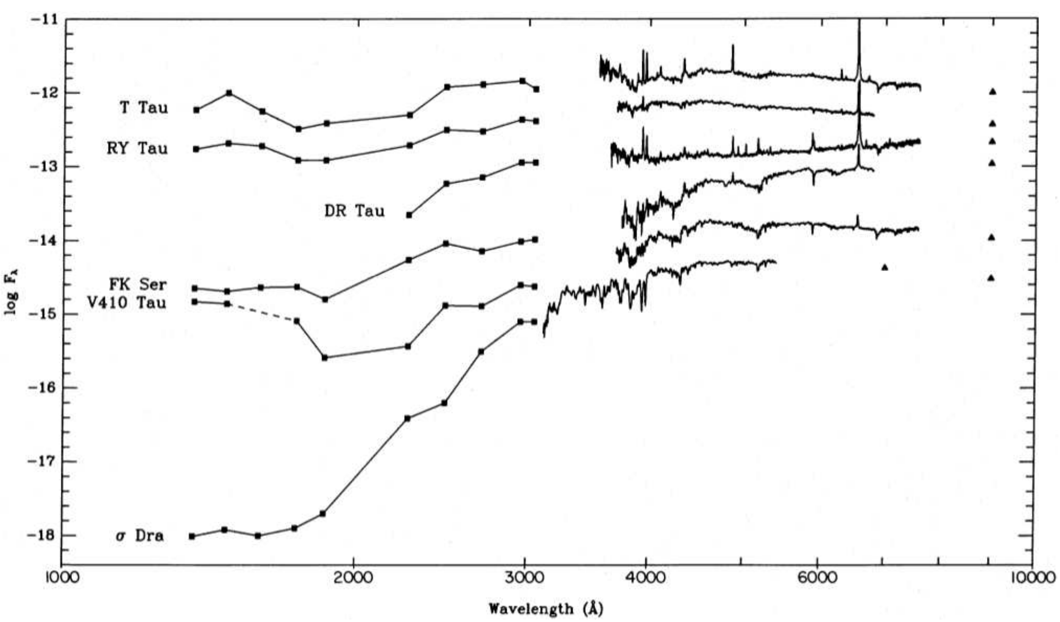


Figure 22: *Composite dereddened UV-optical spectra for five K-type TTS and the normal K0 V star σ Dra (shifted vertically for clarity). In the UV, the lines have been removed and the mean continuum fluxes measured about every 250 Å. The TTS are vastly brighter than the reference star. The points to the right are I-band photometry. Herbig & Goodrich (1986).*

indicating that the shapes of TTS continua in the UV are rather similar in all these stars." (Herbig & Goodrich 1986).

The optical/UV data are plotted in Figure 22. At the time, chromospheric models were popular for interpreting TTS spectra, and this was the framework that Herbig and Goodrich used to interpret their data.

One of the many peculiarities of T Tauri stars that Herbig was grappling with

"[...] is the tendency for absorption components to be superimposed on the strongest emission lines, notably Hα and K. In RW Aur, these components are not greatly displaced, but in several other stars they are shifted shortward. There is no corresponding sign of the return of this rising material, although longward components have been reported on occasion in several stars, and the very rapid variation in line structure that has been reported in T Tau [...] confuses the situation. It is inferred that this rising material is driven from below because of the increasing negative line shifts in higher layers of the atmosphere, and for this reason, although the line displacements do not exceed the velocity of escape at the surface*, it is assumed that much of this material actually leaves the star. It seems reasonable that an envelope supplied in this way is the source of the semi-independent forbidden lines observed in the spectrum of most T Tauri stars"* (Herbig 1962a).

Despite the limitations of the data at hand, Herbig attempted in various ways to estimate the mass loss rate, and although he cautioned that *"this rather speculative computation of the rate of mass loss by T Tauri must be regarded with reserve until a more careful analysis of the spectrum is available"* he did realize that *"the magnitude of this mass loss rate shows that the phenomenon is not a trifling one"* (Herbig 1962a). At about this time, his student Len Kuhi was working on his PhD entitled 'Mass Loss in T Tauri Stars' (Chapter 10), and based on good 120-inch coudé spectra of several T Tauri stars

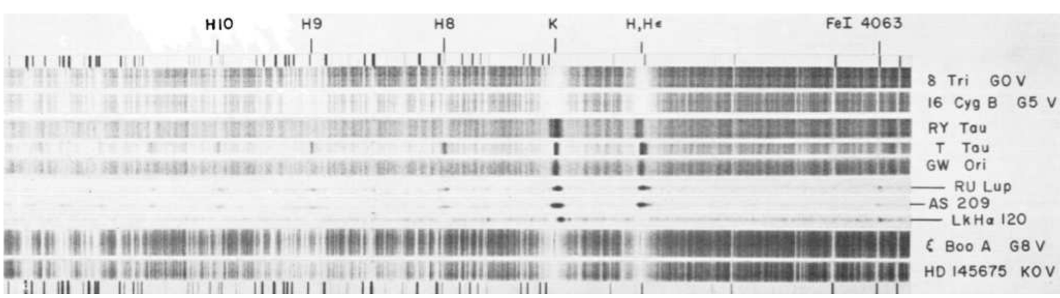


Figure 23: *120-inch photographic coudé spectra in the blue spectral region of six T Tauri stars with normal G-type dwarfs above and below. From Kuhi (1964).*

(Figure 23), Kuhi concluded that they were losing mass at a mean rate of 3.7 $\times$ 10^{-8} $M_\odot$ yr^{-1}, remarkably close to modern-day values (e.g., Hartmann et al. 1998) considering the limited state of knowledge about T Tauri winds in those early days.

Until the emergence of CCDs, almost all spectra of T Tauri stars were performed at shorter wavelengths because most photographic emulsions were sensitive in the blue. A few scattered observations of T Tauri stars were made longwards of Hα, but when the Lick 120-inch telescope went into operation, Herbig used the prime focus spectrograph to get spectra of TTS with the Kodak I-N emulsion in the λ7500–8700 spectral region (then called 'near-infrared' – today better known as 'deep-red' or 'far-red'), and had been struck by the great strength of the infrared Ca II triplet. To improve the sensitivity, Herbig then designed and built a cooled image intensifier (socalled Varo) system for the Lick 120-inch coudé spectrograph, with funding from the NSF, and it was vastly superior to conventional photography at long wavelengths, although the recording medium was still photographic plates. With this equipment a more systematic, higher-resolution exploration of the region around the infrared Ca II triple in T Tauri stars was performed by Herbig & Soderblom (1980). The spectra of T Tauri stars in this spectral domain are dominated by the infrared Ca II triplet at $\lambda\lambda$8498, 8542, 8662 (Figure 24), followed by O I and weak lines of Fe I and Fe II. Herbig and Soderblom used line-ratio diagrams to compare the T Tauri stars with spectra from different regions in the atmosphere of the Sun, which at the time was seen as the physically most relevant environment. They found that the Ca II lines were saturated even at the lowest equivalent widths, and so concluded that the active areas on TTS covered only a fraction of the stellar surfaces. The next major step forward was provided by Hamann & Persson (1992a) who were able to obtain high-

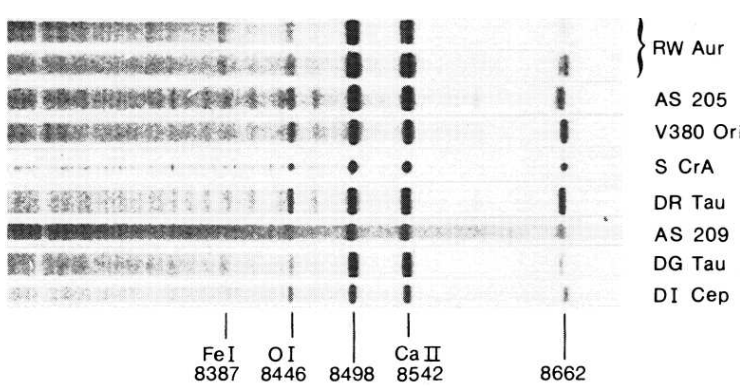


Figure 24: *Coudé spectrograms of 8 T Tauri stars in the 8200–8720 Å region. The more conspicuous lines are indicated. From Herbig & Soderblom (1980).*

resolution spectra of 53 T Tauri stars using a CCD detector, and recognized distinct broad (FWHM $\gtrsim$100 km s^{-1}) and narrow ($\lesssim$40 km $^{-1}$) emission line components, which found a natural explanation in the magnetospheric accretion hypothesis by Muzerolle et al. (1998), who also noted that the infrared Ca II triplet lines are good indicators of the accretion rate in T Tauri stars (see Section 2.16).

2.8 Lithium

Lithium is the third-lightest element and was mainly produced in nucleosynthetic processes during the first three minutes after the Big Bang. It is therefore universally present in the interstellar medium out of which new stars are formed. Fortunately the main line of Li I, a resonance doublet, is located at λ6707 in the optical wavelength range, making observations easy (the second line in the principal series appears at λ3232 in the ultraviolet). Lithium is particularly significant for T Tauri stars, since it is destroyed in nuclear processes at a relatively low temperature ($\sim$2.5$\times$10^6 K). Thus, it survives only in the external layers of a star, and even there lithium has been largely destroyed in low-mass main sequence stars because surface layers over time have been dragged down by convection to hot layers where the lithium is burned. T Tauri stars, on the other hand, are so young that this process in most cases has not had enough time to destroy all surface lithium, and lithium is therefore an important signpost of the youth of T Tauri stars.

Lithium was identified in T Tauri stars shortly after Joy defined the class, but it took another ten years before its importance was fully appreciated. In his 1962 review, Herbig writes:

> *"One of the most exciting recent developments in this field has been the recognition that the T Tauri stars, as a group, show lines of Li I which indicate that lithium is overabundant by perhaps two orders of magnitude with respect to the solar atmosphere. Sanford (1947) first noticed the presence of Li I λ6707 in T Tau, but he made no comment, and it was Hunger (1957) who, during re-examination of Sanford's coudé spectrograms, noticed the strong Li I absorption in both T and RY Tau, and realized its significance. It should be noted that Li I is not found in the emission spectrum, because there it should exist mainly as unobservable Li II."*

Before the 120-inch reflector was constructed at Lick Observatory and equipped with a new high-resolution coudé spectrograph designed by Herbig (see Chapter 11), there were no opportunities on Mt. Hamilton to follow up on the work of Hunger. But at Mt. Palomar, the 200-inch telescope had both the aperture and the echelle spectrograph needed to study faint T Tauri stars at high spectral resolution, so Bonsack & Greenstein (1960) and Bonsack (1961) analyzed 12 T Tauri stars and found lithium abundances relative to heavier metals of the order of one hundred times larger than the solar value and approximately equal to the terrestrial values as well as those of meteorites.

Lithium appears as two isotopes, ^{6}Li and ^{7}Li, which results in a split of the λ6707 line by 0.16 Å, corresponding to $\sim$7 km s^{-1}. Although this is technically not difficult to resolve, it is often several times smaller than the thermal broadening of stellar lithium lines. But, at least in principle, the lithium isotopic abundance ratio is measurable from the detailed shape of the lithium profile, where the much weaker ^{6}Li line appears as a longward asymmetry of the prominent ^{7}Li line. This was precisely what Herbig early on attempted to do by measuring the center of gravity of the λ6707 line using high-resolution photographic spectrograms of fifteen F5-G8 dwarfs (Herbig 1964). The observations were for most stars consistent with theoretical expectations, but for several stars larger values were found. Later work suggested the possibility that outflow and infall might affect the line wings of those stars.

In a subsequent pioneering study, Herbig asked the question of what happens to lithium after stars evolve out of the T Tauri phase and reach the main sequence. His expectation was that the predominant process of Li depletion in solar-like stars would be the longterm – but strongly mass-dependent – convective destruction after a star reaches the main sequence (Herbig 1965a). About 100 nearby F5-G8 dwarfs were observed spectroscopically, and their lithium abundances were found to show major variations. Li abundances of stars in three clusters of known ages showed a trend conforming to expectations (Figure 25). Herbig called for observations to fill out the obvious, major gaps along the theoretical depletion curve, and in the following half century serious efforts have been made to complete this task (e.g., Soderblom et al. 1999, Jeffries et al. 2009, and references therein). Lithium depletion models for different stellar masses are now being tested and refined when held against accurate observations (e.g., Yee & Jensen 2010), and additional transport phenomena related to diffusion, gravity waves, angular momentum loss, etc. are being recognized (e.g., Sestito & Randich 2005).

Herbig left these follow-up studies to a younger generation. Several of his students later did their theses on different aspects of the lithium problem (Zappala 1972, Alschuler 1975, Duncan 1981, see Chapter 10), and many others have dedicated major efforts to understand the way lithium is depleted. But late in life Herbig returned – in a different context – to lithium in two studies of young eruptive variables. In the first, he analyzed several EXors (see Section 5.7), among them V1118 Ori, which he observed at high spectral resolution during an outburst and subsequently again at a much less elevated state. To his con-

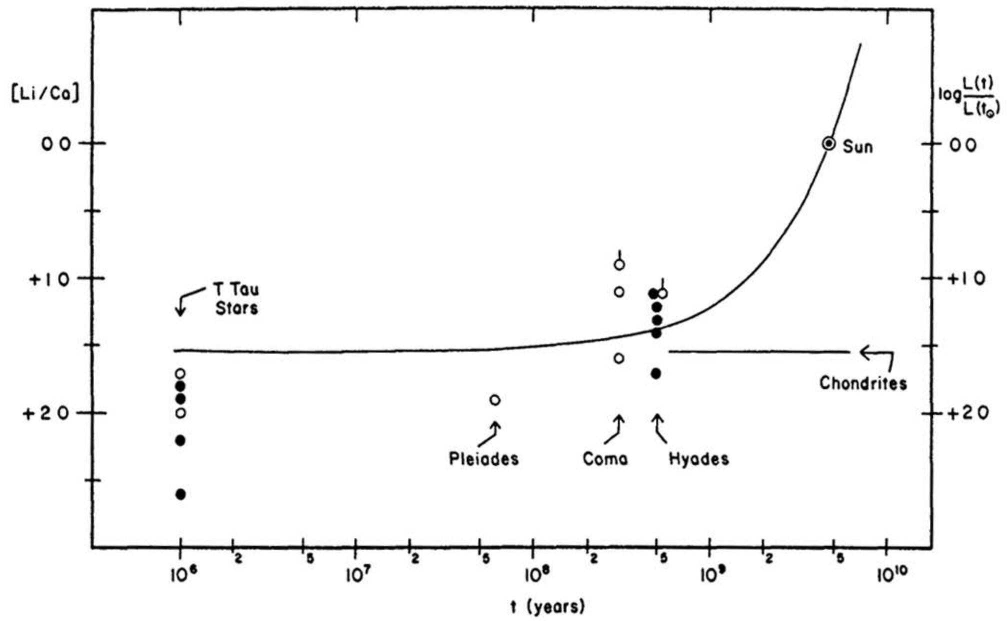


Figure 25: *The curve shows the expected exponential decay of the [Li/Ca] ratio fitted to the meteoritic and solar measurements. Overplotted are the measurements for T Tauri stars and for three clusters. These pioneering results pointed to the need for many more clusters to be analyzed, work that is still in progress. From Herbig (1965a).*

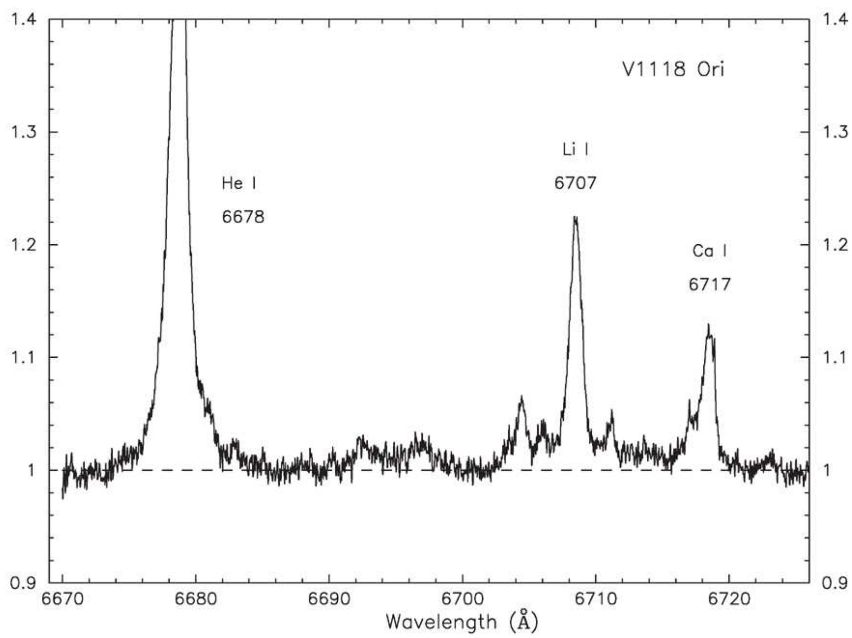


Figure 26: *The lithium λ6707 line is seen in emission in the young eruptive variable V1118 Ori. From Herbig (2008).*

siderable surprise he found the lithium line in emission (Figure 26) during the eruption:

> *"A most unusual feature is the presence of the Li I 6707 line in emission on this spectrogram. This line is always seen in absorption, although often veiled, in CTTS spectra. Its appearance in emission is most unusual. One is struck by the fact that λ6707, the K I lines at $\lambda\lambda$7664, 7698, and Na I $\lambda\lambda$5889, 5895 are the only unblended resonance lines in the spectral region covered in the 2005 Keck spectrogram of V1118 Ori, and all were strong in emission at that time. Except for the Na I lines, the other three had gone into absorption a year later, as shown by a second Keck spectrogram obtained on 2006 December 10, when the star was much fainter. The enhancement of those lines was apparently a consequence of that particular outburst, because λ6707 was not in emission in EX Lup at the time of its 1998 flare-up. The emission line λ6707 shares the radial velocity of the other emission lines, and its HWHM (half-width at half-peak intensity) of 24 km s^{-1}, corrected for instrumental resolution, is also typical. It is unusual only in its symmetry: it lacks the shortward wing present on most of the other emission lines on this exposure. The only other example of emission at λ6707 (known to the author) is V1331 Cyg, observed with HIRES on 2004 July 24 when, like many Ca I and Fe I emission lines in that spectrum, it had the center of λ6707 cut out by a narrow central reversal"* (Herbig 2008).

This unexpected discovery of lithium in emission remains a puzzle. Another case was subsequently found in the eruptive variable V2492 Cyg by Hillenbrand et al. (2013), but remains unexplained as well.

In a second study, Herbig re-visited the FU Orionis variable V1057 Cyg with a view to analyze the outflowing wind from the star (Herbig 2009a). High-velocity outflow is revealed by prominent blueshifted wings at several lines, notably Hα and the Na I doublet at λ5889 and λ5895. The outflow wings in these and other lines are often saturated, but Herbig found that lithium could reveal much finer details in the outflow (Figure 27). He notes:

> *"The Li I line is particularly suitable for an examination of this absorption-line structure because it is a resonance line of a neutral that is of modest abundance, is expected to contain minimal interstellar contribution, and is located in a wavelength region relatively uncluttered with atmospheric features or with lines of the G-type spectrum. The very much stronger D_{12} lines of Na I and the 7664, 7698 Å lines of K I are unsuitable for those reasons."*

High-resolution spectra obtained over many observing runs demonstrated how the lithium line varied, giving information on the fine time-dependent details

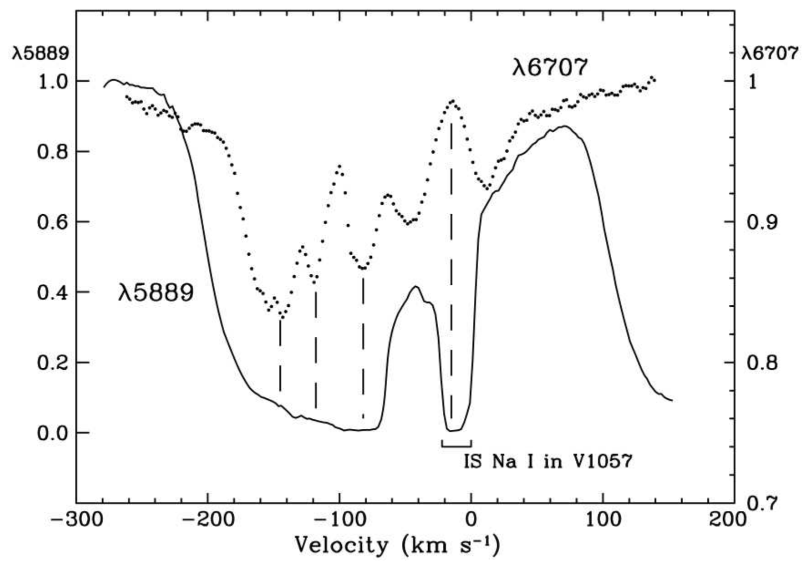


Figure 27: *The Li I λ6707 line in V1057 Cyg superposed on the Na I λ5889 line on the same night, with corresponding intensity scales on left and right. The many features clearly seen in the λ6707 line are lost in the saturated Na I profile. The falloff on the right side of λ5889 is the shortward wing of Na I λ5895. From Herbig (2009a).*

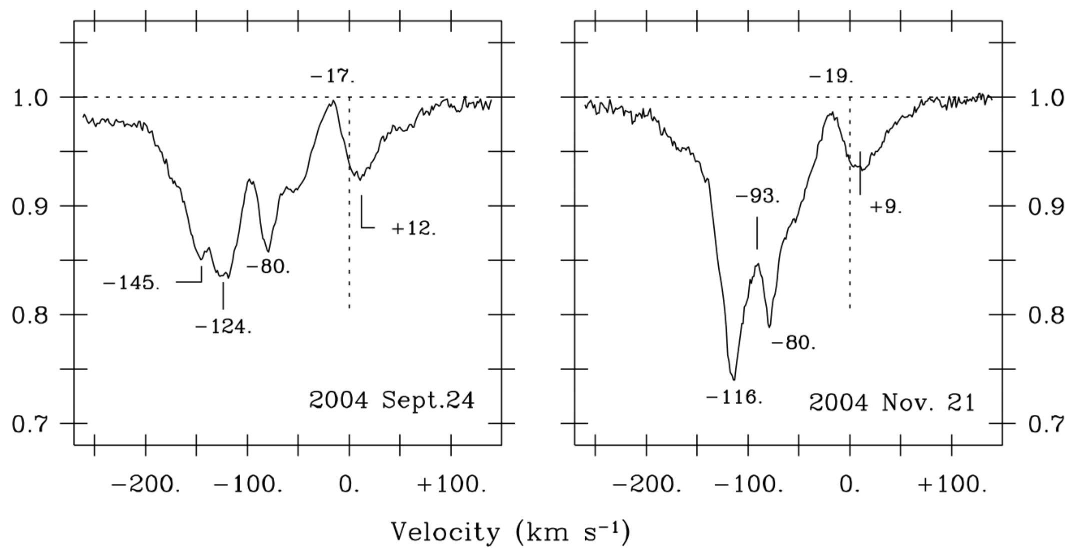


Figure 28: *The lithium line in V1057 Cyg on two different dates in 2004. The horizontal scale is in km s^{-1} with respect to the rest wavelength of the lithium line, marked by the vertical dashed line. Velocities of particular features are marked. From Herbig (2009).*

of the outflowing wind (Figure 28). V1057 Cyg and its powerful winds are discussed in more detail in the chapter on FUors (Section 5).

2.9 Rotation of Young Stars

Shortly after Herbig took up his position at Lick Observatory, he ventured into the field of stellar rotation, which resulted in the only three papers he wrote on the subject (Herbig & Spalding 1953, 1955, Herbig 1957c):

> *"I became seriously interested in stellar rotation as evidenced by line broadening when I returned to Mount Wilson as a guest observer in 1950-51, and obtained spectrograms of 4 of the brightest T Tauri stars with the 100-inch coudé. Sanford had commented several years before that the lines of T Tauri were "somewhat shallow and diffuse for spectral class G" [actually it is about K0], and Joy had already remarked that some T Tauris had wide, or shallow absorption lines (although now one suspects that, given Joy's low dispersion, this may have been due to veiling rather than line broadening). My new coudé spectrograms showed indeed that the lines were broadened significantly, with widths corresponding to* $v \sin i$*'s of 20 to 65 km* s^{-1} *(in the final report* [Herbig 1957c]*). At the time these results were first announced (1952), all that was known about* $v \sin i$*'s of normal F- to K-type stars was based on low-resolution work that had been done at Yerkes in the 1930's. It was clear that that had to be updated, so I went through the Lick files of Mills spectrograms, and estimated the line widths of some 650 stars between types F0 and K5 of all luminosity classes by visual comparison with a set of standards whose* $v \sin i$*'s I had measured by actual photometry of the profiles. A brief account of the work was published in 1953, and the details in a large paper in 1955. (My ostensible co-author in this effort was J. F. Spalding, a young man employed in the Lick optical shop who wanted to become involved in some real astronomy.)*
>
> *These results demonstrated that the rotations of these T Tauri stars (TTS) were indeed abnormal for their spectral types, and I think that my assertion (1957) that they would arrive on the main sequence with normal* $v \sin i$*'s for their final radii and spectral types still holds. However, the implication that some drew from the 1957 paper that TTS in general rotate abnormally fast was incorrect. This sample of 4 of the most luminous T Tauris – the only ones that I could reach with the 100-inch coudé at that time – did rotate rapidly, but they are the most massive TTS in Taurus-Auriga and are therefore headed for destinations higher on the ZAMS than the majority of such objects in those clouds* [Herbig 1962a]*. It was not until much later that Kuhi and Vogel showed that the less luminous TTS have very much smaller* $v \sin i$*'s* [Vogel & Kuhi 1981].

> *Incidentally, the 1955 paper provided new, good (for that epoch) data on line broadening in giants and subgiants, and on the decline of rotation down the main sequence, that was interesting and useful in its own right. I did not pursue this issue myself any further although I remain interested in what has emerged in recent years, as the result of the work of others, on angular momentum evolution in stars."*[1]

Subsequently, further observations confirmed and extended the finding by Vogel and Kuhi that most T Tauri stars are slow rotators (e.g., Hartmann et al. 1986). Since the $v \sin i$ from high-resolution spectra suffer from the unknown inclination of the stellar rotation axis, periods derived from photometric monitoring of young stars with spotted surfaces have taken over (e.g., Herbst et al. 2000), resulting in thousands of periods accurate to $\sim$1%. The angular momentum evolution towards the main sequence has been shown to be not a simple one, and it has been found that, at a given age, disk-bearing PMS stars are, on average, slower rotators than diskless ones (Bouvier et al. 2014), presumably due to disk-locking where stars interacting magnetically with their disks are prevented from spinning up despite contracting (Königl 1991, Hartmann 2002).

2.10 Radial Velocities and Proper Motions of T Tauri Stars

Although by the mid-1970s it was firmly established that T Tauri stars are born in the dark clouds with which they are associated, there had not been any studies that had determined the kinematic relationship between stars and clouds. Herbig set out to investigate this question and measured absorption-line radial velocities for about 50 T Tauri stars on 34 Å/mm spectrograms of the 5850-6700 Å region. The standard deviation of the velocity from an average plate was about 4 km s^{-1}. These velocities Herbig compared to existing molecular line velocities of the clouds on which the stars were projected, and for the large majority found that they were the same within the errors. The intrinsic dispersion in the stellar velocities were hidden in the errors, but were estimated to be less than about 3 km s^{-1} (Herbig 1977b). Some of the velocities were discrepant from the cloud velocities, which were later found to be due to small shifts of the stellar spectra on the Varo plates, although some also might reflect spectroscopic binaries. Subsequent studies have confirmed and refined the close kinematic association of T Tauri stars with their nascent clouds (e.g., Hartmann et al. 1986, Fürész et al. 2008).

A natural extension of the above radial velocity work would be an investigation of the proper motions of T Tauri stars. Due to its proximity, the Taurus-Auriga complex was an obvious choice. Also, this region was included on an already existing set of first-epoch plates from the Lick 20-inch Astrograph taken in the

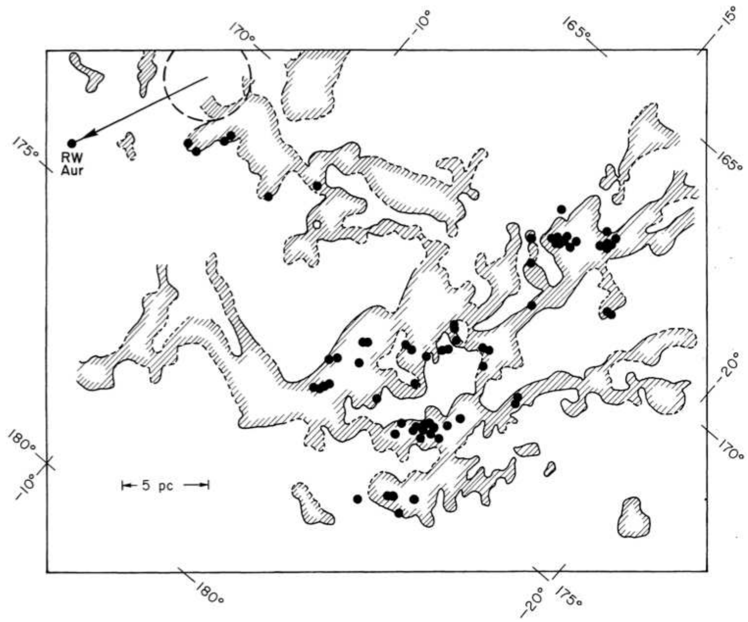


Figure 29: *The distribution of T Tauri stars in the Taurus-Auriga clouds. North is up and east is left, and the numbers along the margins indicate galactic coordinates. The circle indicates the uncertainty of the RW Aur proper motion. Herbig (1977b, 1981a).*

late 1940s as well as on first-epoch plates from the Palomar Schmidt survey from the early 1950s. Identical second-epoch plates were taken to match this material, yielding a time difference of 23-28 years. Jones & Herbig (1979) found that *"those stars known (spectroscopically) to be cloud members show only small dispersions about their means. Within subgroupings, the velocity dispersions (in one coordinate) are 1-2 km s^{-1}."* A question that had occupied Herbig for a long time was whether there was a population of stars that shared the proper motions of the T Tauri stars, but had not been found in the emission-line surveys. However, very few non-emission stars were found to share the motion of the known T Tauri stars, at most 1 for every 4 TTS. Only one star, RW Aur, seemed to have a tangential velocity exceeding the local escape velocity from the cloud (Figure 29). RW Aur is already special in that it is the only one of Tau-Aur stars that is located about 3° away from heavy obscuration. The high cross motion of 16 km s^{-1} eastward would indicate it left the dense cloud region about 6×10^5 yr ago. However, it has later been found that RW Aur is a binary with 1.4″ separation, hence the abnormal proper motion could be due to light variations between the components. The issue has still not been resolved.[13]

Twelve years later, Hartmann et al. (1991) obtained a third-epoch Lick Astrograph plate of one region in Taurus to improve the proper motion vectors, and further obtained spectra of more than 200 stars sharing in the motion of the known young stars. Only about 20% more young stars were found, in agreement with the Jones and Herbig results, and confirming that a large number of post-T Tauri stars do not exist in the clouds (see Section 2.13).

2.11 Variability of T Tauri Stars and Flare Stars

In his 1962-review, Herbig emphasized the importance of variability as a fundamental property of T Tauri stars:

> *"The group of 11 emission-line stars originally described by Joy (1945) and called by him 'T Tauri variables' after one of the brightest and most representative members, were all well-known irregular variable stars whose light variations had been detected long before. The enlargement of the group since that time by nearly an order of magnitude has been due almost entirely to objective-prism surveys of likely regions for stars with the Hα line in emission. Consequently, the condition of light variability has become a secondary one simply because photometric information on such faint stars is usually lacking. It appears, however, that variability in light is a general characteristic of the T Tauri stars: a high percentage of the emission-Hα has been discovered to be variable, it could be said almost by accident, in the course of spectroscopic observations. Indeed, essentially all those T Tauri stars that have been the subject of adequate photometric studies have been found to be variable."*

Significant information about variability had been established by the dedicated studies of the Orion Nebula variables by Parenago (1954) and in various star forming regions by Rosino (e.g., Rosino 1956). And Herbig noted that there were many nebular variables that were not detected in the Hα surveys, and *"that the presence or absence of emission lines does not appear to have much to do with the gross characteristics of the light curves of the nebular variables."* But Herbig strongly discouraged the idea that T Tauri stars could be identified or usefully subdivided through their variability alone. Hoffmeister (1957) suggested the definition of a socalled 'RW Aur' class of variables, but in an examination of 112 variables, including 25 RW Aur variables, Herbig (1960d) concluded that classification on photometric grounds alone would not form a homogeneous group. Subsequent more detailed studies showed that the non-emission nebular variables were just having weaker emission, beyond the reach of early objective prism surveys.

Today variability studies of T Tauri stars, after a period of relative dormancy, have been rejuvenated by the availability of long-term uninterrupted monitor-

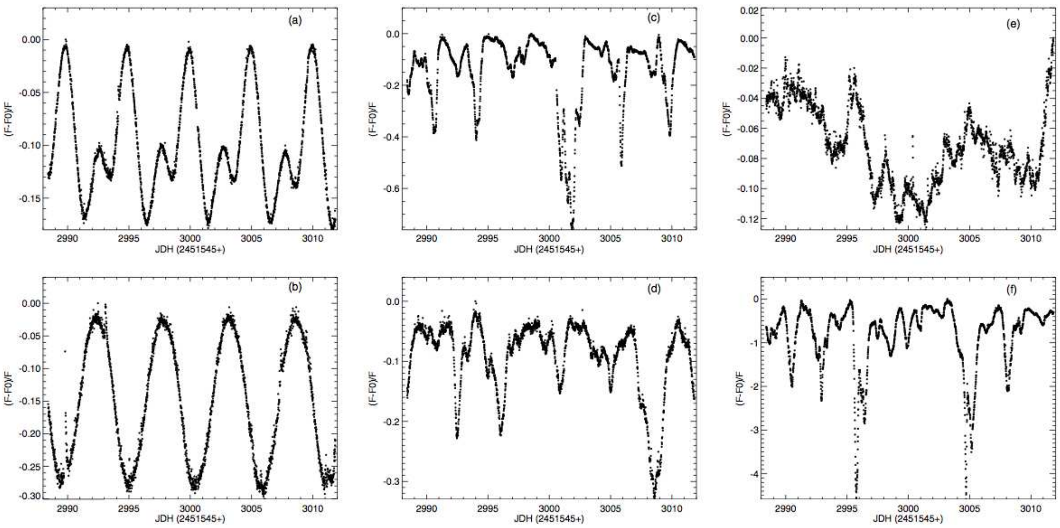


Figure 30: *Six light curves of classical T Tauri stars in NGC 2264 observed continuously for 24 days with the COROT satellite. The two left are spot-like, the two middle display semi-periodic variable obscuration from a disk, and the two to the right appear to show accretion variability. From Alencar et al. (2010).*

ing of star forming regions using spacecraft such as Spitzer, Corot, and Kepler, resulting in spectacular light curves of hundreds of young stars (Figure 30, Alencar et al. 2010, Cody et al. 2014).

A group of variables that generated much early discussion and confusion were the flare stars (Figure 31). Much of the pioneering work on flare stars was done by Guillermo Haro, who discovered numerous flare stars in different regions, including the Orion Nebula, the Pleiades, as well as older clusters. During the previously mentioned IAU Symposium that Herbig organized in 1955 in Dublin, Haro discussed his discovery of many flare stars in Orion and Taurus and stated that he had come to believe 'that these objects belong to the family of the T Tauri stars, and that whenever there exists a T-association there is the possibility of finding, related to it, rapid variable stars of characteristics similar to those of UV Ceti.' Instead of concluding that T Tauri stars possess the same outburst mechanisms as the UV Ceti stars, Haro concluded, erroneously, that 'stars of the UV Ceti type are to be considered as objects related to the T Tauri stars' (Haro 1957).

Haro (1968, 1976) continued to emphasize the similarities between the T Tauri stars and UV Ceti-type flare stars. Herbig, always worried to reach conclusions too fast, early on cautioned to Haro that it was not a given that the flare stars found in young associations and clusters would be the same as those much older

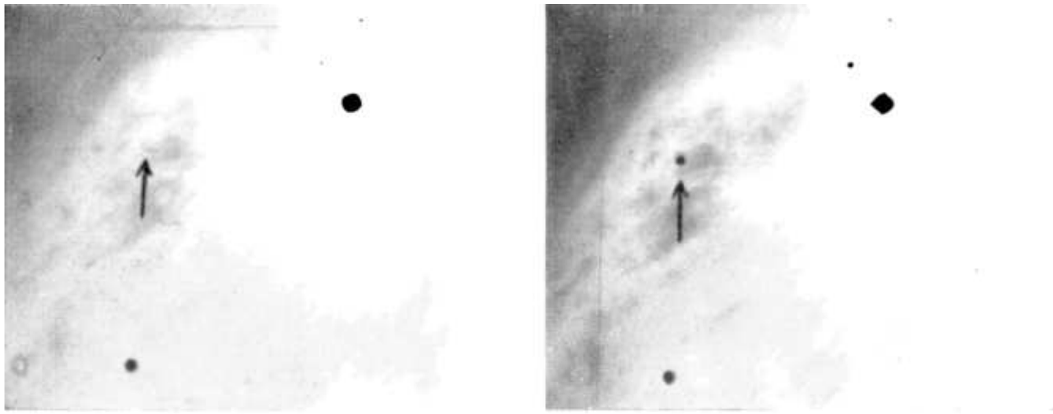


Figure 31: *A giant flare is caught on the young variable MN Ori = COUP 752. The two plates were taken 20 minutes apart. The same star was producing a giant X-ray flare during the Chandra Orion Ultradeep Project (Favata et al. 2005). Image from Rosino (1956).*

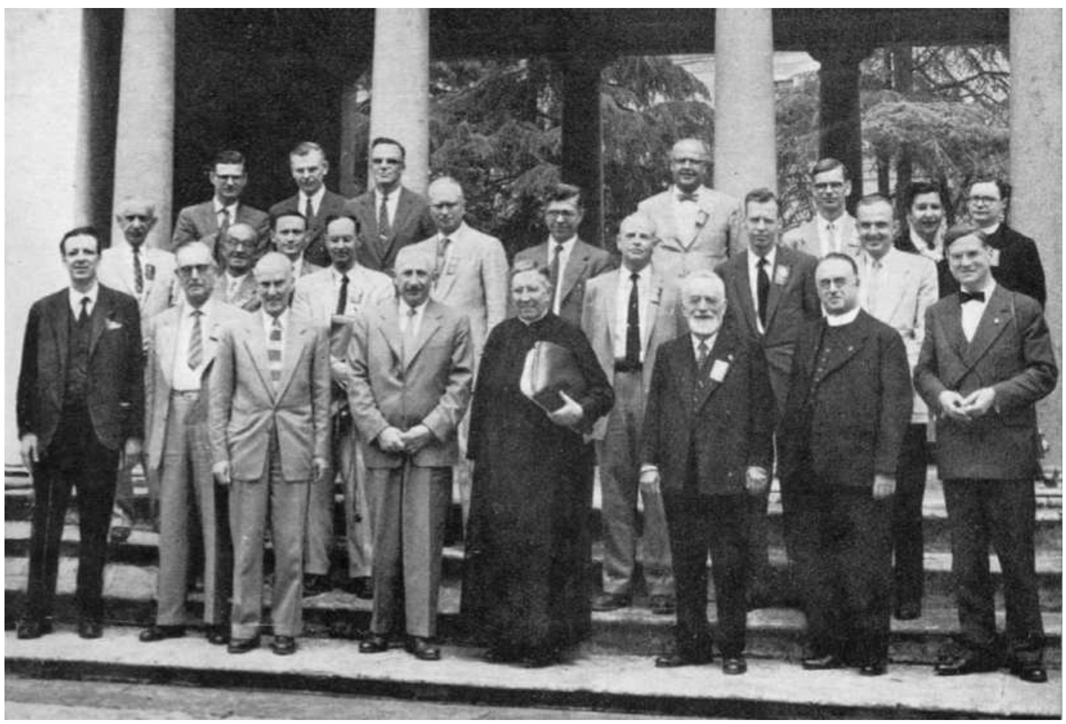


Figure 32: *Herbig presented his work on T Tauri stars at the 1957 Vatican Conference attended by many of the leading stellar astronomers at the time.*[18]

UV Ceti-type flare stars found in the solar neighborhood, and he suggested to use the term 'flash'-variables for the former. Herbig described these flash variables[14] as follows at the Vatican conference (Figure 32) in 1957:

> *"They exhibit quick, flarelike outbursts of light separated by long intervals of quiescence. Their spectra are those of late-type dwarfs, but emission lines are generally weak or absent at minimum light. They do not fit the definition of a T Tauri star used here, nor are they 'flare stars' in the precise sense of the variable Me dwarfs in the solar neighborhood. The fact that the fainter 'flash stars' even at minimum light are considerably more luminous than main sequence stars of their spectral types suggests that, like the T Tauri stars, they are probably relatively young objects."* (Herbig 1958e).

One of many ideas that were debated was that very low-mass T Tauri stars might evolve into the ubiquituous dMe stars, and that these latter stars would still be contracting while approaching the main sequence (Herbig 1962d). Eventually the dMe stars in this picture would evolve into dM stars. This evolutionary sequence is now known not to be correct.

Interest in flares on young stars gradually faded away, partly because of the extreme difficulty in catching and studying in more detail such events. But the similarity between solar flares and the flares on young stars, apart from the orders of magnitude difference in energy release, inspired a host of early models of T Tauri stars built on solar phenomena before the concept of circumstellar disks emerged (Section 2.16). The study of flares eventually received a renaissance when X-ray satellites like Chandra and XMM-Newton monitored star forming regions and were able to determine physical properties of thousands of flare events (e.g., Montmerle et al. 1983, Gahm 1990, Feigelson et al. 2007).

2.12 Binarity of T Tauri Stars

Already when Joy was preparing his large study in which the T Tauri stars were defined he noticed that surprisingly many were visual binaries, with 5 out of the initial sample of 11 stars being double (Joy & van Biesbroeck 1944). Evidently this was based on small-number statistics, but no systematic follow-up on this result occurred until 18 years later when Herbig in his large 1962 review published a table of 29 T Tauri doubles, half of which he had himself discovered among the many new Hα emission line stars he found in his surveys. He noted that *"The list is not exhaustive, because a number of faint and/or very wide pairs have been excluded"*. He further commented that *"it is not obvious that the fraction of visual doubles among the T Tauri stars is significantly larger than among normal stars"*. Here Herbig touched upon an issue that would prove central to the study of young binaries. Not a lot happened in the field of pre-main sequence binaries until the fall of 1993, when within one month three major surveys were published (Reipurth & Zinnecker 1993, Leinert et al. 1993, Ghez et al. 1993). Examples are shown in Figure 33. The key result of these studies was that there is indeed an excess of binaries

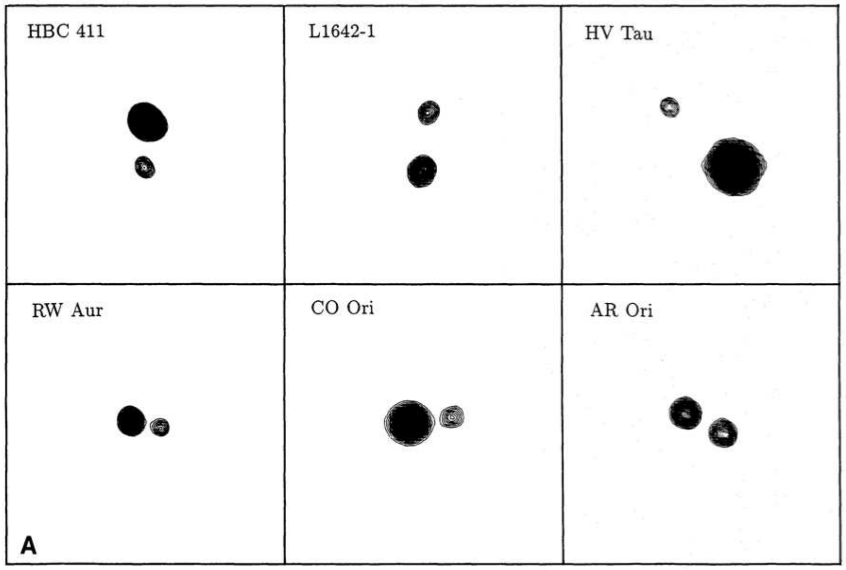


Figure 33: *Six young visual binaries, three of which were discovered by Herbig. The images are 13×13 arcsec and taken through a* z*-filter (Reipurth & Zinnecker 1993).*

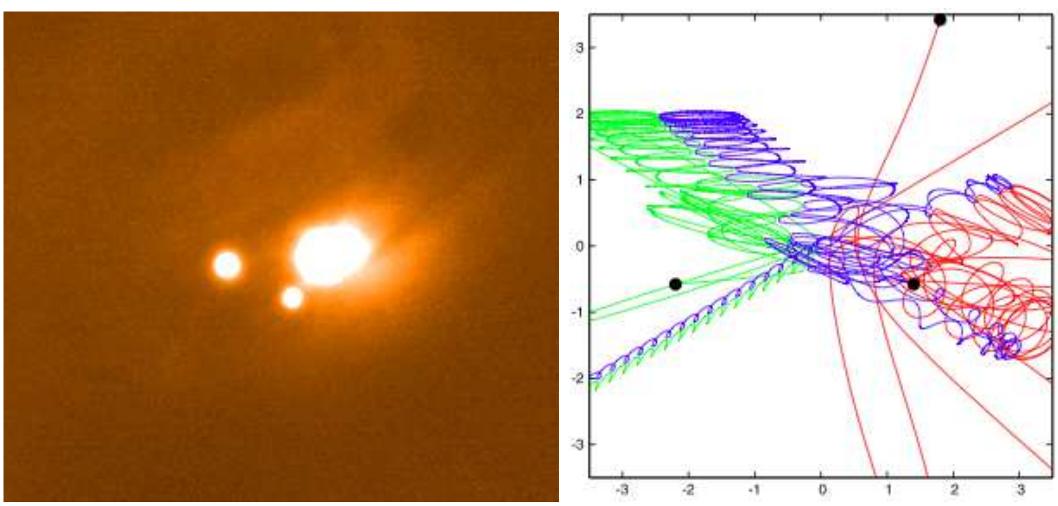


Figure 34: *(left) The young non-hierarchical triple system LkHα 336 discovered by Herbig in the L1622 cloud in Orion. Hα image obtained at the 8m Subaru telescope from Reipurth, Herbig, Aspin (2010). (right) Numerical simulation of a non-hierarchical triple system showing the chaotic motions of the members until a hierarchical configuration is established. From Reipurth & Mikkola (2015).*

among very young stars, a result that has been supported by many subsequent studies. Evidently this excess must disappear as the stars evolve, and the key to that lies in higher-order multiples.

Among the many Hα emission line stars that Herbig found was an unusual pre-main sequence triple system, LkHα 336, in Orion (Figure 34a). While triple systems are not rare – about 8% of the solar-type stars in the field population are triples (Raghavan et al. 2010) – LkHα 336 is very unusual in having a non-hierarchical configuration. Such a geometry is not stable, leading to chaotic motion of the three stars. An example of a calculation of such motion is shown in Figure 34b. While the details of this chaotic motion cannot be predicted, the end result is firmly established: either the triple system transforms into a stable hierarchical configuration, with two components bound together in a close binary and the third star in a distant orbit, or the system breaks up with one component escaping, leaving behind a tighter binary.

The excess of binaries among pre-main sequence stars can be understood in this dynamical framework: some of the binaries we observe are likely to be unresolved triple systems, and some of those will disintegrate, until the stars reach the distribution of singles, binaries, and higher-order systems observed in the field (Reipurth et al. 2014).

2.13 The Post T Tauri Problem

During the 1950s it was established to everyone's satisfaction that T Tauri stars are young stars with typical ages of a few million years and still contracting towards the main sequence. Early pre-main sequence evolutionary tracks (Henyey et al. 1955, Hayashi 1961, Iben 1965) showed that while most massive stars would reach the main sequence in less than a million years, the lower mass stars would take much longer, around 30 Myr for solar-type stars and more than 100 Myr for the least massive M stars. This was observationally confirmed when Walker (1956) showed that T Tauri stars are located above the main sequence in a color-magnitude diagram. It was therefore natural for Herbig to ask the question: what are the properties of stars after they have lost their T Tauri characteristics, but before they reach the main sequence, and how would one detect them? These stars he dubbed the post T Tauri stars, and at a conference in Yerevan, Armenia he gave a talk with the title *"Can Post T Tauri Stars Be Found?"* in which he argued that such evolved pre-main sequence stars should be common (Herbig 1978a):

> *"The restricted location of T Tauri stars in the H-R diagram, above the main sequence and cooler than type F, suggests that during the later stages of their contraction to the main sequence they must for a time no longer be*

recognizable as members of that class. If the T Tauri stage represents only a fraction `p` *of a star's pre-main sequence lifetime, then there must exist somewhere, still above the main sequence,* `(1-p)/p` *times as many 'post-T Tauri stars' (or PTTS) that have escaped detection. The value of* `p` *is not known, but if an early estimate of* `p`*∼0.05-0.1 (Herbig 1970d) is approximately correct, then there must be many times more PTTS than there are T Tauri stars. If one can assume that a mass of 1-2 $M_\odot$ is representative, then such PTTS ought to lie along the radiative tracks that connect the lower part of the T Tauri region with the main sequence.*

T Tauri stars as a group possess several distinctive observational characteristics which are diminished or absent in the stars that one believes to be their main sequence counterparts. [...] The observations encourage one to believe that the possession of an appropriate intermediate value of these characteristics (here arranged approximately in order of lengthening decay time) ought to identify a PTTS:

Hα emission
Irregular variability
Infrared excess
Ca II emission
Surface Li abundance"

Herbig goes on to discuss each of these features in the light of what was known at the time, and considers the feasibility of making systematic surveys to identify PTTS. He concludes that the least biased method would be to select stars that are kinematically associated with a star forming cloud complex by measuring their proper motions. He and Burt Jones embarked on such a study of the Taurus-Auriga clouds (Jones & Herbig 1979, see Section 2.10):

"It has often been remarked (Herbig 1973a, 1978) that if star formation in a certain cloud continues for a time comparable with the Kelvin time of a representative star, the cloud ought then to contain many more 'post-T Tauri stars' than emission-line objects. [...] Yet very few such PTTS have as yet been found. The present investigation has furnished the most convincingly negative information to date: only a small number of non-emission stars that have been detected are moving with the emission-line members of the Tau-Aur clouds. Instead of a limiting ratio N(PTT)/N(T Tau) ∼ 5-10, the results [presented here] suggest a value of 0.26±0.1.

The most obvious explanation for this departure of the ratio from expectation is that star formation in these clouds has been in progress for only slightly longer than the duration of the T Tau phase of the most massive examples."

This last point is important, and will be discussed further below.

A possible example of a post T Tauri star, BD –10°4662 = FK Ser, was examined by Herbig (1973a). It was found to be a close visual binary with the components having spectral types of K5pV and K7pV. Both components show modest Hα emission, the H and K lines of Ca II are in emission and strong Li I λ6707 absorption is present. The binary is located in a region rather devoid of dark clouds, but 1.5° to the north-east are the dense clouds B94, B96, and B97, from where the stars may have originated. Their location away from known star forming regions and their modest emission with strong lithium suggested to Herbig that FK Ser would be past its T Tauri stage, a conclusion that is still regarded as likely today.

However, the assumption that Hα emission would gradually decay with time was questioned when Herbig et al. (1986) undertook an objective prism survey of the Taurus-Auriga clouds for stars with Ca II H and K in emission (see also Section 2.5):

> *"The H, K survey described here was initiated as a search for the hypothetical radiative-track PTTS population of the Taurus-Auriga clouds. The survey indeed revealed a substantial number of late-type stars associated with those clouds, amounting to about 20% of the number of T Tauri stars to the same limit. However, our data indicate that these stars are too faint and too cool to be identified with the PTTS sought: from their location with respect to theoretical isochrones, they do not as a group appear to be older than the conventional T Tauri stars. In fact, they are probably TTS whose Hα emission was merely too weak for detection by classical methods.*
>
> *This result demonstrates once again that line emission does not decay in any smooth, age-dependent way among the T Tauri stars or between the T Tauri region and the main sequence,* provided *that initial conditions are similar and that ages of pre-main sequence stars can correctly be inferred from correlating their observed luminosities and temperatures and theoretical evolutionary tracks."*

A few years earlier, five pre-main sequence stars were discovered in Taurus-Auriga due to their strong X-ray emission (Feigelson & Kriss 1981, Walter & Kuhi 1981). All five stars were recovered in the Ca II H, K survey undertaken by Herbig et al. (1986):

> *"The faint K and M dwarfs found in our H, K survey are spectroscopically and photometrically indistinguishable from the five pre-main sequence X-ray sources already known in these clouds."*

The discussion about post T Tauri stars was re-vitalized when Walter (1986) announced the discovery through X-ray surveys of a population of stars that are all young, but for which the traditional characteristics of young stars such as

Hα emission and infrared excesses were often weak or absent. Walter pointed out that some of these X-ray sources were likely to be post T Tauri stars with ages of $\sim 10^7$ yr, while others were 'naked' T Tauri stars coeval with classical T Tauri stars but lacking circumstellar material. These latter are now primarily known as *weak-line* T Tauri stars (WTTS), a term that Herbig coined to distinguish these mostly X-ray detected objects from the *classical* T Tauri stars mostly detected by objective-prism surveys. The threshold between the two groups was set at an Hα equivalent width of 10 Å (Herbig & Bell 1988).

With the recognition that WTTS could be detected mainly by X-ray observations, the possibility arose that a substantial population of young stars might have been missed in and around star forming regions. Feigelson (1996) estimated that the number of stars with ages of more than 2-5 Myr might exceed that of younger stars by a factor of 5 or 10, and expected that these stars should be found dispersed outside well-surveyed regions. An important implication of such a large undiscovered population would be that the star formation efficiency of molecular clouds would be much larger than the few percent traditionally estimated.

This was, however, disputed by Palla & Galli (1997), who argued that the lack of older stars in low-mass star forming regions is intrinsic to the star formation process itself. They noted that giant molecular clouds will typically have lifetimes of 10-20 Myr, but much of this time the clouds spend establishing the proper initial conditions that will eventually lead to collapse and formation of stars. In this picture the star formation efficiency of clouds is very low in the beginning, but increases steeply at later times. Thus, observations of a star forming cloud should reveal a spread in ages of young stars, as indeed observed, but the large bulk of stars will have ages of only a few million years. The absence of post T Tauri stars that Herbig noted in star forming regions is therefore a consequence of how molecular clouds form stars. This was precisely the point that Herbig made to explain the otherwise surprising low ratio of PTTS to TTS around star forming clouds.

Nonetheless, young stars grow older, and so post T Tauri stars must exist in abundance somewhere. The practical issue is how to distinguish such moderately young stars from stars that have already reached the main sequence (e.g., Briceño et al. 1997). In the years since Herbig drew attention to the problem, a number of studies have successfully identified post T Tauri stars. In a fine study, Lindroos (1986) found numerous wide low-mass companions bound to OB stars. Since ages of OB stars are more easily constrained, and components in binary systems are virtually always coeval, Lindroos could show that these low-mass companions were having ages of up to 150 million years. Although half of these low-mass secondaries have strong lithium absorption and some emission lines, their degree of variability and infrared and ultraviolet excesses are strongly reduced or absent relative to normal T Tauri stars. Placed in a Hertzsprung-Russell diagram, they also fall in a location between the T Tauri stars and the zero-age main sequence. These stars fit the predictions of Herbig, and are accepted as bona fide post T Tauri stars.

In recent years, a number of loose stellar associations have been recognized in or near the solar neighborhood. These are groups of often widely scattered stars that move together, indicating that they were born together in a small cluster, but after removal of the placental clouds they are no longer bound to each other, so they are very slowly dispersing. As a consequence they are spread out all over the sky, making their identification very difficult. With increasingly accurate proper motion and radial velocity surveys, many new members have now been identified in moving groups with ages typically between 10 and 100 Myr. These stars are therefore all post T Tauri stars. The great advantage of studying post T Tauri stars identified by their kinematics as members of moving groups is that no a priori assumptions have been made on what they should look like, thus providing an unbiased view of the full range of properties of these stars (e.g., Mamajek et al. 2002).

Finally, there are clusters with ages less than the typical pre-main sequence duration for low mass stars, such as the 125 Myr old Pleiades cluster, most of whose low-mass members have not yet reached the main sequence. Their cluster members are well studied, but in contrast to more isolated post T Tauri stars, their properties may have been altered over time due to dynamical interactions.

As both observations and models have continued to improve, the relation between CTTS and WTTS has been further clarified. Bertout et al. (2007) used spectroscopic and photometric information for young stars in Taurus-Auriga with accurate parallaxes to place 72 individual stars in an HR-diagram with evolutionary tracks. Figure 35 shows that CTTS and WTTS are distributed differently such that CTTSs are, on average, younger than WTTSs. These results, which are corroborated by similar results in Lupus (Galli et al. 2015), indicate that CTTSs evolve into WTTSs when their disks are fully accreted by the stars.

It would thus seem that PTTSs are simply WTTSs. But this is not quite so. A prime indicator of whether a T Tauri star is classified as CTTS or WTTS is the strength of the Hα emission line. In his systematic surveys for Hα emission stars in star forming regions (see Section 2.5), Herbig noticed that when a region was revisited, typically up to 10% of the stars had Hα emission that either newly appeared or had switched off. The transition from CTTS to

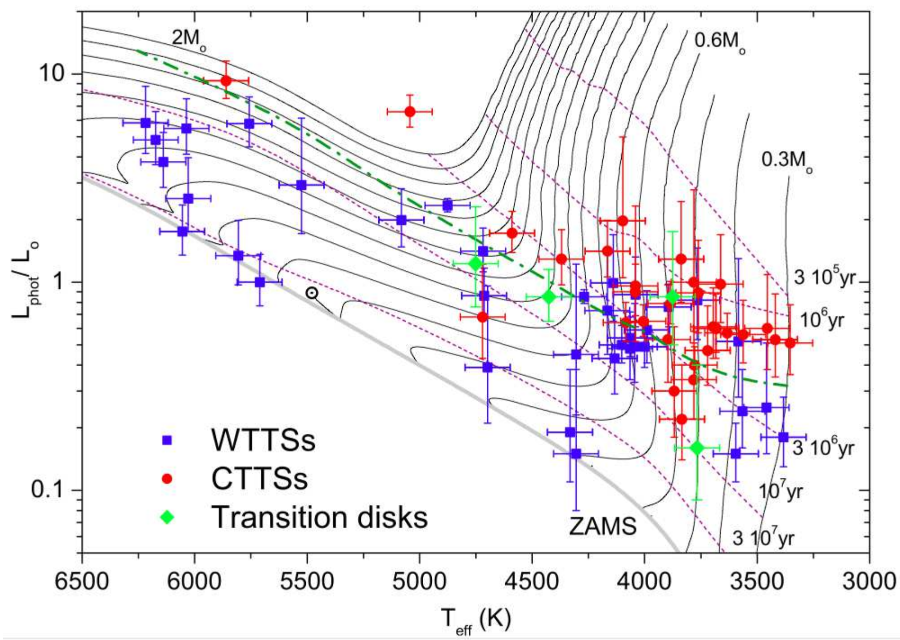


Figure 35: *The distribution of classical (red) and weakline (blue) T Tauri stars from Taurus-Auriga in a Hertzsprung-Russell diagram. From Bertout et al. (2007).*

WTTS is thus not monotonic over time, but irregular, with the Hα emission flickering as it dies out. Much of this Hα emission is due to disk accretion, and its episodic nature reveals the manner in which the disk disappears. A WTTS therefore only becomes a PTTS when the primordial disk has finally disappeared, thus ensuring that the CTTS-stage does not re-appear.[15]

At some level the distinction between WTTS and PTTS is semantic, and the PTTS concept is therefore fading away. Herbig's interest in the PTTS was to identify this additional population of stars that had not reached the main sequence. Many such stars have now been discovered through a variety of surveys, especially in X-rays. More will be found when Gaia provides accurate proper motions that will establish membership in moving groups across the sky.

2.14 The Early Solar System

At the same time that Herbig founded the modern study of young stars, a similar development occurred in the field of cosmochemistry, which matured during the 1950s and 1960s and gained much attention as a result of the returned lunar samples during the 1970s.

> *"A leader in this field was Harold Urey, who I first met at a conference on the abundance of the elements that was held at Yerkes in 1952, and encountered from time to time until he died in 1981. He was an energetic, forceful, influential, persuasive person, and of course his strengths were in the chemical and physico-chemical domains where I had to take him on his word. He was full of ideas on the constitution of the planets, the history of the moon and its surface, on what the isotopic results meant, and I found him very inspiring. [...] The obvious fact that the Sun must have been a T Tauri star at about the time the solar system was taking shape made it natural that the interests of Urey and I should overlap. I gave several papers on what I thought of early stellar evolution in the light of the solar system studies at a number of meetings, notably at Newcastle (1978) and lastly as an Invited Discourse at the IAU General Assembly at Patras (1983)* [Herbig 1983]. *The subject has since become an active one, fostered significantly by NASA's support of such studies."*[1]

Herbig did not directly conduct research in cosmochemistry, but took on the role as liaison between the two emerging fields of low mass star formation and cosmochemistry in the hope of facilitating cross-fertilization. He attended conferences on meteorites and the early solar system and presented the newest results on the properties of young solar-type stars and explained their relevance to the origin of the solar system. An issue that still lingered at the time was whether our planetary system was somehow a rare occurrence, perhaps due to a peculiar event long time after the Sun was formed, or whether planet formation was a universal process and a natural by-product of star formation. Herbig was firmly supporting the latter:

> *"I believe that there is no scientific reason to claim that the circumstances which produced our planetary system were highly unusual or unique. Hence it is fair to attempt to connect the planetary and meteoritic record with the processes and activities that we see taking place during the early evolution of solar-type stars. The event that took place here 4 1/2 billion years ago was governed by the same physics and chemistry and dynamics that operate in the Taurus clouds and in the Orion Nebula tonight, and the overall astronomical conditions should not have been significantly different"* (Herbig 1983).

Herbig always wanted to replace supposition with fact, and the obvious way to settle the question whether planet formation was universal was to detect planetary systems around other stars. Consequently, Herbig invited a small select group of astronomers up to Lick Observatory to attend 'The First Workshop on Extrasolar Planetary Detection' on March 23-24, 1976, chaired by Jesse Greenstein and attended by, among others, Frank Drake, Roger Griffin, K.Aa.

Strand, and Charles Townes. The minutes[16] of the workshop summarize discussions about the accuracy of radial velocities required to detect the wobble induced by a planet and accuracy of photometry to observe planetary transits, as well as other techniques. The origin of the Earth's oxygen-rich atmosphere (Herbig 1981b) and the question of life on other planets also fascinated Herbig, and he was the first to draw attention to how FU Ori-like outbursts would have major photochemical consequences upon the primitive Earth (Herbig 1978b), a subject that has still today not been fully understood.

2.15 Peculiar Young Stars

Herbig had a lifelong fascination with stars that were somehow unusual and did not conform to the expectations for their categories, and he wrote numerous papers about such stars. Thanks to his prodigious memory, he was a seemingly inexhaustible source of peculiar or rare objects. His famous studies of FU Orionis objects are discussed in detail in Chapter 5, and below are brief accounts of a few of the other young stars that attracted his attention.

2.15.1 **LkHα 101**

Early in his career, Herbig developed an interest in the little-known nebulosity known as NGC 1579, initially discovered by William Herschel. The nebula is located between the Taurus-Auriga and the Perseus clouds, but kinematic studies show that it is probably unrelated to these nearby star forming regions, and is located at a distance of 500-700 pc (Andrews & Wolk 2008). In his 1956 paper, Herbig described it thus: *"The diffuse nebula NGC 1579 is an irregular, mottled mass of rather bright nebulosity lying in a dark lane, in which are also found a number of nebulous stars. Direct photographs do not show any bright near-by star that can be convincingly identified as the source of illumination of NGC 1579"* (Herbig 1956). Consequently, Herbig surveyed the region for Hα emission stars, and found that a faint star located towards the dark lane had prominent Hα emission, and named it LkHα 101 (Figure 36). Photographic plates taken in different filters indicated that the star is highly obscured. Fifteen years later Herbig returned to this region and obtained spectra in the 7600-8500 Å spectral region (at that time called 'the near-infrared'). He found that spectra of star and nebula were the same, except for their slopes, indicating that NGC 1579 is just *"a dust curtain illuminated by the star"* (Herbig 1971a). The stellar spectrum is rich in emission lines of H, OI, [OII], [FeII], [CrII], etc., and is quite unlike that of T Tauri stars. In fact, the only object to which Herbig could find any resemblance was Eta Carinae. Then in 2004, Herbig and his students Sean Andrews and Scott Dahm published a detailed study of LkHα 101 and its surrounding cluster, using modern instruments (Section 6.4). The little cluster contains three dozen

Figure 36: *An HST image showing LkHα 101 in NGC 1579 and a number of fainter cluster members surrounding it.*

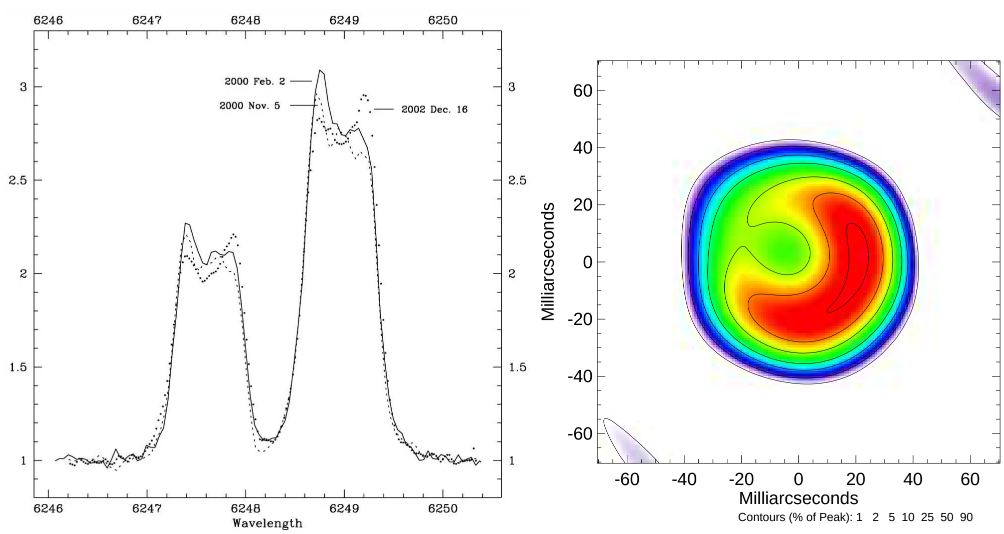


Figure 37: *(left) Fe II emission lines in a high-resolution spectrum of LkHα 101 on three dates. Each line is a blend of two components with a velocity difference of 19 km s^{-1}. From Herbig et al. (2004). (right) A horseshoe-shaped disk surrounds LkHα 101, which may account for the double Fe II emission lines. The companion is outside the field at a separation of 180 mas to the east-northeast. From Tuthill et al. (2002).*

Hα emission stars with a mean age of half a million years. Herbig et al. (2004) found that LkHα 101 is heavily reddened with $A_V \sim 10$ mag and has a high luminosity of at least 8×10^3 $L_\odot$. Today the star is considered a member of the class of Herbig Ae/Be stars. LkHα 101 displays a number of spectroscopic peculiarities, in particular Fe II lines are double-peaked, while [Fe II] lines and most lines from other elements are not (Figure 37a). This was interpreted as due to a rotating or expanding annulus around the star, consistent with the interferometric images of a horseshoe-shaped feature surrounding the star on milli-arcsecond scales from Tuthill et al. (2002), see Figure 37b. Herbig et al. concluded that *"there is reason to suspect that LkHα 101 may be a star of mass about 15 $M_\odot$ in an interesting phase of its early evolution."* Recent work on LkHα 101 is reviewed by Andrews & Wolk (2008), but even today a full understanding of this peculiar star remains elusive.

2.15.2 θ^1 **Ori E**

Since Herbig's visit to McDonald Observatory with Otto Struve in the winter of 1948/49 (Section 1.6), he maintained a strong interest in the young variable stars of the Orion Nebula, in particular the highly irradiated region around the massive stars in the Trapezium. In contrast with the four brighter Trapezium members, θ^1 Ori A, B, C, and D, which are well studied, the two fainter members E and F are essentially unstudied, perhaps on account of their proximity to the very bright OB stars (Figure 38). At McDonald, Herbig took several spectrograms on photographic plates of both E and F, and noted that the spectrum of E appeared composite, with a G-type spectrum and a mid/late B-type spectrum. In 1998, with the newly installed HIRES spectrograph on the 10m Keck-I telescope, Herbig obtained a much better spectrum of E. The B-type spectrum was not seen, it was probably caused by scattered light from the much brighter Trapezium star A, only 4 arcsec away. But the HIRES spectrum showed, together with subsequent series of spectra, that θ^1 Ori E is a short-period (9.9 days) double-lined spectroscopic binary consisting of two essentially identical mid-G-type giants, both showing a strong Li I λ6707 line (Herbig & Griffin 2006). This is of great interest, partly because it allows the determination of important physical parameters of the system, but especially because G-type T Tauri stars are very rare. Of particular interest is the fact that the system velocity differs from the velocity of the surrounding HII region by about 7 km s^{-1}. One of the possible interpretations is that the star is escaping from the Trapezium as the result of a dynamical ejection. This idea was explored further by Costero et al. (2008), who independently discovered the spectroscopic binary nature of θ^1 Ori E. Herbig & Griffin conclude:

> *"The components of θ^1 Ori E are clearly very young (<1.0 Myr) and lie in the type G-K region of the H-R diagram, where one expects to find T*

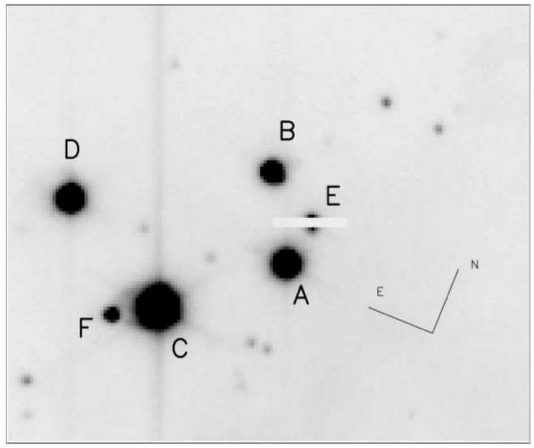


Figure 38: *The Orion Trapezium with the six brightest components marked. A spectroscopic slit is placed across θ^1 Ori E. From Herbig & Griffin (2006).*

> *Tauri stars. Yet they do not resemble conventional TTSs spectroscopically, and their masses (3-4 $M_\odot$) are larger than generally ascribed to the TTS population. A seemingly similar object is SU Aur, in Tau-Aur, of type G2 III with weak, variable H and Ca II line emission. But it is 1.4 mag fainter (in M_V) than the components of θ^1 Ori E and is believed (by DeWarf et al. 2003) to have a mass of only 2.0 $M_\odot$.*
>
> *No convincing examples of stars more massive than about 3 $M_\odot$ evolving across that region of the H-R diagram have been identified. There are photometric candidates (such as NGC 1579/D; Herbig et al. 2004), but they do not resemble TTSs spectroscopically, because they do not display the powerful chromospheric and disk-accretion phenomena that are the TTS signature. The components of θ^1 Ori E lie in that mass range, so if they do not resemble TTSs, it may be because they lack circumstellar disks. But θ^1 Ori E is a very close binary (the separation is 0.15/ sin i AU), and such disks are not expected to survive under that circumstance: see the discussion by Mathieu et al. (2000). Thus, θ^1 Ori E does not provide an example of how young single stars in that mass range might be recognized."*

An intriguing aspect of θ^1 Ori E that Herbig and Griffin had uncovered is the fact that neither William Herschel nor John Herschel saw θ^1 Ori E in their detailed studies of the Trapezium, despite both being master observers using the best instruments at the time. John Herschel's fine drawing of the region from 1824 did not show E, but already in 1828 it was considered an obvious object with much smaller telescopes (Smyth 1844). Evidently the star must be highly variable, possibly eruptive, although this has not been documented or characterized even today.

2.15.3 **MWC 778 in IC 2144**

IC 2144 is a small nebulosity, about 16×25 arcsec, found towards the Galactic anticenter (Figure 39). It is a reflection nebula illuminated by the bright (V=12.8) star MWC 778, discovered as an Hα emission star by Merrill & Burwell (1949), who considered it a peculiar B star. Its distance is unknown, but is likely around 1 kpc. At that distance the luminosity is about 500 $L_\odot$. Herbig obtained high-resolution HIRES spectra at the Keck I telescope (Figure 40) and noted that *"The spectrum of MWC 778 is cluttered with line emission, but an absorption-line spectrum is dimly discernible in the clearer regions. No real classification is possible, but most of the detectable lines are those of an F- of G-type star, although a late A-type cannot be ruled out. Those lines are shallow, probably because of veiling, and are not sharp; their widths correspond to a* v *sin* i *of 30-40 km s*$^{-1}$*. [...] The Li I 6707 Å line is present in MWC 778, as expected for a pre-main sequence star, at an equivalent width of 47 mÅ"* (Herbig & Vacca 2008). The B-type spectrum previously suspected was not seen. Furthermore it was concluded that *"The emission spectrum of MWC 778 is very similar to that of another high-luminosity pre-main sequence object, LkHα 101, in which the FeII lines are also double, the [FeII] lines are single at an intermediate velocity, the [OI] lines are double, and the Si II lines are very broad"*, see Section 2.15.1. [...] *"On the basis of the evidence presented here, MWC 778 is an F- or G-type pre-main sequence star several magnitudes above the ZAMS. It is not a TTS, but might be considered a later-type analog of the HAeBe stars."*

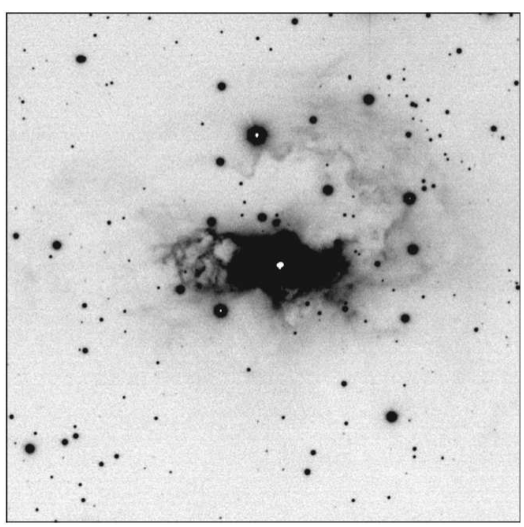


Figure 39: *The peculiar pre-main sequence object MWC 778 illuminates the compact reflection nebula IC 2144. From Herbig & Vacca (2008).*

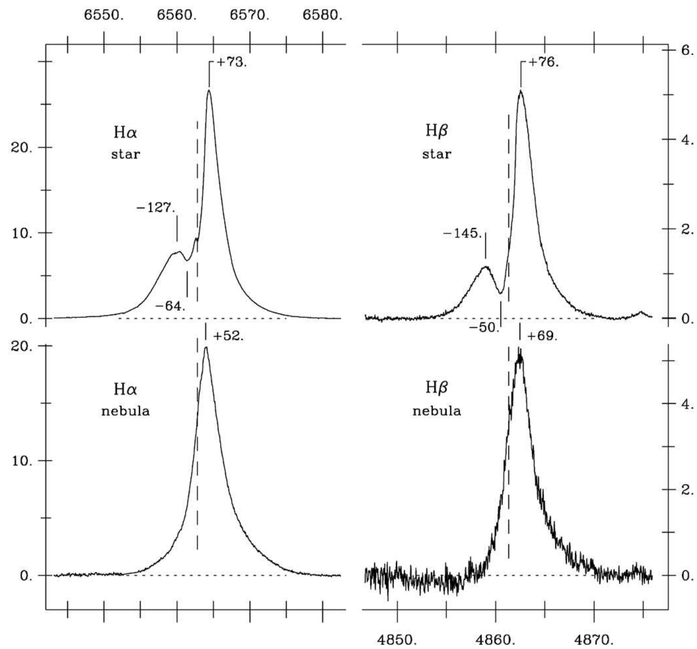


Figure 40: *The profiles of Hα and Hβ in MWC 778 (top) and towards the associated reflection nebula (bottom). The vertical dashed lines mark the zero velocity positions. Major structural differences are evident. From Herbig & Vacca (2008).*

Following extensive analysis of these spectra and other observations, it was concluded that MWC 778 is surrounded by a rotating disk structure that is concealed within the unresolved image of MWC 778. This would imply that MWC 778 would look quite different as seen from our direction and from any point in the dust that it illuminates.

2.15.4 VY Tauri

Herbig observed hundreds of T Tauri stars over the years, and a few special cases attracted his intense interest, among them VY Tau. The star was first noted by early observers who reported that the photographic magnitude of the star varied from 13 to 9.7 mag in 1906-1922.

> *"Scientists always like to classify things: to define boxes or pigeonholes into which things (flowers, birds, viruses, stars, ...) can be dropped and thereby lose their individuality and become faceless members of a class. Examples: T Tauri stars, FUors, H-H objects. But sometimes things turn up which defy existing classification schemes, at least as long as they remain unique, until one is justified in creating a new box to contain them. VY Tauri remains unique in this sense. It is an 'eruptive' variable, showing sporadic outbursts at intervals of several years to a decade or more. It is clearly a*

pre-main sequence object, but when bright it presents a completely bizarre, unprecedented emission-line spectrum that has no resemblance to any TTS or FUor. I first observed this strange spectrum on Crossley spectrograms in the 1950's, and followed the star at every opportunity until I wrote up a summary of 30 years' observations [Herbig 1990c]. *Since that paper it has been discovered that VY Tau has a close infrared companion. It may be that the presence of a nearby star is the key to the peculiar behavior of VY Tau."*[1]

Herbig notes the following in the Introduction of his 1990-paper:

"VY Tauri is certainly a pre-main-sequence object akin to the T Tauri stars: at minimum light in 1975-1976 it had a spectral type near M0 with Hα and Ca II H,K in emission and strong Li I λ6707 in absorption; it is projected upon a minor extension of the Taurus-Auriga dark clouds. [...] However, Hα emission is so weak that it was not detected in the early objective prism and grism surveys of the Taurus clouds. [...] VY Tau differs from ordinary TTS's in at least two respects. First, it sometimes undergoes sudden flare-ups from minimum magnitude about B=14, rising to maxima at B=11-12 over an interval which, with a few exceptions, has ranged between 50 and about 200 days. The star then subsides again after a total time above minimum of 90-650 days. [...] It is now realized that in this respect VY Tau resembles a number of other pre-main-sequence stars, recently given the name EXors (see Herbig 1989a for a review), all of which erupt sporadically in a similar manner but whose flare-ups exhibit a wide range of rise times, durations, and spacings. [...] There was a dormant interval from 1929 to 1940 when no maxima were observed, and the star has again been essentially inactive since 1972 until the date of writing (late 1989). [...] A second unusual characteristic of VY Tau is the nature of its emission-line spectrum on the few occasions the star has been observed spectroscopically when active. The spectrum is then dominated by very low excitation lines of neutral metals, particularly Fe I, while Fe II is quite weak and the Balmer emission lines are inconspicuous. This extraordinary spectrum is quite unlike that of any known TTS. Although spectroscopic information on other EXors is very limited, none have been reported to show an emission spectrum quite like that of VY Tau."

Herbig further discussed the spectroscopic material that he had obtained over 30 years during different phases of the star, and speculated that the most likely explanation for the observed behavior would be that VY Tau is a binary: *"then one might imagine that a companion in an eccentric orbit could, near periastron, initiate an active period either by stimulating surface activity in the brighter star or by forcing the accretion of circumstellar matter. If binarity of*

VY Tau could be demonstrated, such speculation would be worth pursuing.”

Not long after, Leinert et al. (1993) discovered a companion to VY Tau with a separation of 0.66 arcsec. Orbital motion was seen by Dodin et al. (2016), but with a period exceeding several hundred years, so this companion is unlikely to be the one disturbing the disk. A putative third body in a closer orbit may excite the disk leading to accretion events and outbursts.

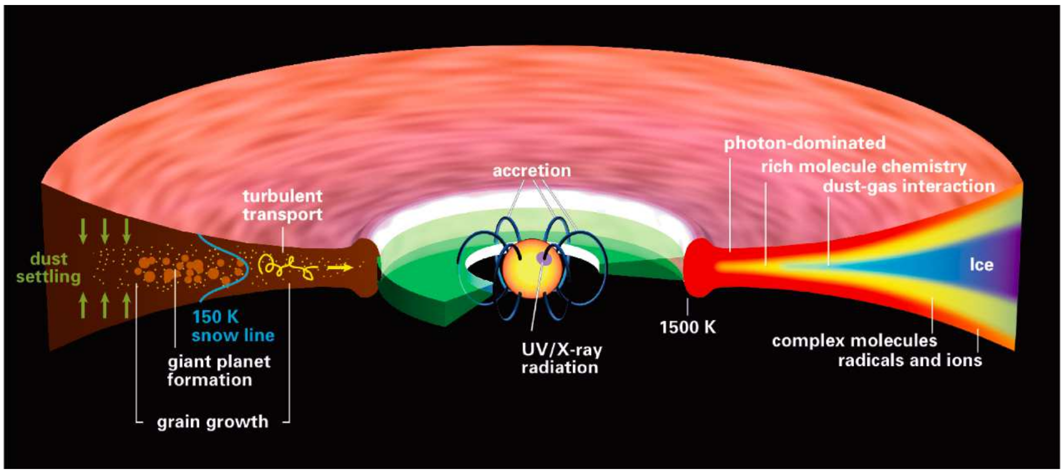


Figure 41: *The structure of a protoplanetary disk accreting onto a young star. From Henning & Semenov (2013).*

2.16 Putting it All Together: Accretion Disks

Following Herbig's 1962-review on the T Tauri stars, interest arose in modelling the observed characteristics of these stars. Already Joy (1945) noted a similarity between the solar chromospheric spectrum and strong-lined T Tauri stars. In subsequent years it was speculated that perhaps the TTS peculiarities could be sought in magnified versions of current solar physics, and TTS spectral features were often discussed in terms of extended stellar atmospheres/envelopes, or extreme chromospheric-like regions (e.g., Cram 1979). Indeed Herbig's early interpretations of his data turned around comparisons with solar phenomena.

Numerous other ideas appeared over time, only to fade away again. For example, it was suggested that the peculiar emission features of T Tauri stars were the result of emission processes in a hot (T∼20,000 K) ionized gaseous envelope surrounding the stars (Rydgren, Strom, Strom 1976).[17] An essential step forward in the interpretation of T Tauri stars came with the now famous Lynden-Bell & Pringle (1974) paper, which concluded that most of the observed properties of T Tauri stars can be explained as a consequence of viscous evolution of a circumstellar disk. Observational signatures of disk-like structures around young stars, however, only began to emerge in the early 1980s. Forbidden emission lines in T Tauri stars were found to be mostly blueshifted, suggesting that disks could occult the red emission (Appenzeller et al. 1984). Far-infrared observations of T Tauri stars, enabled by the launch of IRAS, indicated an amount of circumstellar dust that – were it distributed spherically – would make the stars optically invisible, whereas the energy distributions of T Tauri stars from the ultraviolet to the far-infrared were very well fitted with disk models (e.g., Adams, Lada, Shu 1987, Kenyon & Hartmann 1987, Bertout et al. 1988). Finally, some young stars were observed to have elongated structures surrounding them, seen in reflected light (Smith & Terrile 1984). These and other studies may individually not have been a turning-point, but collectively they started a paradigm shift toward an understanding of T Tauri stars as combined star-disk systems. The concept of a T Tauri star coupled to its disk that has emerged over time is illustrated in Figure 41.

On the theoretical side, another major step occurred when Uchida & Shibata (1985) and Königl (1991) applied to T Tauri stars a theory of magnetospheric accretion originally proposed for neutron stars by Ghosh & Lamb (1978). The basic idea is simple, although the details are highly complex and continue to be polished and debated. A rotating convective star will generate a magnetosphere, and indeed T Tauri stars have observed surface magnetic fields of several kiloGauss (e.g., Johns-Krull et al. 1999), which manifest themselves as strong X-ray and centimeter radio emission (e.g., Montmerle et al. 1983).

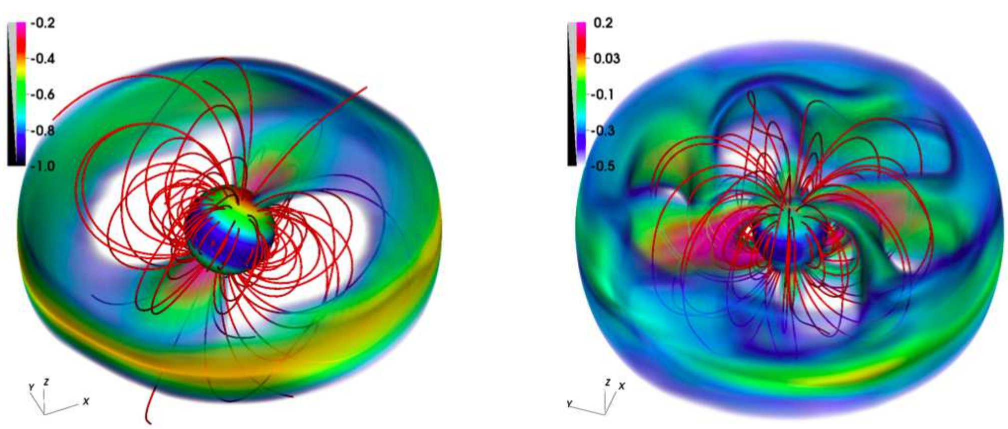


Figure 42: *Models of magnetospheric accretion from the inner disk edge onto a magnetized T Tauri star. The left panel shows a stable regime with two polar funnel flows, the right panel shows an unstable regime with multiple funnel flows. The colors indicate density in logarithmic units and in arbitrary units. From Kurosawa & Romanova (2013).*

This magnetosphere will interact with the magnetic field embedded in the circumstellar disk, resulting in the disk being truncated at a distance of a few stellar radii from the surface of the star. Accretion from the disk onto the star occurs when material with low angular momentum locks onto closed magnetic field lines and as funnel flows free-fall onto the star, forming luminous hot spots where they impact the stellar surface, thus accounting for the hot excess continuum emission that causes veiling in TTS spectra. Disk winds consisting of material with higher angular momentum can lift off the inner disk edge (the 'X-point', Shu et al. 1994) or as an extended disk wind (e.g., Blandford & Payne 1982). The models have been greatly refined over the years, and now allow detailed comparison with observations (Figure 42).

Observations of disks have been revolutionized with new technology, and images or photometry of disks have been obtained in the optical (HST), at infrared wavelengths (Spitzer, Herschel), and at millimeter and centimeter wavelengths (SMA, ALMA, EVLA). The most stunning image of a T Tauri disk is the recent ALMA image of the disk around HL Tau (Figure 43).

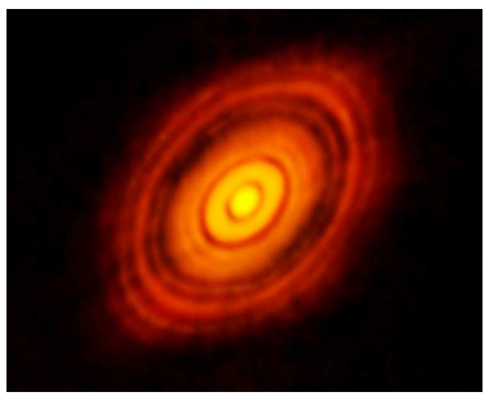


Figure 43: *ALMA 1 mm continuum image of the disk surrounding HL Tau. The disk is ∼0.8 arcsec in radius, corresponding to about 100 AU. ALMA Partnership et al. (2015).*

Herbig pioneered and later witnessed the amazing evolution of the T Tauri concept and the role that disks play in their interpretation. This evolution can be crystallized by comparing the following five review articles: Herbig (1962), Cohen (1984), Bertout (1989), Petrov (2003), and Bouvier et al. (2007).

Probably because of the grand debate about the disk interpretation for FU Orionis objects, it is sometimes assumed that Herbig did not believe in disks. This is certainly not the case, and Herbig was clear about this in our conversations. In fact, Herbig was probably the first to model the infrared excess emission in the energy distribution of a young star (VY CMa) as the result of a circumstellar disk (Herbig 1970b, see Sections 5.4.2 and 9.6).

3 HERBIG-HARO OBJECTS

3.1 Discovery

Scientific discoveries are often the result of a long and sometimes winding process, far removed from the 'Eureka moment' widely imagined by the public. This is also the case with the recognition of the Herbig-Haro phenomenon, which played out over several years.

The earliest detection of Herbig-Haro objects occurred serependitiously, when Herbig searched for new nebulous stars in regions of dark and bright matter. As mentioned earlier, in 1946 Herbig published a note on his discovery of the nebulous star in Orion that we now know as V380 Ori (Herbig 1946). On his plates of the region, Herbig noticed some small *"semistellar clots of nebulosity"*, which, however, were cropped out of the figure accompanying his 1946 paper. These would later be known as Herbig-Haro objects 1, 2, and 3.

Before pursuing a study of these small nebulous objects in Orion, Herbig had taken an interest in the so-called Burnham's Nebula next to T Tauri. This is a small compact nebula surrounding T Tauri only a few arcseconds in extent and discovered visually by Burnham in 1890; Herbig gives a historic account of the early studies of T Tauri and its surroundings in a Leaflet of the Astronomical Society of the Pacific (Herbig 1953). About the impetus for his study of Burnham's Nebula, Herbig noted:

> *"At some time while I was talking with Baade in Pasadena (I think this must have been in 1947), he called my attention to Burnham's Nebula at T Tauri. This appears as a bulge on the side of the image of T Tauri that is reproduced in Joy's 1945 paper (from a plate by Baade) and Baade told me about his visual observations of it at the 100-inch. So I took spectra of T Tauri at McDonald, with the slit in various position angles through the star, and found that the [O II] and [S II] lines were extended in the directions of the nebular structure. This was published in 1950"*[1] [Herbig 1950a].

We now know that T Tauri is associated with the HH objects 155 and 255, the latter includes Burnham's Nebula (Böhm & Solf 1994). T Tauri has an embedded infrared companion, and observations suggest that it is actually this companion that is responsible for Burnham's Nebula (HH 255). Wide-field images have revealed a giant Herbig-Haro flow, HH 355, extending north-south along the same axis as HH 255, suggesting that the embedded source has undergone several periods of activity (Reipurth et al. 1997).

So while HH 1 and 2 were the first HH objects to be imaged, the first spectra

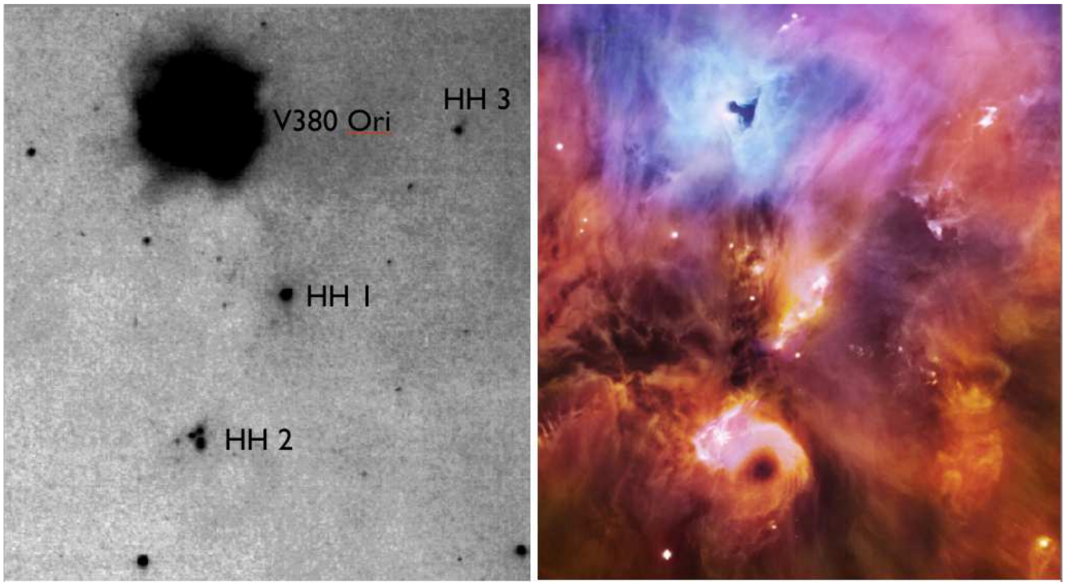


Figure 44: *(left) HH 1, 2, and 3 as seen in an enlargement of the Jan 20, 1947 plate which was published in Herbig (1951). This plate was taken in the blue spectral region with the Crossley reflector at Lick Observatory. (right) The same region imaged in Hα and [SII] interference filters with the 8m Subaru telescope from Reipurth et al. (2013). The blue reflection nebula around the Herbig Ae/Be star V380 Ori is from an HST image that has been blended into the Subaru image by Robert Gendler.*

of an HH object were actually of the otherwise little known object HH 255.

After seeing the nebulous objects near V380 Ori on his 1946 plate, Herbig revisited the region in the following years, and the earliest surviving plate is from January 20, 1947 (Figure 44). The 50th anniversary of this image was celebrated at an IAU Symposium on Herbig-Haro objects in 1997 (Reipurth & Bertout 1997), and for the introductory remarks Herbig provided the following reminiscences (Reipurth & Heathcote 1997):

> *"To the best of my recollection, and without going through all my early records and correspondence, it went about like this. While looking around for new T Tauri stars as part of my thesis, I ran across BD -6° 1253 (now V380 Ori), which illuminates NGC 1999. A note on this was published in PASP in 1946. In 1946-47, I took some direct photographs of the region of NGC 1999 with the Crossley reflector at Lick, and noticed some odd little fuzzy blobs nearby; these later became HH-1, -2 and -3. According to my notes, the first such plate was taken on 1946 Jan 24, followed by 2 others in Jan. and Feb. 1946. I have among my papers only an enlargement of a plate taken the next year, Jan. 20, 1947, with the same telescope and*

exposure time. This shows the 3 HHs.

I paid no serious attention to these Objects at the time, but in December 1949 I met Haro at the AAS meeting in Tucson. He gave a paper on his objective-prism discoveries of emission-H-alpha stars around the Orion Nebula, an abstract of which appeared in AJ in 1950, and called attention to the emission-line spectra of these Objects near NGC 1999. He published details later in ApJ in 1952 and 1953 [Haro 1952, 1953]*. This re-ignited my interest in these spectra, because during the winter of 1948-49 at McDonald I had obtained spectra of Burnham's Nebula at T Tauri, which had the same odd combination of emission lines including [S II] and [O II]; a paper on this appeared in ApJ in 1950.*

So at Lick in 1950, I obtained slit spectra of HH-1 and -2, from which came the note in ApJ in 1951, in which attention was drawn to the similarity to Burnham's Nebula [Herbig 1951]*. It was probably this connection with T Tauri that gave rise to the conjecture that Herbig-Haro Objects, as they were named by Ambartsumian*[19]*, had something to do with early stages of star formation."*

Table 2

EMISSION LINES MEASURED IN SPECTRA OF OBJECTS NOS. 1 AND 2 NEAR NGC 1999

Wave Length	Identification	Estimated Intensity	Wave Length	Identification	Estimated Intensity
6727*........	[*S* II] λ 6717, λ 6731	50	4359.........	[*Fe* II]	2
6562.........	$H\alpha$	100	4340.........	$H\gamma$	8
6363.........	[*O* I]	20	4287.........	[*Fe* II]	2
6300.........	[*O* I]	60	4249*........	[*Fe* II]+?	2
5006.........	[*O* III]	3	4101.........	$H\delta$	4
4958.........	[*O* III]	1	4070.........	[*S* II] λ 4068, λ 4076	10
4861.........	$H\beta$	15	3970.........	*Ca* II, $H\epsilon$, [*Ne* III]	5
4657†........	[*Fe* III]?	1	3933.........	*Ca* II	2
4571†........	*Mg* I?	1	3888.........	*H*8	1
4452.........	[*Fe* II]	1	3868†........	[*Ne* III]	1
4416*........	[*Fe* II] λ 4413, λ 4416	2	3727.........	[*O* II] λ 3726, λ 3729	15

* Measured wave length of unresolved pair or blend.
† Measured wave length; the line was seen only on the most strongly exposed plate.

A list of the emission lines with estimated intensities that Herbig identified on his photographic plates is given here in Table 2 (from Herbig 1951). A modern spectrum of an HH object obtained with the HST is shown in Figure 45. Herbig was struck by the curious combination of emission lines he saw both in Burnham's Nebula and in HH 1/2, which were unlike any other spectrum he had seen. Herbig concluded his 1951 paper on spectroscopy of HH 1/2 with the words: *"These objects define another type in the growing list of peculiar objects that occur where stars and nebular material are intimately associated."* Little could he know that these objects would open up a dynamic and fruitful field of research that would provide a novel outlook on the formation of stars.

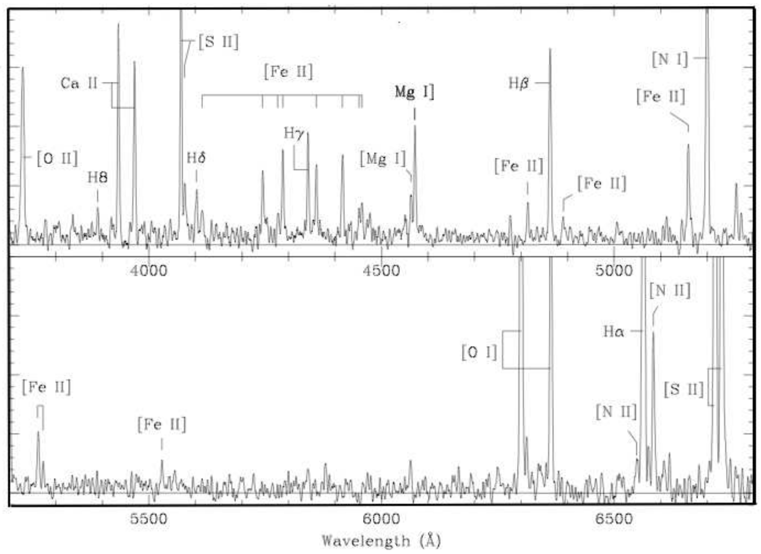


Figure 45: *An optical spectrum from 3700 to 6800 Å of HH 47A obtained with STIS on the Hubble Space Telescope. From Hartigan et al. (1999).*

3.2 The Nature of HH Objects

Most telescopes 60 years ago were, from today's perspective, rather small, and this, in combination with the low efficiency of photographic plates, made it difficult to study HH objects in much detail. It was clear that their spectra were unusual, and that they consisted of small groups of stellar-like nebulae. In his 1951 paper presenting the first spectra of HH 1 and 2, Herbig noted that

> "*These spectra are remarkable for several reasons:* (a) *the great strength of [S II];* (b) *the large range in excitation energy (as represented by ionization plus excitation potentials) between such lines as those of [O I] (2 e.v.) to [O III] and [Ne III] (51 and 65 e.v.); and* (c) *their striking dissimilarity to the spectra of ordinary T Tauri-like stars in the same dark nebula and in the Taurus-Auriga dark clouds. The explanation of reason* b *undoubtedly is that we are observing the integrated radiation from nebulous envelopes in which there exist very large variations of density."*

Herbig goes on to consider the energy source of the rich emission line spectra observed in HH 1 and 2:

> *"The generally accepted mechanism for the production of the emission lines in the gaseous nebulae involves the photoelectric ionization of the abundant lighter elements by the intense ultraviolet radiation of the very hot exciting star. The permitted lines then result from recombination or fluorescent excitation by recombination lines, while the forbidden lines are due to collisional excitation of metastable levels by the free electrons."*

The puzzle to Herbig was that he saw no evidence within the HH objects for a hot blue star that could provide the necessary ultraviolet radiation. Based on the photographic magnitudes measured for the "stars" in the HH objects, he found it more reasonable that they would be K- or M-type dwarfs rather than hypothetical low-luminosity, high-temperature stars. To explain how a late-type star could provide the energy to produce the high-excitation lines in HH objects, Herbig had the prescient insight to invoke accretion energy from infalling gas onto the star. However, in his 1952 paper, Haro noted the absence of any visible stars on a red I-N plate and so concluded that if stars were present in HH objects, one would have to postulate the existence of faint, very blue, hot stars. Ambartsumian (1954) speculated that these unusual stars, whatever their nature, might be precursors to the T Tauri stars. Indeed, failing to find any stars embedded in the HH knots during further studies with the best observations possible at the time, Haro & Minkowski (1960) concluded that protostars might be embedded within the HH knots.

This conundrum clearly required additional data and some novel thinking, so using the Crossley reflector at Lick Observatory, Herbig obtained the hitherto best spectrograms of HH 1, covering the wavelength region from λ 3700 to λ 6800. For the analysis, he gave this material to Karl-Heinz Böhm, a young German astronomer, who had studied with Albrecht Unsöld, and so had a strong background in the new field of astro-physics. When Böhm arrived in 1954 at Lick Observatory on a German-US exchange program, Herbig suggested that he should determine the physical parameters of HH 1 and try to find excitation and ionization mechanisms to explain the data. Upon analysis, Böhm found for HH 1 a mean electron temperature of $\sim$7500° and a mean electron density of $\sim 1.3\times10^4$ cm^{-3}, very close to the modern values (Raga et al. 2015). In the end, however, he concluded that if a "central star" would be the energizing source of HH 1, the number of ultraviolet quanta beyond the Lyman limit had to be equivalent to that emitted by a black body with T = 29,000° (Böhm 1956). The original conundrum thus persisted.

A further complication was recognized by Osterbrock (1958), who applied the ionization theory of Strömgren (1939), and found that if a hot blue star was responsible for the observed emission line spectrum, then the hydrogen gas should be fully ionized in the interior of an HH object, with only a thin shell-like transition region between ionized and neutral hydrogen. But Osterbrock pointed out that a conspicuous difference between HH objects and the more familiar planetary nebulae and diffuse nebulae is that hydrogen in HH objects is only partially ionized. Thus Osterbrock had the important insight that radiative processes cannot be the dominant ionization mechanism in HH objects. But it would be more than 15 years before the right idea emerged that would clarify the situation.

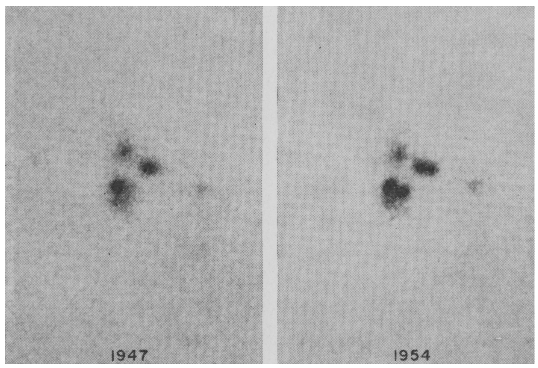


Figure 46: *Herbig noted variability and the emergence of new knots in HH 2. Knots G and H appeared between 1947 and 1954. Note that these images are mirrored relative to the one in Figure 47. From Herbig (1957).*

Meanwhile, Herbig focused on his work on the T Tauri stars, but he continued to monitor the region of HH 1 and 2, and to his astonishment soon found that the objects were significantly variable. By comparing his early Crossley plates from 1946 with more recent ones from 1951, he saw that two new nuclei had appeared in HH 2 (see Figure 46). Only much later, after accumulating substantial documentation, did Herbig write these results up (Herbig 1957a, 1969a, 1973b). In Herbig (1969a), he writes:

> "*[HH 2] was first photographed at adequate scale in 1946-47, and when the plates were repeated in 1954-55 it was found that two new nuclei had appeared within this complex Object in the interim. Thereafter the region was photographed annually with the same telescope and emulsions ... through 1959. A number of plates were obtained with the 120-inch reflector in 1959-63, but the Crossley series was not resumed until 1968.*"

Herbig went on to note that while two knots (G and H in Figure 47) had appeared, some other knots had actually faded, so he warned that the spectacular brightening of knots G and H "*should not be identified with the 'birth' of two 'new' stars.*" In fact, Herbig examined in detail a variety of possible explanations, and found them all wanting.

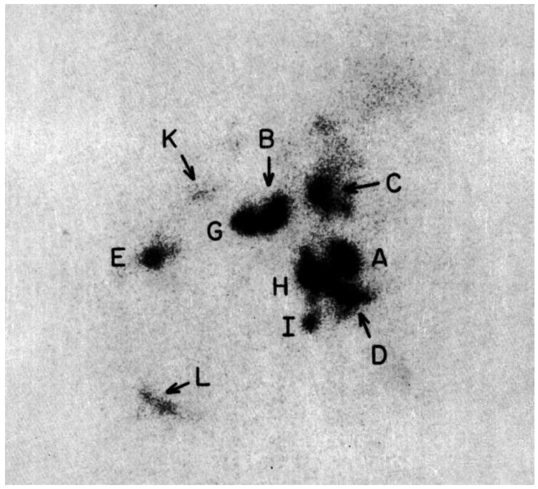


Figure 47: *The fragmented nature of HH 2 is evident in this detailed photograph from Herbig (1969). North is up and east is left.*

In parallel with these studies, Herbig maintained a list of new HH objects and in 1974 published a "Draft Catalog of Herbig-Haro Objects", which contained coordinates, finding charts, and other information on 43 HH objects, almost all of which he had found himself on his direct and objective-prism plates (Herbig 1974c). Herbig was well aware that many more objects were likely to await discovery, hence the word "Draft" in the title, and for the same reason he did not publish the catalog in any journal, but only as a Lick Observatory Bulletin. With modern wide-field CCD detectors mounted on large telescopes and with the use of narrowband interference filters, the discovery of HH objects in star forming regions has exploded. An informal listing of all known HH objects is maintained by myself, and at the time of writing contains 1165 HH objects, with more being discovered every year. Interestingly, only a few more objects (HH 47, HH 80 and HH 81) are as bright as HH 1 and 2, thus lending themselves to detailed study, and most other HH objects are very much fainter.

For more than 15 years the study of Herbig-Haro objects then languished, seemingly held up by the absence of a mechanism that would produce the observed spectra, and with no detections of stars within the HH objects that could provide an energy source. Then in 1974 came a paper that approached the problem from a new angle and presented a radically different perspective. Strom et al. (1974a) used the newly available infrared detectors to observe HH objects, and at an HH object they had discovered in the Corona Australis cloud, HH 100, they found a bright near-infrared source, which was so embedded in the associated dark cloud that it was not visible at all in the

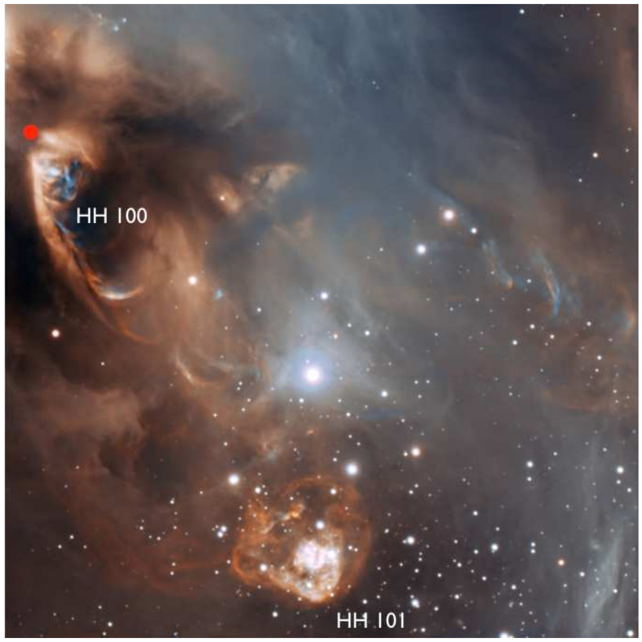


Figure 48: *The nebula labeled HH 100 is a complex mixture of Herbig-Haro emission and reflection nebulosity from an embedded driving source (marked with red dot). Outflow from the source powers a large bow shock labeled HH 101. Image from the ESO Very Large Telescope.*

optical. Remarkably, the infrared source was not centered on the HH object, but was displaced from it (Figure 48). Strom et al. suggested that this could naturally be understood if an HH object represents light cast by an embedded T Tauri-like source in the fashion of a light-house beam that is scattered off a cloud surface. Several more embedded infrared sources were discovered near HH objects in a follow-up study (Strom et al. 1974b). In one of these objects, now known as HH 24, Strom et al. found strong polarization, as expected from scattered light.

These results motivated several follow-up studies, but with sensitive observations Schmidt & Vrba (1975) found that HH 1 and 2 were not polarized. And more detailed observations showed that in HH 24 the emission lines are not polarized, while the associated continuum is strongly polarized, suggesting separate origins for emission and continuum (Schmidt & Miller 1979).

The breakthrough in the study of HH objects came in the mid/late seventies, when Richard Schwartz published two papers (Schwartz 1975, 1978). In the first, Schwartz studied the velocity field in the emission nebula around T Tauri, and found velocities which were supersonic relative to the surrounding cloud, and hence shocks would be expected to occur. The observed relative line strengths were found to have similarities to those measured in a supernova remnant, and it was found that shock models could account for the characteristics of the observed spectrum, so Schwartz hypothesized that mass loss from T Tauri would drive the shocks.

Generalizing this picture, Schwartz suggested the until then novel idea that HH objects would be shocks. All of a sudden, the mysterious spectra of HH objects could be modelled and interpreted in the framework of well understood physics! What was needed was a physical model that would explain the geometry and formation of such shocks. In his second paper, published in 1978, Schwartz provided a first attempt to do just that. Here he suggested that HH objects occur when a strong stellar wind from an embedded pre-main-sequence star impinges upon small ambient cloudlets. The resulting bow shocks would wrap around the cloudlets and would produce the main features of many HH objects, including their low excitation spectra, observed radial velocities, luminosities, and time scale of variability. To produce the properties of HH 1 and 2 would require the stellar source to have a wind velocity of about 100 km s^{-1} and a mass loss rate of about 10^{-5} to 10^{-6} $M_{\odot}$/yr, at least for a brief period of time.

These two papers marked the beginning of what could be called the "golden age" in HH research, an interval of about twenty years from the mid-seventies to the mid-nineties, during which the fundamental properties of HH objects were recognized through a massive observational effort and largely understood through intense theoretical work. Large sets of plane shock models were developed and applied to observations of HH objects by Dopita (1978) and Raymond (1979), and later by Hartigan et al. (1987), outlining the basic physical parameters of the objects and their environments. Karl-Heinz Böhm and his collaborator Josef Solf and their students obtained some of the best spectra of HH objects and produced a long series of important papers (e.g., Böhm et al. 1976, Brugel et al. 1981, Solf et al. 1988). An unexpected surprise was the realization that HH objects are strong emitters at ultraviolet wavelengths, discovered by Ortolani & D'Odorico (1980) and further studied by Böhm et al. (1981). This rich collection of data allowed comparison with the shock models. However, none of the plane-parallel shock models could reconcile the simultaneous presence of low excitation lines of [O I] and [S II] with highly ionized species like C IV. The introduction of bow shock models resolved many of the inconsistencies inherent in the plane-parallel shock geometry. A bow shock produces a range of shock velocities, because only the component of the flow velocity perpendicular to the bow shock is thermalized. A single bow shock can therefore produce high excitation near its apex, where the shock is strongest, and simultaneously much lower excitation lines from the increasingly oblique shocks along its wings, and a bow shock also produces a characteristic kinematic signature that can be observed with high-resolution long-slit spectroscopy (e.g., Hartmann & Raymond 1984, Raga & Böhm 1985, Hartigan et al. 1987).

An essential new insight that made much of this progress possible came from a series of studies by Herbig and his collaborators, as discussed in the following.

3.3 Proper Motions

By the late seventies, shock waves were clearly recognized as a fundamental aspect of HH objects, and Schwartz had proposed a possible model for how these shocks could be generated, and other models would rapidly follow. But the key to fully understand the origin and nature of HH objects came from an unexpected side. Buried in obscure corners of the literature were two observations by Luyten (1963, 1971), who was an expert in measuring proper motions of stars. Two of the tens of thousands of objects he measured, LP-415-1166 and LP-415-171, had unusual proper motions for the region in which they were located. Herbig and a young Yerkes astronomer, Kyle Cudworth, realized these objects were identical to the objects HH 28 and 29. Cudworth has provided these recollections:[20]

"As an undergraduate at Minnesota 1965-1969 I worked for Luyten measuring plates. I then went to Lick (Univ. of Calif. Santa Cruz) for graduate school (1969-74) and had a class from Herbig in my first year. During grad school I visited my parents in Minneapolis at least once or twice each year and nearly always spent a little time at the University, including talking with Luyten and often with his assistant Roland Mohr. I was thus in a unique position between Luyten and Herbig. On one of my visits to Minnesota (possibly in 1972) Roland Mohr mentioned the weird moving red nebulae Luyten had discovered several years earlier. Around Minnesota they were always referred to as 'moving red nebulae', or by their LP numbers, so I think Luyten was not aware that they were H-H objects. I talked with Luyten a bit about them and then with Herbig when I returned to Santa Cruz. Herbig was aware of the Harvard Announcement Card that Luyten had put out in 1963 but did not believe they were likely to be actual motions. He seemed to think they were probably cases of one edge of an object dimming or brightening relative to the other edge and thus giving the appearance of motion. However, he gave me an old and a new plate, which I put on a blink microscope and immediately saw the proper motions. The ~20 years of epoch difference gave a displacement approximately as large as the size of the objects – definitely not simply changes in brightness of opposite edges. I went down the hallway and got Herbig, who took a look through the blink microscope and said something like *'Well, that's* *pretty definite, isn't it?'*. I don't think I have ever seen someone change an opinion on a scientific question quite that quickly. After grad school I took a faculty position at Yerkes, but at some point Herbig told me he thought we should put out a paper on these proper motions. I measured and reduced all the plates at Yerkes, and Herbig and I put the paper together by mail and on one of my visits to Santa Cruz."

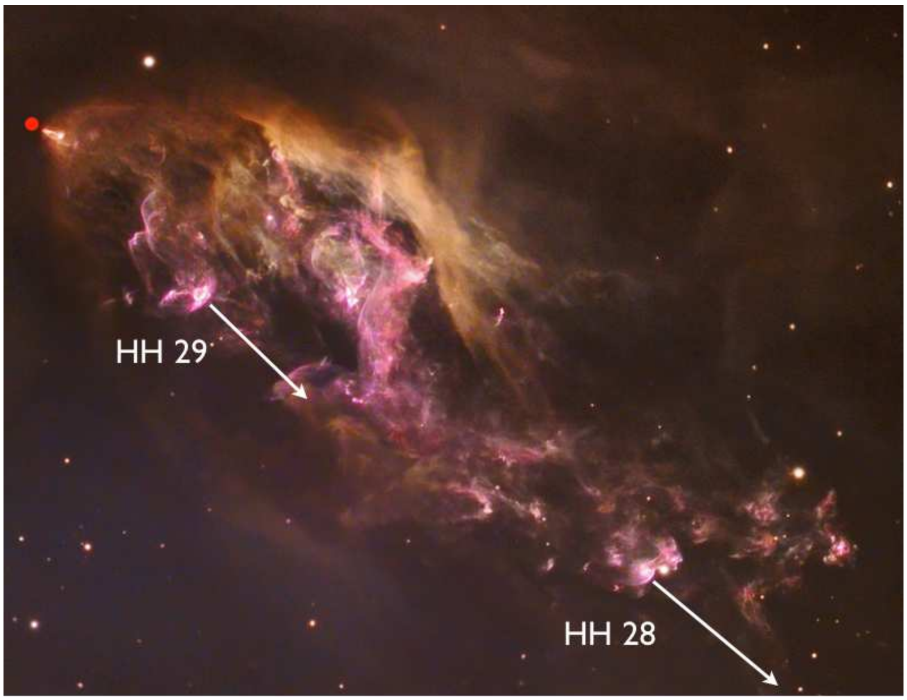


Figure 49: *The outflow activity from the embedded source L1551 IRS5 (red dot) in the L1551 cloud has created a cavity in the cloud that has opened up revealing a complex maze of shocks. The HH 28 and 29 objects are marked with their proper motion vectors as measured by Cudworth & Herbig (1979). Hα and [SII] images by Bo Reipurth and color composite by Robert Gendler.*

The resulting study became a fundamental paper on HH objects (Cudworth & Herbig 1979), in which it was pointed out that at the 140 pc distance of the Taurus clouds, the proper motions of HH 28 and 29 corresponded to tangential velocities of around 145 km s^{-1} relative to their local environment (Figure 49). With some hesitation, they also noted that the proper motion vectors pointed away from an infrared source discovered a few years earlier by Strom et al. (1976).

These observations naturally begged the question whether also the classical HH 1 and 2 objects had similarly large motions. To answer this question, the long series of Crossley plates that Herbig had obtained spanning from 1946 to 1980 turned out to be invaluable. These data were augmented with newer plates obtained between 1959 and 1980 at the 120-inch Lick reflector.

Around 1980, Burton Jones was hired into a faculty position as head of the Lick astrometric program. Jones had previously been working at Lick Observatory as a postdoc and a research assistant, and among other things had been working with Herbig on an astrometric study of the proper motions of T Tauri stars (Jones & Herbig 1979, also see Section 2.10). Jones has provided these reminiscences:[21]

"Shortly after I assumed my position, George approached me and asked if I would be interested in measuring the motions of HH 1 and HH 2. I jumped at the chance, and George gave me the Crossley and 120-inch plates. At the time, the Lick Northern Proper Motion program had the best blink comparator in the world. As soon as I put two Crossley plates in, aligned them, and blinked, the motions were more than obvious. I immediately called George to see the blink, and he was as excited as I. What followed was the tedious process of actually measuring all the knots on all the plates that George had taken from 1946 to 1980, indicating tangential velocities of individual knots between 100 and 350 km s^{-1}. We also got the idea to make a time lapse movie of the motions, and with a mini-grant from UC Santa Cruz and a lot of effort and a lot of help from the UC AC department, I put together a short (~2 min) movie which George narrated."

The proper motions of HH 1 and 2 seen in Figure 50 evidently indicated that the source had to lie along a line between the HH objects. An infrared survey of the region by Cohen & Schwartz (1979) had revealed a faint, isolated T Tauri star on this line, but much closer to HH 1 than to HH 2. With proper motion vectors of both HH 1 and HH 2 pointing away from the Cohen-Schwartz star, it was obvious for Herbig and Jones to conclude that it was the driving source of the HH objects. However, just a few years later, a deeply embedded radio continuum source was found midway between HH 1 and 2, and associated with a faint collimated HH jet pointing towards HH 1 (Pravdo et al. 1985, Strom et al. 1985); this is now recognized as the true source of the HH 1/2 complex.

Following the proper motion study of HH 1/2, Herbig and Jones studied the motions of several other HH objects. Their next study was of HH 39, which are associated with the young star R Mon (Jones & Herbig 1982). This star was recognized as a luminous B8-type object belonging to the class of the Herbig Ae/Be stars (Herbig 1960a, also see next chapter), and illuminating the bright reflection nebula NGC 2261. The object is shown in Figure 51, and is described thus (Jones & Herbig 1982):

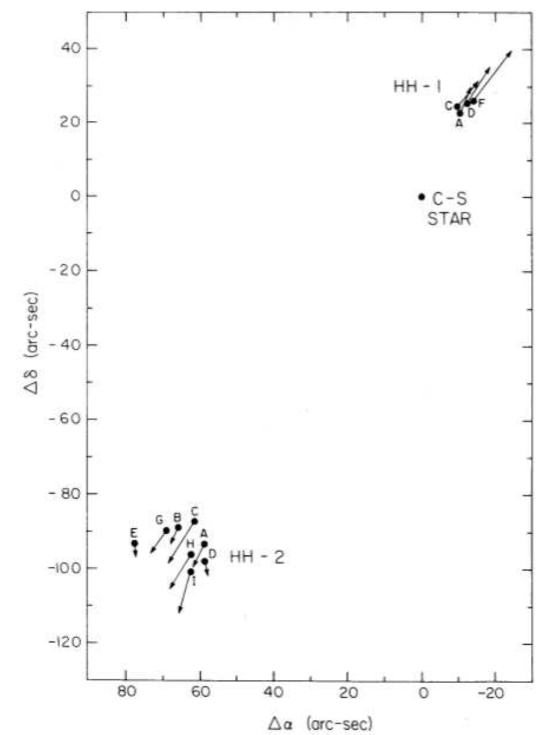


Figure 50: *The proper motions of HH 1 and 2 determined by Herbig & Jones (1981) showed HH 1 and 2 moving in opposite directions away from a young star located in between on the flow axis. This image revolutionized our understanding of the Herbig-Haro phenomenon and ushered in a wealth of similar studies of other Herbig-Haro objects.*

> "*The object called R Mon is actually a tiny (∼5 arcsec)* triangular nebula *of high surface brightness, with what may be a stellar nucleus at its southern tip. On conventional photographs, all this appears as a nebulous star. [...] The* fan *of NGC 2261 is an order of magnitude lower in surface brightness. It extends about 3 arcmin to the north of R Mon, in continuation of the outline of the triangular nebula. [...] The Herbig-Haro object HH 39 is a cluster of non-stellar nuclei distributed over an area of about 25×45 arcsec. It lies 7.5 arcmin north of R Mon, completely outside the NGC 2261 fan but closely upon its axis of symmetry.*"

The HH 39 group of HH objects was discovered by Herbig (1968a) in an earlier study of R Mon. The proper motion study of HH 39 by Jones & Herbig (1982) showed that these HH objects move straight away from R Mon with tangential velocities around 300 km s^{-1}. At the time, R Mon was the first Herbig Ae/Be star known to drive Herbig-Haro objects, and demonstrated that also more massive stars can form HH objects, although this is not as common as for the

Figure 51: *R Mon and its coneshaped reflection nebula NGC 2261. Courtesy Carole Westphal & Adam Block.*

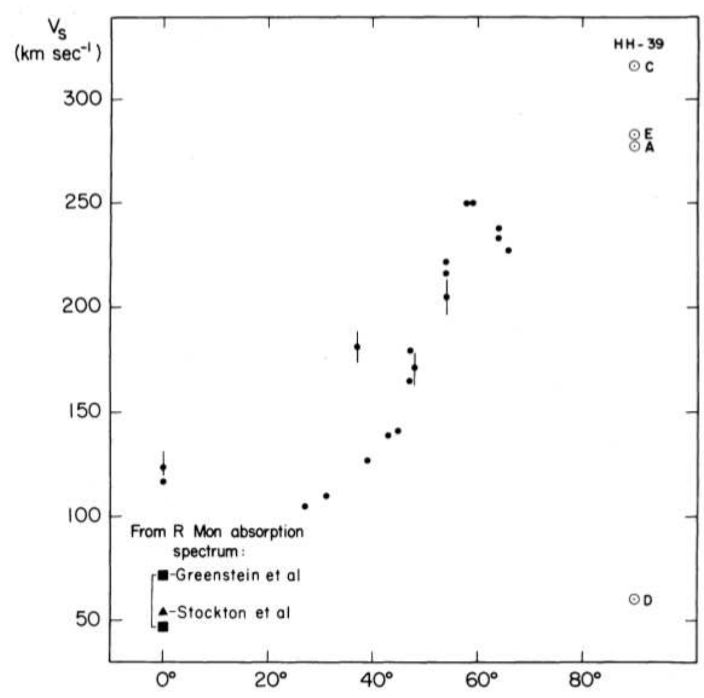


Figure 52: *The coneshaped nebulosity emanating from R Mon reflects light from the star, and radial velocities of absorption lines along the nebula vary such that velocities are low near the star but gradually grow higher further up the nebula, indicating a latitude dependence of a stellar wind. The tangential velocities of the HH 39 knots appear to fit this latitude-dependence. Since the flow axis of HH 39 is likely to lie very nearly in the plane of the sky, this suggests that the HH objects move away from the star at approximately the full stellar wind velocity. From Jones & Herbig (1982).*

lower-mass T Tauri stars. Jones & Herbig (1982) reported that absorption lines measured along the walls of the concave reflection nebula showed an increasing radial velocity with latitude, with the tangential velocities of the HH 39 knots fitting the velocity distribution if placed on the polar axis (Figure 52). Since the outflow axis most likely is very close to the plane of the sky, this suggests that the HH objects move away from the star at approximately the full stellar wind velocity. These observations provided crucial constraints on models for HH objects.

Herbig and Jones collaborated on one more proper motion study of HH objects, dealing with the HH 7-11 chain of HH knots driven by a young embedded star, and with HH 32 powered by the bright T Tauri star AS 353A (Herbig & Jones 1983). At that point, most of the novel science was done, and it had become clear that HH objects move away from nearby young stars at supersonic speeds. This conclusion has been borne out by numerous subsequent studies, and the accuracy of measurements improved greatly when data from the Hubble Space Telescope became available (e.g., Bally et al. 2002, Reipurth et al. 2002, Raga et al. 2012).

3.4 The Jet Phenomenon

With the recognition of the large proper motions of HH objects, Herbig ended his work on HH objects and moved on to other subjects, as discussed in the following chapters. But Herbig's proper motion studies had opened the door for one further major new insight that would finally clarify the nature of HH objects. This unfolded within the span of a year, and had such a profound impact on our understanding of the HH phenomenon that it is worth to examine the developments in some more detail.

In the mid seventies, Richard Schwartz had gone to Cerro Tololo in Chile to search for new Hα emission stars and more HH objects in the relatively little studied southern sky. This was highly successful (Schwartz 1977a), but one discovery stood out, the HH objects that would become known as HH 46/47 (Schwartz 1977b). A deep photo with higher resolution was obtained of HH 46/47 by Bart Bok at the 4m Blanco telescope at Cerro Tololo, and in this he noted that HH 46 and HH 47 were connected with "a luminous emission bridge" (Bok 1978). A modern CCD image is seen in Figure 53. These objects were studied in great detail by Michael Dopita, Richard Schwartz and Ian Evans, and what would turn out to be a classical study was published a few years later (Dopita, Schwartz, Evans 1982). In their paper, they write: "The remarkable linear alignment of HH 47A, HH 46, and HH 47C suggests a high degree of collimation in the bipolar flow. [...] Theoretical models to explain these phenomena are in a state of infancy. [...] Common to the models is the idea that a spherically symmetric stellar wind will be focused into bipolar jets upon expansion in a medium such as a circumstellar disk with anisotropic density and pressure distributions. Instabilities in the jets or interaction of the jets with ambient cloudlets could hence be implicated with the production of HH nebulae." In other words, collimated jets were driving the formation of HH objects! This scenario was supported by further observations from Graham & Elias (1983).

Figure 53: *HH 47 was the first Herbig-Haro jet recognized as such in an important study by Dopita et al. (1982). A young binary star is embedded in an isolated Bok globule and produces a bipolar outflow, with one lobe bursting out of the globule to the upper left, and a counterlobe burrowing into the globule and emerging at its edge towards the lower right. Image from Reipurth & Heathcote (1991).*

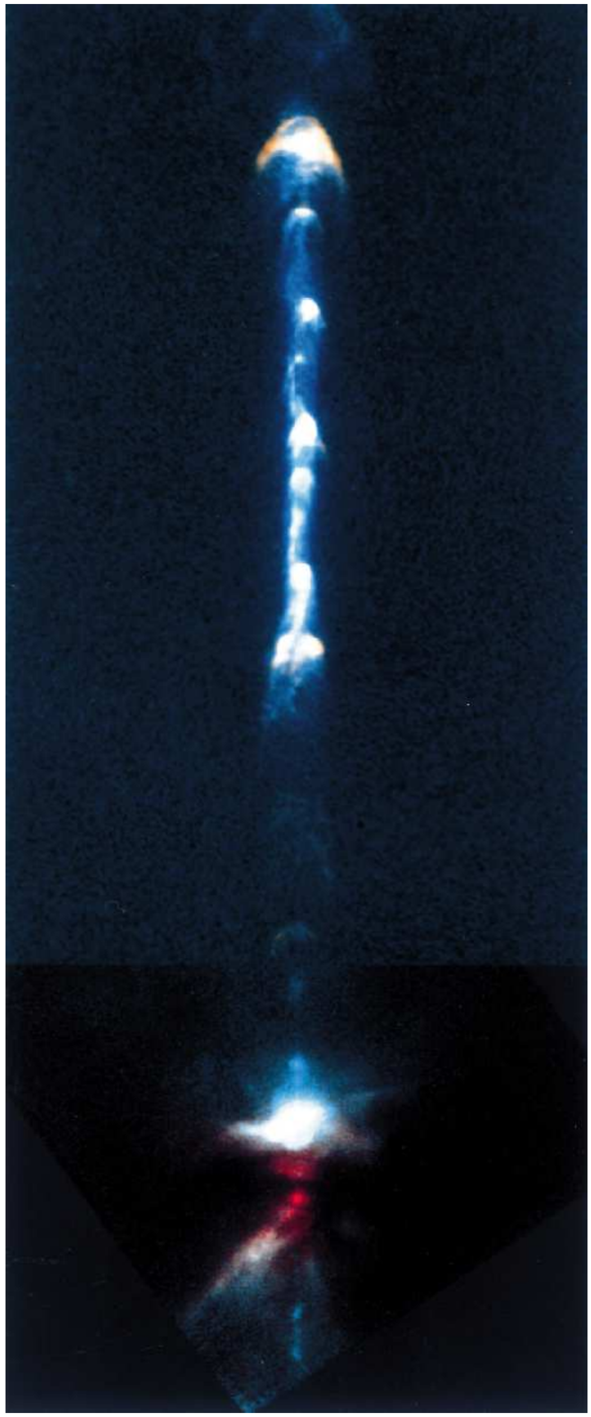


Figure 54: *One of the finest collimated Herbig-Haro jets is the HH 111 jet, seen here in an optical HST image (upper part) combined with an infrared HST image (lower part). The latter reveals the driving source as a highly reddened source embedded within a cloud core. From Reipurth et al. (1999).*

The study of Dopita et al. was widely circulated as a preprint, and made a real impact among researchers. Herbig and Reinhard Mundt of the Max Planck Institute for Astronomy in Heidelberg were exchanging letters at the time in connection with observations of T Tauri stars, and in a letter to Herbig dated September 24, 1982, Mundt writes: "Today I got a preprint from Dopita, Schwartz, and Evans on their observations of HH46,47. I think there is a good chance with modern techniques to detect similar cases within the next few years." And this was precisely what Mundt set out to do. During an observing run at Calar Alto observatory shortly after, from January 10 to 26, 1983, he and Josef Fried surveyed 15 regions with T Tauri stars or HH objects. In this sample they discovered no less than 4 objects with emission features resembling the HH 46/47 jet. Their resulting paper, submitted June 3, 1983, was entitled 'Jets from Young Stars', and this caught the imagination of the astronomical community (Mundt & Fried 1983).

At the same time I was myself busy observing Herbig-Haro objects using the Danish 1.5m telescope at La Silla in Chile. I clearly remember the night of December 20, 1982, when I decided to study the little-known object HH 34. In those days the CCD images did not just appear on a TV screen, but slowly rolled up one line at a time. While I admired the clear bow shape that the image showed of HH 34, slowly another feature appeared further to the north, a spectacularly collimated jet pointing straight towards the HH 34 bow shock. I almost fell from my chair, I had never seen anything so beautiful, so I embarked on a detailed study of this new jet (Reipurth et al. 1986).

With the discovery of the jet phenomenon it became clear that HH objects are shocks powered by collimated jets from newly born stars (Figure 54). The driving sources undergo repeated accretion events, which lead to outflows that are collimated by magnetic fields. Details on the nature of HH objects and their associated jets can be found in the review by Reipurth & Bally (2001).

4 THE HERBIG Ae/Be STARS

4.1 Defining Young Intermediate Mass Stars

In parallel with his early work on the T Tauri stars during the 1950s, Herbig pondered the following question:

> *"Over the past decade the accumulation of observational material, together with a growing understanding of some of the processes of stellar evolution, have led many astronomers to the belief that the T Tauri stars are young stars still in the stage of gravitational contraction toward the main sequence. If this belief is correct, then the luminosities of the T Tauri stars indicate that they are objects of small to intermediate mass that will in time become main-sequence stars of type F and later. The next step is to inquire whether some newly formed stars of still larger mass may be identified in a similar manner."*

The above quote is from the Introduction to Herbig's famous paper entitled '*The Spectra of Be- and Ae-type stars Associated with Nebulosity*'. This study, which is by far Herbig's most cited paper, introduces what has become known as the Herbig Ae/Be stars, often abbreviated as Herbig stars or HAeBe stars (Herbig 1960a). In the paper, he identified 26 stars which are now known as classical Herbig Ae/Be stars.

Herbig later recalled the beginning of the identification and study of HAeBe stars:

> *"In the years before the 120-inch became available, I observed often with the old prism spectrographs at the 36-inch refractor, although I was very aware that they were not in the class as those at McDonald or at Mount Wilson. Out of this, and out of the direct photography and slitless surveys at the Crossley, came the 1960 paper on Be and Ae's in nebulosity which has provided many targets for later observers in every imaginable spectral region. This emerged from my conviction, that if stars form at 1-2 solar masses, then more massive stars must also form and ought to be recognizable in some way. Most people now seem convinced that the "Herbig Ae/Be stars" are such objects. I think that some of the original sample are interlopers, as are some stars that later investigators have shoved into the same box, but that there is merit to the idea."*[1]

In the paper, Herbig first calculated the number of still contracting stars of spectral type B within 1 kpc of the Sun. While Herbig recognized that this number would be dependent on many assumptions, the main result remained, namely that the number could not be negligible. Armed with this assurance, he

Table 3

Be AND Ae STARS ASSOCIATED WITH NEBULOSITY

	Star	Other Designation	α(1900)	δ(1900)	Magnitude*	Spectral Type	Nebula†
1....	LkHα 198	....	0h06m1	+58° 17′	*15*	A:eα	Anon.
2....	BD+61°154	MWC 419	0 37.5	+61 22	10.6	B2–B5 eq	Anon.
3....	AB Aur	HD 31293	4 49.4	+30 23	*7.2– 8.4*	B9e+shell	Anon.
4....	HK Ori	MWC 497	5 25.9	+12 05	*11.4–12.5*	Ae	Bar. Atlas no. 100
5....	T Ori	MWC 763	5 30.9	− 5 32	9.5–12.6	B–Aeα+shell	(Orion)
6....	V380 Ori	−6°1253	5 31.6	− 6 47	9.7–10.3	B8–A2e	NGC 1999
7....	RR Tau	AS 103	5 33.3	+26 19	10.2–14.2	B8–B9e+shell	Anon.
8....	HD 250550	MWC 789	5 56.2	+16 31	*9.7*	B9eq	Anon.
9....	LkHα 208	....	6 02.1	+18 42	*13.0*	B5–B9e+shell	Hubble anon.
10....	LkHα 215	....	6 27.2	+10 14	10.7	Be+shell	NGC 2245
11....	HD 259431	MWC 147	6 27.6	+10 24	8.7	B5:e	NGC 2247
12....	R Mon	MWC 151	6 33.7	+ 8 50	*11.3–13.8*	e+shell	NGC 2261
13....	LHα 25	....	6 35.2	+ 9 53	13.0v?	B8pe+shell	(NGC 2264)
14....	Z CMa	MWC 165	6 59.0	−11 24	*8.8–11.2*	eq	Anon.
15....	HD 53367	MWC 166	6 59.7	−10 18	7.0	B0 IV:e	IC 2177
16....	MWC 297	....	18 22.4	− 3 55	*11.0*	?	Anon.
17‡....	R CrA	....	18 55.2	−37 06	*10.0–13.6*	Ae	NGC 6729
18‡....	T CrA	....	18 55.2	−37 06	*11.8–13.9*	F0eα	(NGC 6729)
19....	BD+40°4124	MWC 340	20 17.0	+41 03	10.6	Be	Anon.
20....	BD+41°3731	....	20 20.8	+41 58	9.9	B2–B3e	NGC 6914*b*
21‡....	HD 200775	MWC 361	21 00.4	+67 47	7.4	B3e+shell	NGC 7023
22....	BD+65°1637	AS 475	21 40.6	+65 39	11	B5e	NGC 7129
23....	LkHα 234	....	21 40.8	+65 39	*13*	Aeβ	NGC 7129
24....	BD+46°3471	AS 477	21 48.7	+46 46	10.1v?	A0e+shell	(IC 5146)
25....	LkHα 233	....	22 30.3	+40 08	*14.5*	A7eα	Anon.
26....	MWC 1080	....	23 12.9	+60 18	*13.0*	eq	Anon.

had then set out to uncover some of these intermediate-to-high mass stars. He expected that such young stars would be closely associated with the material from which they were born, so to avoid confusion with older objects that might be projected on a star forming region, the further important condition was imposed that the stars should illuminate nearby nebulosity.

Herbig was clear about the scope of the paper and well aware that much more would need to be done in the future. He writes:

> *"The present investigation is intended to be no more than a reconnaissance of the field. Therefore, no effort has been made to obtain first-class observational data purely for its own sake, and no apology is offered for the approximate nature of some of the magnitude and color data employed. Because of the exploratory nature of the investigation, a considerable amount of information was collected that, in retrospect, appears to have had little direct bearing on the main issue. Its omission would have resulted in a more*

> *concise presentation; nevertheless, a considerable amount of this material is included here on the chance that it may prove useful or relevant in the future."*

With these humble words Herbig introduced a paper that has had a profound impact on the study of young stars and star formation. More than a thousand papers have been published with 'Herbig Ae/Be stars' in the title, and several conferences have been devoted to the subject, which continues to be intensely studied.

Table 3 lists the 26 stars that Herbig identified and selected for detailed study through the following criteria:

- *(a) The spectral type is A or earlier, with emission lines.*
- *(b) The star lies in an obscured region.*
- *(c) The star illuminates fairly bright nebulosity in its immediate vicinity.*

Herbig did not presume that the three criteria were so comprehensive that they would capture all pre-main sequence stars of intermediate mass. Rather he hoped that they would be sufficiently stringent to avoid contamination by other types of stars that could pollute the sample. Herbig forcefully stressed the importance of avoiding such contaminations during a talk at the first conference devoted to Herbig Ae/Be stars (Herbig 1994, see Figure 58). He there posed 4 questions, all related to the question of how we distinguish Herbig Ae/Be stars from older intermediate-mass stars. One of the questions, and Herbig's answer, was as follows:

> ***"Is there some common observational characteristic that sets massive pre-main sequence stars apart from their older look-alikes?***
>
> *If so, I do not think we have found it yet. Even among the subset of those we regard as bona fide Ae/Be pre-main sequence stars, there is such a motley collection of optical spectra that one cannot examine a candidate and decide immediately whether it qualifies for membership or not. There are members that look like shell stars, some that look like ordinary Be stars, some with many emission lines that suggest a hot T Tauri-like spectrum. This is completely different from the case of the classical T Tauri stars, and for many weak-line TTS, which are immediately recognizable. Certainly a careful examination of those non-emission B and A stars that lie above the ZAMS in the color-magnitude diagram would be warranted: perhaps some tell-tale indicator can be found.*

> *There is a syllogism that I think illustrates our problem, as we grope about among stars that we do not understand very well, trying to discover the key criteria:*
>
> *First observer:* 'All leopards have four legs, spots, and live in Africa'.
> *Second Observer:* 'Over there is a four-legged African animal with spots'.
> *First Observer:* 'Then it must be a leopard'
> *Unfortunately, it is a giraffe.*
>
> *The moral here is that we have to look more critically and more thoughtfully."*

Later efforts to select Herbig Ae/Be stars have unfortunately not always heeded this admonition, and as a result today's lists of Herbig Ae/Be stars are not only more extensive but also more infected with various types of interlopers.

In his 1994 review talk, Herbig further commented on the abovementioned defining criteria:

> *"It is remarkable that a group of stars defined thirty years ago should have survived subsequent scrutiny with the techniques and the deeper understanding of early stellar evolution that have developed since 1960. One of the original criteria for Ae/Be membership was that the star possess emission lines; that was simply in analogy to the T Tauri experience. A second requirement was that the star illuminate reflection nebulosity, which provided assurance that the object was indeed associated with the dark cloud, as it ought to be if it had been formed nearby. Nowadays, molecular-line and sub-mm continuum mapping provide almost the same guarantee, so the requirement of illuminating nearby dust, although comforting, is no longer a necessary condition. In the early days the presence of a reflection nebula was also an operational convenience in that it was a way of discovering candidate objects from simple inspection of direct photographs."*

4.2 Three Herbig Ae/Be Stars

In the following, three Herbig Ae/Be stars, selected from Herbig's 1960 compilation, are briefly discussed, to highlight their principal properties and the environments of these Herbig Ae/Be stars:

LkHα 198 (V633 Cas).
The star is located in the L1265 cloud in Cassiopeia, and is part of a scattered population of young stars in the region. It is likely located at a distance of about 600 pc (Chavarria-K. 1985) and is an early-type star of spectral type ~A5 with strong Hα emission but otherwise no significant emission lines (Cohen & Kuhi 1979, Hillenbrand et al. 1992). It has a close companion,

LkHα 198 A2, only 60 milli-arcsecond distant (36 AU, Smith et al. 2005), and a deeply embedded infrared companion, LkHα 198 B, is 6 arcsec distant (Lagage et al. 1993). Figure 55 shows an HST image of the highly structured reflection nebula associated with LkHα 198, illustrating the impact on the molecular cloud of a strong outflow from the star, detected as a molecular outflow (Matthews et al. 2007) and as a giant 2 pc Herbig-Haro flow HH 800-802 (McGroarty et al. 2004).

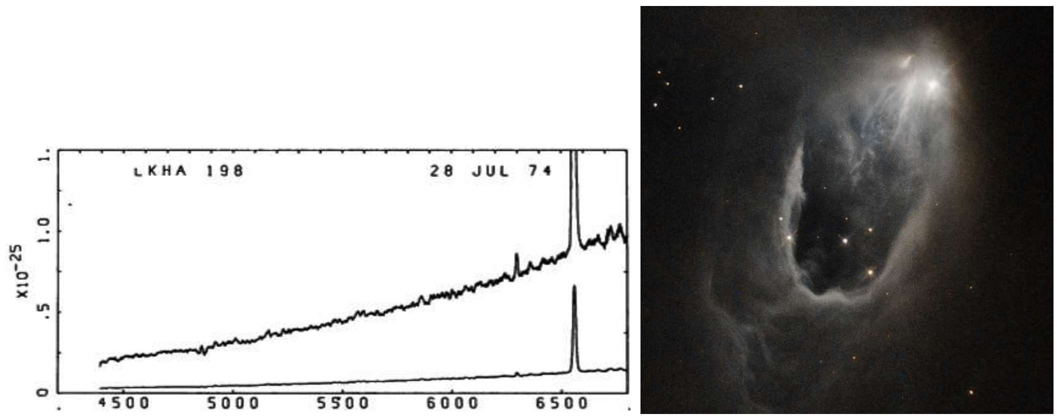


Figure 55: *(left): A low-resolution spectrum of the Herbig Ae/Be star V633 Cas (Cohen & Kuhi 1979); (right): V633 Cas and its outflow cavity as seen in an image obtained with the Hubble Space Telescope.*

R Coronae Australis.
R CrA is significantly variable and is surrounded by the prominent reflection nebula NGC 6729 (Knox Shaw 1916). It was included as one of the original eleven T Tauri stars in Joy's (1945) paper, but Herbig reclassified it in his 1962 paper as a HAeBe star on account of its A0 spectrum, and further noted that in his spectra *"it showed H and Fe II emission upon an absorption spectrum featured by strong Balmer lines together with weaker lines of He I, Ca II, and perhaps Mg II."* In a later study, Mendoza et al. (1969) declared that the star could not be uniquely classified on the MK system because of peculiarities such as narrow cores and broad wings in the hydrogen lines, enhanced Ti II, and strong Balmer continuum, but suggested a type of A5pe, noting significant spectral change since Herbig's A0 classification. Graham & Phillips (1987) confirmed the spectral variability, and noted rapid changes in NGC 6729, which they interpreted as shadow play from dust condensations moving close to the star. R CrA was one of the first young stars that was found to have a strong far-infrared excess (Cruz-Gonzalez et al. 1984). Near-infrared surveys have uncovered a small cluster of young low-mass stars, the Coronet, embedded in the molecular cloud around R CrA (Taylor & Storey 1984). The Corona

Figure 56: *The Corona Australis molecular cloud contains four Herbig Ae/Be stars: R and T CrA in the NGC 6729 reflection nebula, and TY CrA and HD 176386 in the large blue reflection nebula NGC 6726/27. Courtesy Chart32/Johannes Schedler.*

Australis molecular cloud contains no less than four HAeBe stars: R CrA, T CrA, TY CrA, and HD 176386 (see Figure 56). Of these TY CrA is of particular interest since it is an eclipsing binary, yielding precise masses for the components, and a distance of 129±11 pc (Casey et al. 1998). Submillimeter observations have located a luminous source between R and T CrA, which may be a proto-HAeBe star (Chini et al. 2003).

V380 Orionis.
This star was discovered by Herbig (1946) while he was still a student, and independently by Morgan & Sharpless (1946) (see Sect. 2.2). It displays a rich emission line spectrum (Hamann & Persson 1992b) and has a spectral type around B9 and a luminosity of $\sim$100 $L_\odot$. V380 Ori has been observed in great detail and over many wavelength ranges. Herbig (1960a) notes: *"V380 Ori is the illuminating star of NGC 1999, a round mass of reflection nebulosity about 1.5 arcmin in diameter. It lies in the broad lane of obscuration, strewn with feebly luminous nebulosity, that extends several degrees south and eastward of the Orion Nebula.*[22] *A striking feature of NGC 1999 is an extremely dark triangular cloud silhouetted against the bright nebulosity."*

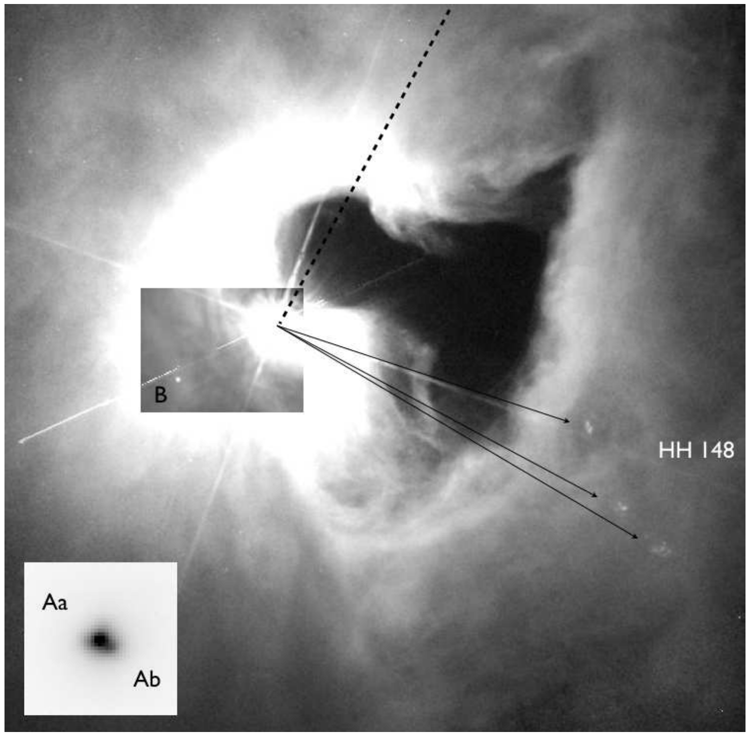


Figure 57: *An HST image of V380 Ori and the reflection nebula NGC 1999. The dark structure is not a dense globule, but a cavity blown by the star. Three Herbig-Haro knots are indicated. The dashed line shows the direction to the giant bow shock HH 222. The low-mass companion V380 Ori B is seen at a distance of 9 arcsec. The insert in the lower left shows that A is a close binary, and spectroscopic observations reveal that Aa is a spectroscopic binary. From Reipurth et al. (2013).*

CCD images obtained with the Hubble Space Telescope clearly show that this is not a dense dark cloud core, but a cavity in the bright reflection nebula (Figure 57), as discussed by Stanke et al. (2010). V380 Ori is the most massive star in this part of the L1641 cloud, and modern deep Hα images show that it illuminates a wide surrounding area; radial lines in the cloud surface suggests a streaming motion centered on V380 Ori (e.g., Reipurth et al. 2013). Millan-Gabet et al. (2001) has used long baseline interferometry to search for a circumstellar disk around V380 Ori, and find an elongated circumstellar structure suggesting a disk that lies almost edge-on. V380 Ori has a close infrared companion, with a separation of 0.15 arcsec (Leinert et al. 1997). The two components (labeled Aa and Ab) can be seen in an archival NACO image from the ESO VLT (inserted in Figure 57). More recently, Alecian et al. (2009) found that V380 Ori Aa is itself a spectroscopic binary with a period of 104 days, with the secondary being a massive T Tauri star.

They determine an effective temperature for the primary of 10,500 K, and for the secondary of 5500 K, with a mass for V380 Ori of roughly 2.8 $M_{\odot}$. Finally, a low-mass companion at the brown dwarf limit is located 9 arcsec from V380 Ori (Corcoran & Ray 1995, Reipurth et al. 2013). Altogether, V380 Ori is a hierarchical quadruple system.

4.3 Development of the Field

Herbig's 1960-paper stood alone for a decade before the slowly growing community interested in young stars picked up the subject. The next major and influential study to appear was by Steve and Karen Strom and colleagues, and it was in this paper that the stars were named 'Herbig Ae/Be stars' (Strom et al. 1972). In the paper, the authors observed a significant sample of Herbig Ae/Be stars spectroscopically at moderate dispersion in order to obtain accurate hydrogen line profiles with the goal to estimate the surface gravity. If the gravity of a star was less than the gravity expected for a main sequence star of the same spectral type, it would indicate that the stars were above the main sequence, and thus provide another strong argument that the stars were young (it was reasonably assumed that post-main sequence stars that had begun evolution towards the giant branch would be weeded out by Herbig's three criteria). The data indeed indicated that the late B and early A stars had gravities lower than the main sequence gravities by more than 0.4 dex, thus strongly supporting Herbig's original contention that the stars were young. As an aside, it is interesting to note that already in this early paper, the authors considered the possibility that the circumstellar 'shells' of the HAeBe stars might be shaped as disks.

In the following two decades many more studies appeared, among them five PhD theses, which represented major and important contributions to the subject:

Loren (1975) took advantage of the newly developed millimeter wavelength techniques to detect CO and other molecules toward a sample of Herbig Ae/Be stars. Garrison (1976) obtained optical spectrophotometry, UBVR Hα polarimetry, and high resolution Hα spectra. Finkenzeller (1983) did a spectroscopic study and analyzed line profiles. Corcoran (1994) used deep interference filter images to find Herbig-Haro objects and jets in association with several Herbig Ae/Be stars, indicating a similarity to the outflows from T Tauri stars. Finally, Hillenbrand (1995) performed molecular mapping, optical and infrared imaging, and a stellar-classification spectroscopic survey of Herbig Ae/Be stars which are isolated from large complexes of extensive star-formation with the aim to identify small partially-obscured stellar aggregates projected onto the same molecular cores as the more massive stars. It was found that Herbig

Ae/Be stars rarely are formed in isolation, but appear together with small groups of T Tauri stars.

In the last twenty years the subject has blossomed into one of the most dynamic areas of current star formation studies. The development of the field has been documented in the proceedings of two conferences. The first was held in October 1993 in Amsterdam (Thé et al. 1994), and Herbig was the key speaker (Figure 58). The second conference was held in April 2014 in Santiago de Chile, shortly after Herbig passed away, and it was dedicated to his memory. The conference provided an overview of our current understanding of the Herbig stars (de Wit et al. 2014).[23]

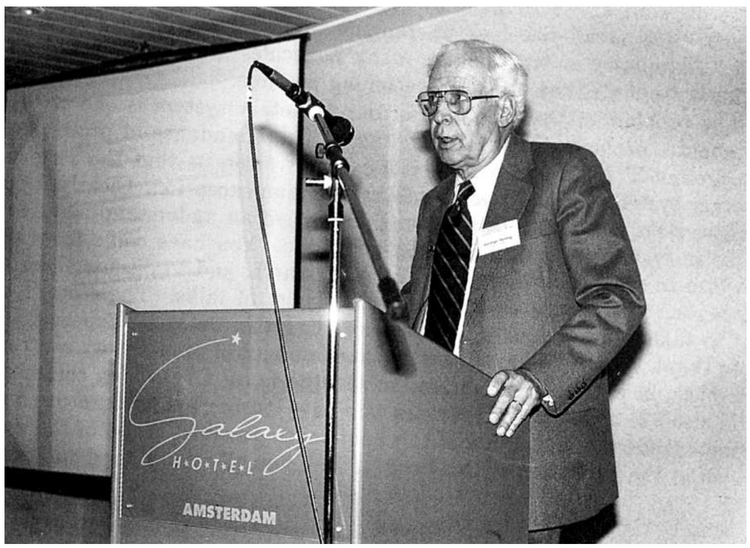


Figure 58: *Herbig introducing the 1993 conference on HAeBe stars in Amsterdam. Photo courtesy the Astronomical Society of the Pacific.*

It was early on established that HAeBe stars are generally surrounded by massive circumstellar accretion disks (e.g., Hillenbrand et al. 1992), and this has driven most of the subsequent research into these stars. A subset of HAeBe stars, the socalled UX Ori stars, show deep irregular eclipses suggesting that giant dust 'clumps' occult those stars (e.g., Herbst & Shevchenko 1999). With the advent of modern high resolution imaging techniques it has been possible to directly image disks around a number of HAeBe stars. Significant structure is evident in such disks (Figure 59), suggesting that persistent disturbances affect the disks. It has been determined that most HAeBe stars have stellar companions (e.g., Baines et al. 2006), which conceivably might perturb such disks, but an intriguing possibility is that planet formation is ongoing in some of these disks (e.g., Quanz 2015). Because the disks around HAeBe stars are larger, brighter, and thus easier to observe, they have become prime targets for studying disk structure and for attempts to image planets in the process of formation.

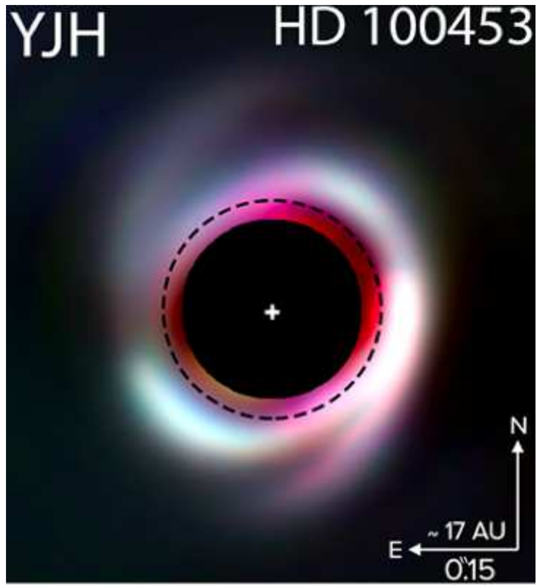


Figure 59: *Two-armed spiral structure is seen in the disk around the Herbig Ae star HD 100453. The spiral structure is likely induced by a M-dwarf companion at a projected separation of 120 AU. From Wagner et al. (2015).*

For many years after his 1960 paper, Herbig left the study of the young Ae/Be stars to others. However, when the HIRES spectrograph on the Keck I telescope became available in the early 1990s, he embarked on a long-term study of a number of young intermediate-mass stars, and some of these data he published in connection with more extensive studies of young clusters (see Chapter 6). In our conversations, he often remarked about his particular fascination with abundance anomalies that he had found in certain Ae/Be stars and which he tried to understand. In a paper on star formation in the L988 cloud, he briefly summarized the state of chemical peculiarities in HAeBe stars (Herbig & Dahm 2006):

> *"Chemically peculiar (CP) Bp and Ap stars do not figure in conventional pictures of early stellar evolution. There has been some debate over whether very young CP stars exist; a recent (photometric) search of five young clusters by Paunzen et al. (2002) found none. But long ago, Garrison (1967) called attention to three Ap(Si) stars in the ρ Oph cloud, and Abt & Levato (1977) found three more in Orion OB1. The case of HR 6000, situated among the TTSs of Lupus 3, is well known. More recently, three Hg-Mn*

> *stars have been found in Orion OB1 by Woolf & Lambert (1999), a He-wk Bp Si star has been discovered in the young cluster NGC 2244 by Bagnuolo et al. (2004), and this paper describes an Ap star that we have found still embedded in its parental cloud. Earlier, we discovered that BD +30° 549, the illuminating star of NGC 1333 and the brightest member of that young cluster, is of type Bp (G. H. Herbig & S. E. Dahm 2004, unpublished). It therefore stands demonstrated that the pattern of peculiar abundances that characterize such stars can be established very early in their history, although it may be that the age threshold for these peculiarities to appear is not the same for every subtype (Si, Hg-Mn, and Sr-Cr-Eu), as suggested by Abt (1979)."*

In his last years, when he realized it was unlikely that he would be able to publish these and other results, he expressed the hope that his spectra would some time in the future be picked up from the Keck archive and analyzed by competent, young people, so the results could see the light of day.

5 FUors AND EXors

5.1 The Eruption of FU Orionis

In the winter of 1936/37 an anonymous 16th magnitude star in the λ Orionis region brightened to 10th magnitude in less than a year (Figure 60). The event was caught by patrol plates, and a brief note drawing attention to it was published by Wachmann in 1939 in a German circular for observers. Herbig, who was a voracious reader, knew of this obscure announcement, and when he became an assistant at Lick Observatory in 1943, FU Ori was among the targets he explored:

> *"FU Orionis had flared up in the dark cloud B35 in 1937, and although its spectrum contained no bright lines and the star refused to fade from maximum light, the variable star experts of that era had no classification for it other than 'slow nova'. When I read about FU Orionis, and heard that a small reflection nebula had appeared around the star when it brightened up, I became convinced that this was no nova but some phenomenon of early stellar evolution. I took Lick spectrograms of this star in the mid-1940's, some better McDonald spectrograms in 1948-49, [and] a 100-inch coudé plate during a Mount Wilson visit in 1950 or 1951."* [1]

Following the 1939 announcement, little attention was paid to FU Ori by the community. Fifteen years after the outburst, Wellmann (1951) determined a spectral type around late F with supergiant characteristics and noted that the hydrogen lines were blueshifted, and Wachmann (1954) presented a detailed light curve from 1928 to 1954, showing that FU Ori barely had faded since its eruption. Like Herbig, Ambartsumian (1954) felt that the existing evidence was consistent with FU Ori being a young star,

During the 1950's Herbig had been preoccupied with his fundamental studies of the T Tauri stars and the recognition of the Herbig Ae/Be stars and had not devoted time to write up his material on FU Ori, although he had continued to obtain more and better data. But when he was invited to speak at a symposium on 'Aspects of Stellar Evolution' in 1964 in honor of Ejnar Hertzsprung, he decided this was a good opportunity to focus more closely on these data.

5.2 The Hertzsprung Symposium

In June 1964 Herbig went to the Hertzsprung Symposium in Flagstaff and presented his data and thoughts on FU Ori. He first discussed the unique spectrum of FU Ori:

> *"The spectrum of FU Ori at low dispersion (40–80 Å; see Figure 61) resem-*

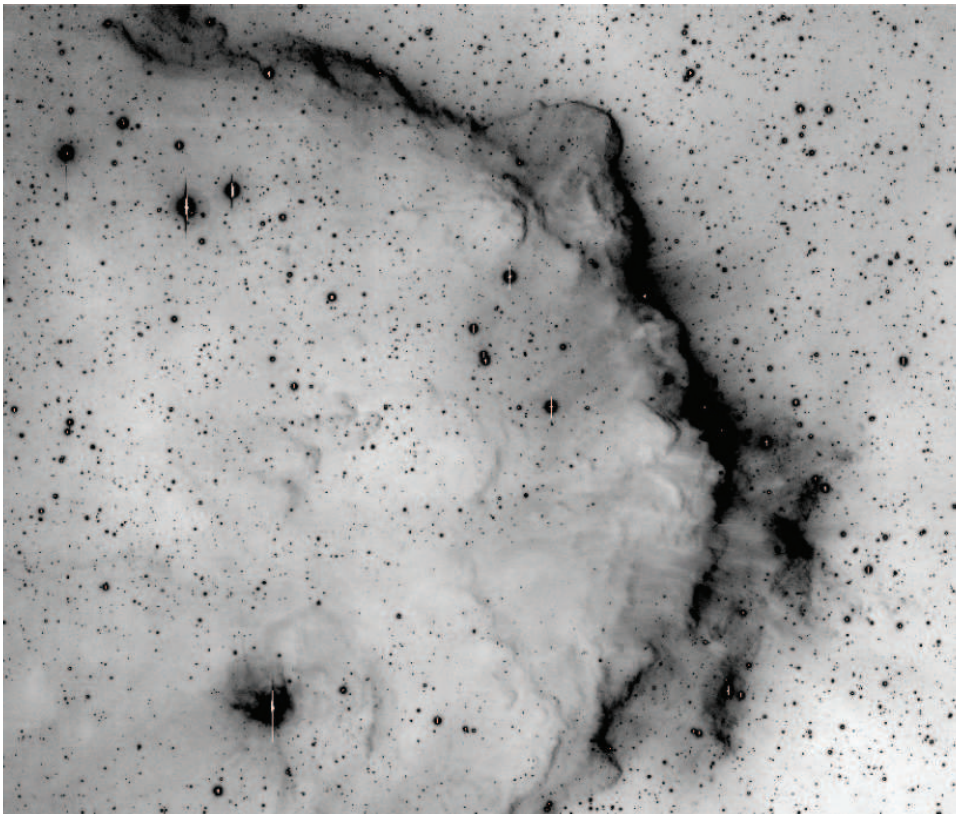


Figure 60: *FU Ori is the nebulous star in the lower left of the figure. It is associated with the small cometary-shaped cloud B35 with a bright rim facing the massive star λ Ori. Hα image obtained at the Subaru telescope by Bo Reipurth.*

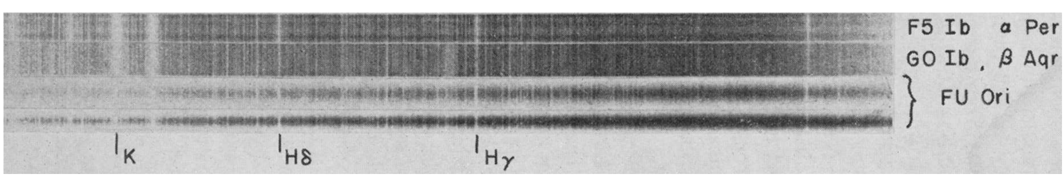


Figure 61: *A spectrum of FU Ori at moderate dispersion, with two normal yellow supergiants for comparison. Both spectra of FU Ori was obtained by Herbig in December 1948 during his observing run with Otto Struve at McDonald Observatory. For modern eyes used to plots of digitized spectra this material is difficult to work with, but Herbig was an expert in reading spectroscopic information from such photographic prints. From Herbig (1966).*

> *bles that of a G-type supergiant but with Balmer absorption lines that are abnormally strong, as was first recognized by Wellmann (1951). Detailed examination shows, however, that even if the H lines are disregarded, the spectrum cannot be matched with that of a normal star. The full complexity is apparent only at coudé dispersion. [...] The grossly peculiar properties of the spectrum of FU Ori as seen at low dispersion come from the fact that there are actually two distinct spectra present: a set of somewhat diffuse lines which can be matched (except in certain details) by an early F-type star of high luminosity, and another set of lines displaced about 80 km* s^{-1} *shortward. These displaced shell components are very strong at the H lines and at the low-level lines of both neutral and ionized metals. [...] The abnormally strong Balmer lines are the result of the superposition of the lines of the two spectra at an overlap of 80 km* s^{-1}*"* (Herbig 1966a).

Herbig further noted that he had seen no significant spectral variability, except for a redshifted emission component at the K-line of Ca II. He also demonstrated that what he, with the terminology of the time, called the 'shell' spectrum had to originate above the source of the F-G spectrum. But the crucial observation was that lithium was observed in considerable strength.

Herbig went on to systematically dismantle the various hypotheses that had emerged to explain the FU Ori eruption over the years, from a slow nova to the emergence of the star behind a sharp edge of extinction. He then proceeded to demonstrate *"the observational reasons for believing that the 1936 flare-up of FU Ori represented some phenomenon of early stellar evolution."* This is today such a given that it is hard to see the need for any arguments, but half a century ago that was not at all the case. Based on the little that was known theoretically about the formation of young stars, Herbig suspected, as supported on statistical grounds, that FU Ori might have emerged at the top of the Hayashi tracks as the result of gravitational collapse of an object of about 1 solar mass, and that it might in the future evolve to pass through the T Tauri stage.

These results were received with great excitement by the participants, and in his concluding remarks at the end of the Symposium Bart Bok said:

"Perhaps the most striking paper of the whole Symposium was that by George Herbig on FU Orionis. This star has all the earmarks of one being caught in advanced stages of formation, and the sudden increase in its brightness in the late thirties, coupled with the first appearance of lithium, makes this one of the most striking objects available to us." (Bok 1966).

5.3 The Russell Lecture

In 1975, Herbig was awarded the Henry Norris Russell Lectureship by the American Astronomical Society in recognition of a lifetime of eminence in astronomical research, joining a roster of luminaries like Struve, Baade, Hoyle, and Strömgren. Herbig chose the occasion to summarize his work up to that time on the FUors [Ambartsumian (1971) coined the term FUor, which is less cumbersome than 'FU Orionis object', and this terminology has taken hold]. Following his earlier presentation at the 1964 Hertzsprung Symposium, in which he concluded that FU Ori must represent a rare stage of early stellar evolution, nothing much had happened in the field until 1970, when a new FUor appeared. The sudden appearance of a second FUor (Figure 62) changed FU Ori from being a pathological one-of-a-kind case to being the member of a class. The discovery and Herbig's subsequent detailed study of this new eruptive star is discussed in the following.

In the fall of 1969, Gunnar Welin, a young Swedish student at the University of Uppsala was engaged in a study of Hα emission stars in the North America Nebula, when he noticed that one star, LkHα 190, was rapidly brightening from an initial 16th magnitude to about 10th magnitude by August 1970 (Welin 1971). In January 1971 Welin was writing Herbig a letter about another star they had corresponded about, and additionally mentioned the outburst more than a year earlier of LkHα 190 (subsequently named V1057 Cyg). Herbig immediately realized the potential significance of this event, but unfortunately the star was by then nearly in conjunction with the Sun, so a more detailed spectroscopic study had to wait until early April, at which time the description of the spectra was circulated as a rapid Information Bulletin on Variable Stars (Herbig & Harlan 1971). Here it was described that the star showed a blue absorption spectrum near a spectral type of A1, that the Hα line had a P Cygni profile with an absorption trough blueshifted to about 420 km s^{-1}, and that lithium was rather strongly present in the spectrum. Importantly,

> *"the outburst of V1057 Cyg is highly reminiscent of the brightening of FU Orionis in 1936, even to details such as the sudden appearance of a reflection nebula and to the high abundance of lithium. If the two events represent the same basic phenomenon, then V1057 Cyg has established a very important point that could not be settled in the case of FU Ori for lack of a pre-outburst spectrogram. That is, the fact that the spectrum of V1057 Cyg changed fundamentally from minimum to maximum light proves that an intrinsic change in the star took place, and that the explanation is not that it was simply unveiled by the dissipation of a circumstellar dust cloud"* (Herbig & Harlan 1971).

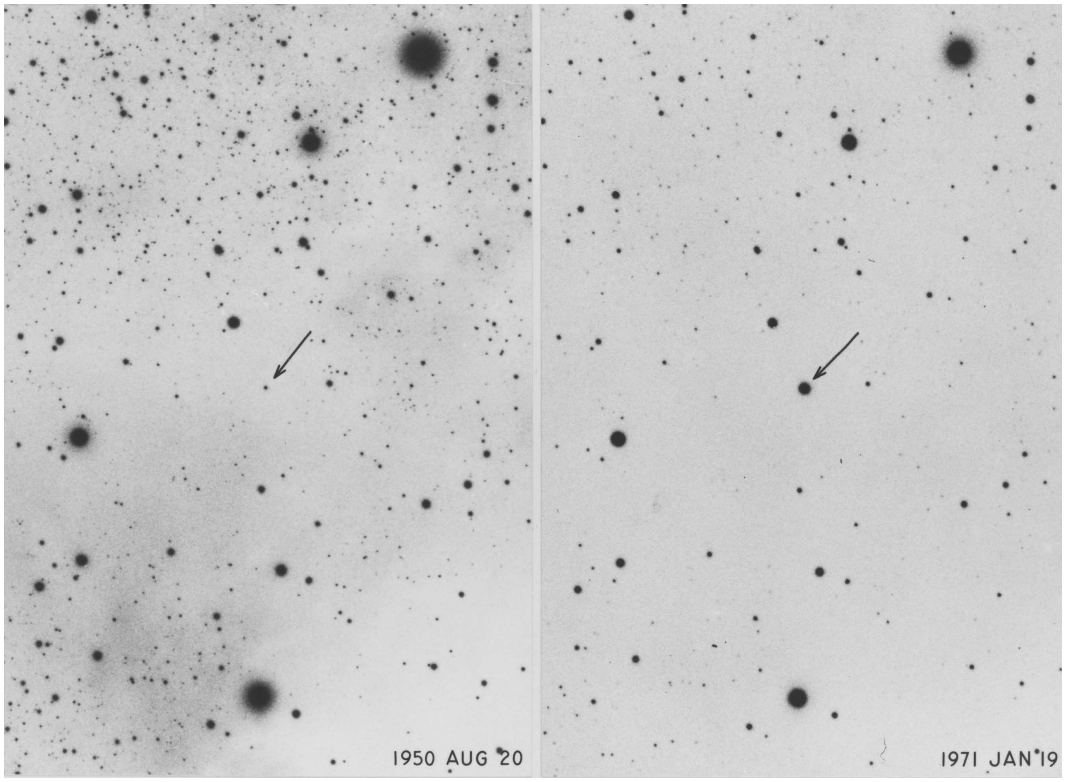


Figure 62: *Pre- and post-outburst photographic plates of V1057 Cyg. From Herbig's personal archives.*

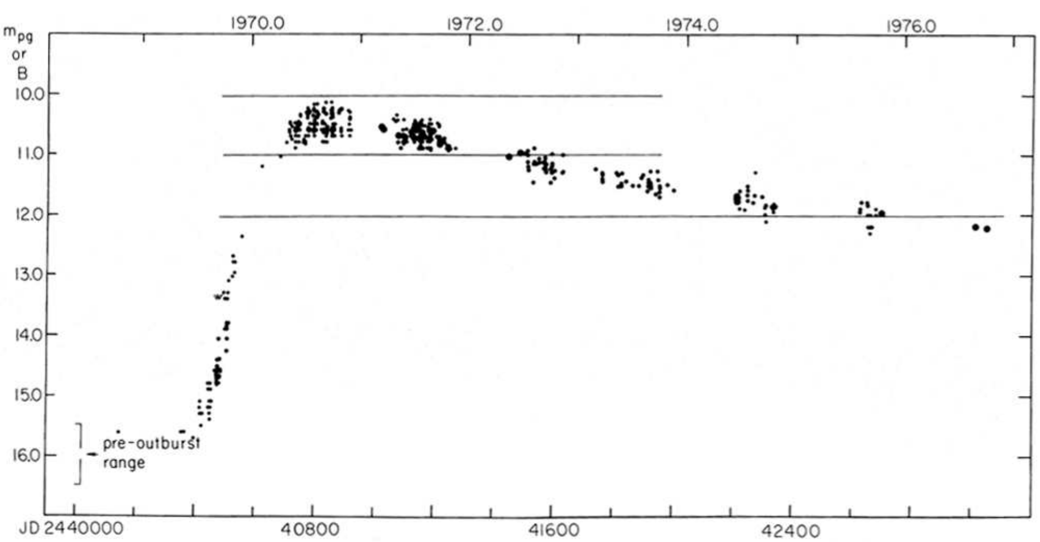


Figure 63: *Light curve of V1057 Cyg. From Herbig (1977a).*

A much more detailed discussion of the spectral features was presented in the now famous paper from the Russell Lecture (Herbig 1977a), and Herbig noted that, like FU Ori, it was not possible to assign a unique spectral type for V1057 Cyg due to a number of anomalous line ratios. Of special importance, Herbig noticed what would become an important characteristic of FUors: *"One unexpected feature is that the spectral types of V1057 Cyg in the 3900–4300 Å region are systematically earlier than those determined from the 6000–6600 Å lines."*. In the blue the spectral type was early A and of fairly high luminosity, while in the red it was more like F5 II. He further noted that over the period of a few years during which he had monitored the star spectroscopically, the spectral types in the blue and red changed slowly to slightly later types, from F5 II to G2-5 II/Ib in the red, indicating a cooling. In terms of radial velocity, Herbig found the kinematic link between star and surrounding interstellar material to be beyond question. The P Cygni profiles at Hα, the Sodium doublet, and the H and K lines of Ca II were very similar to what was seen at FU Ori. Finally, in concert with the fading of the star (Figure 63), the bright reflection nebula that had appeared at the time of the eruption continued to fade, which was documented over a 10 year period (Duncan, Harlan, & Herbig 1981).

Herbig himself discovered a third FUor, V1515 Cyg, this one in the NGC 6914 star forming region in Cygnus (Figure 64):

> *"About 1954, in connection with the search for emission-Hα stars near the reflection nebula NGC 6914 (Herbig 1960), a faint variable star was discovered in the same obscured area, 8$'$ southwest of BD +41°3731. The variable was noted as about 3 mag brighter on a 1954 Crossley plate than on one of 1912, but despite this unusually large range and the fact that a curious arc of nebulosity protruded from the photographic image, no follow-up observations were made at Lick until 1974. [...] Two 120 inch coudé spectrograms of the red region taken soon thereafter revealed a spectrum very much like that of FU Ori: an early G-type star of high luminosity with broad lines, P Cygni structure at Hα, powerful shortward-displaced absorption at Na I $D_{1,2}$, and a strong Li I λ6707 line. Furthermore, the star was significantly brighter than it had been in 1954"* (Herbig 1977a).

The light curve, assembled from an assortment of photographic patrol plates, showed V1515 Cyg having a much more gradual rise to maximum light than FU Ori and V1057 Cyg (Figure 65), with a rise time lasting at least a decade.

Armed with data for these three FUors, Herbig attempted to understand the FUor phenomenon in the context of early stellar evolution. First he made the two fundamental assumptions that:

Figure 64: *The FUor V1515 Cyg (arrowed) is located in the rich star forming region NGC 6914. Image courtesy Capella Observatory.*

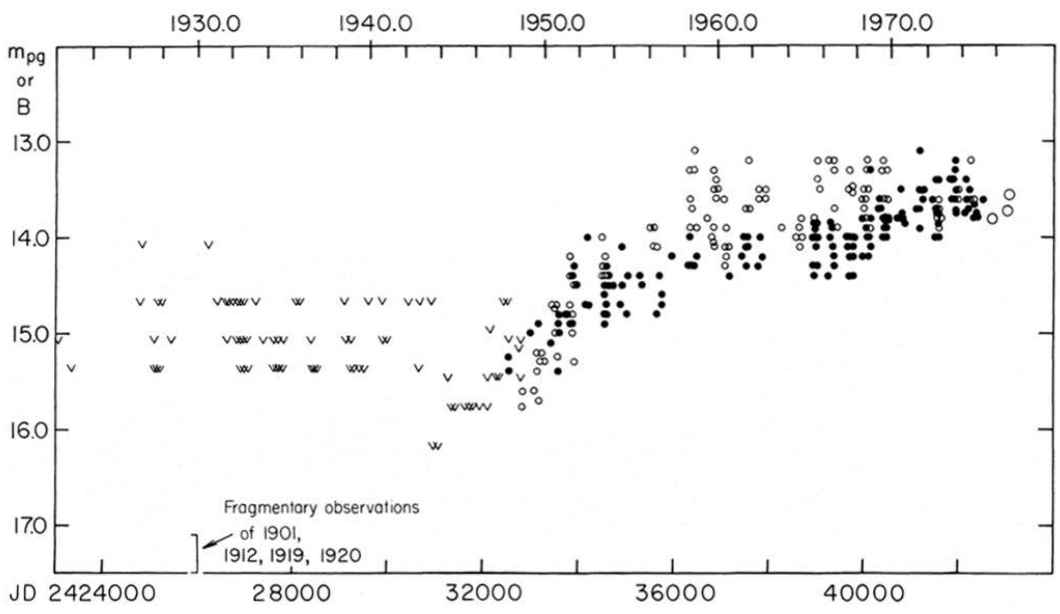


Figure 65: *Light curve of V1515 Cyg. From Herbig (1977a).*

> "(a) *no other such events have occurred within 1 kpc in the northern sky during the past 80 years, and* (b) *it is not some special minority of T Tau stars, which is susceptible to the FU Ori phenomenon, but rather the total population of T Tau stars brighter than about* $M_{pg} = +4$ *in this volume are candidates (because the* M_{pg}*'s of the three known examples range from +3 to +4)"*

Herbig demonstrated that the assumption that a T Tauri star would have only one eruption during its lifetime was inconsistent with available observations of star forming regions.

> *"For these reasons, the 'only-once-per-star' assumption for the FU Ori phenomenon is dismissed. The point of view taken here is that such an eruption represents a relatively superficial event after which the star returns to essentially its former state."*

In fact, Herbig's statistical analysis indicated that the FUor phenomenon should occur in all T Tauri stars and be repetitive with a (highly uncertain) mean time between successive FUor outbursts of the order of 10^4 years. *"This suggestion that the FU Ori phenomenon is recurrent, and with a spacing of only about* 10^4 *years in a given star is unexpected."* Herbig did consider the possibility that it is only a subset of T Tauri stars that would erupt, but concluded that there is *"no evidence either in support of or in contradiction to this more complicated counterproposal, so it seems preferable to remain with the simpler hypothesis."*

Finally, Herbig considered various mechanisms that might account for the FUor outbursts, all of which he found were subject to criticism, and concluded that *"no convincing explanation of the FU Ori phenomenon is as yet available."*

Herbig's Russell lecture was greeted with enthusiasm.[24] And in the audience was also a young graduate student about to finish his studies, Lee Hartmann, who was excited and inspired by the lecture, and who would eventually engage in a lively debate with Herbig over many years about the interpretation of the FU Ori phenomenon.

5.4 The Grand Debate

Herbig's Russell lecture was the catalyst for an explosion of both observational and theoretical studies of the FUor phenomenon, which was soon recognized as an important, albeit mysterious, phase of early stellar evolution. On the observational side, efforts focused on monitoring FUors with high spectral resolution, to study their energy distribution across the whole electromagnetic spectrum, and to find more cases. The ensuing accumulation of a large observational material placed severe constraints on possible outburst models. On the theoretical side, two problems were addressed, first the question of which physical configuration would lead to the observed properties, and second how such eruptions were triggered. Soon two starkly different models were competing, one assuming that a FUor eruption occurs in a disk, the other that it occurs in a star.

5.4.1 The Hartmann-Kenyon Model

In the 1980s, Lee Hartmann and Scott Kenyon, then both at the Harvard-Smithsonian Center for Astrophysics, suggested that a FUor could represent a massive accretion event in the circumstellar disk around a T Tauri star, see Figure 66 (Hartmann & Kenyon 1985,1996). The fundamental idea is that disk accretion onto a young star is highly episodic, ranging from low states ($\sim 10^{-8}$ $M_\odot$/yr) as seen in T Tauri stars to very high accretion rates ($\sim 10^{-5}$ $M_\odot$/yr) represented by FU Ori objects. A Keplerian accretion disk heats up due to energy release as the gas spirals in towards the star, and the surface temperature of the disk varies with distance from the star in a simple manner, with warmer regions near the star and cooler regions further out. As a result, at longer wavelengths the observed emission is dominated by the outer cool regions, while at shorter wavelengths the inner warm disk dominates. At high enough accretion rates, the total emission from the disk overwhelms the emission from the central star by a factor of 100 or more, suggesting that when we observe a FUor we are not seeing the central star, which is 'drowned' out, but rather a hot self-luminous disk. This readily explains the change of spectral type with wavelength observed by Herbig from blue to red, a phenomenon that later observers found continued into the infrared. A steady accretion disk model can nicely fit the observed energy distribution of FU Ori. Furthermore, a luminous disk generates double-peaked line profiles quite different from the elliptical profiles from a spherical rotating star. And a Keplerian disk rotates faster near the star and gradually slower further out, which predicts that optical lines formed in the inner disk should be wider than infrared lines from cooler more distant disk regions. Comparison between observations and models show remarkably good fits, e.g., Zhu et al. (2008) (Figure 67). Finally, the strong winds detected by Herbig as broad and deep P Cygni profiles in Balmer and certain other lines found a natural explanation as a magnetocentrifugally accelerated disk wind, where magnetic field lines rotating with the disk drive out the upper disk layers to high velocities.

Lee Hartmann remembers the beginning of the disk-hypothesis:

“I became interested in the FUors when, as a finishing grad student at Wisconsin (the official designation was “terminal“), I went to my first AAS meeting

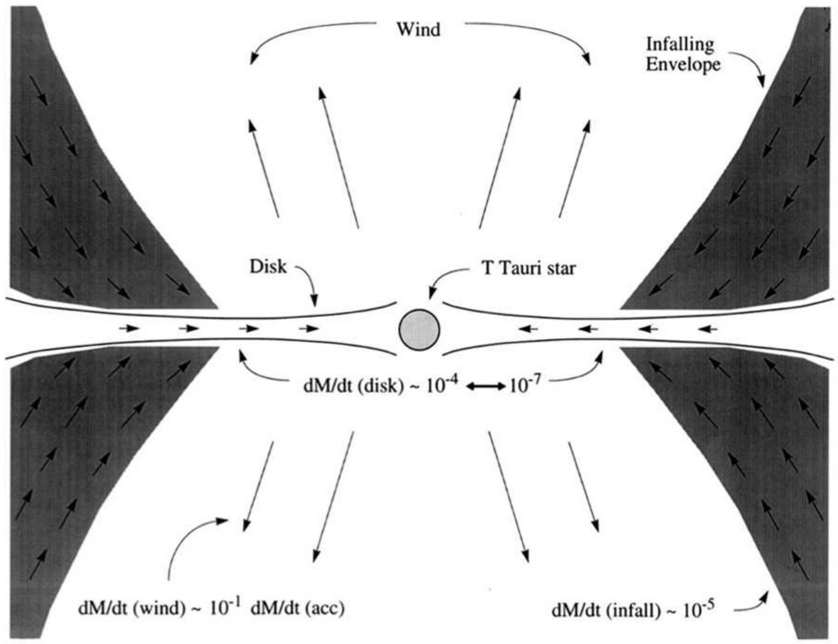


Figure 66: *A schematic FUor model of a star with an infalling envelope feeding a disk that episodically empties out onto the star. From Hartmann & Kenyon (1996).*

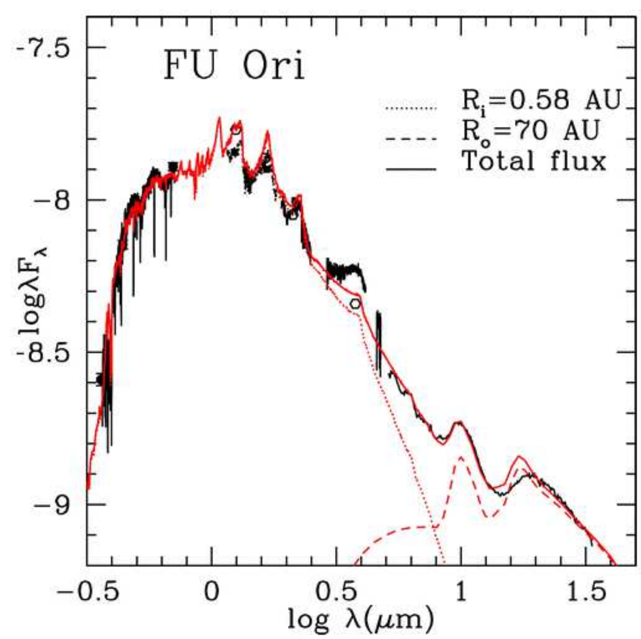


Figure 67: *Observed spectral energy distribution (black) compared with a disk model (red). From Zhu et al. (2008).*

and heard George Herbig's wonderful Russell Lecture on "Eruptive Phenomena in Early Stellar Evolution". This paper stuck in my mind for years, so when Scott Kenyon came to CfA and gave a talk on novae, I went up to him afterward and asked if FU Ori could also be some kind of young nova. Scott said he didn't think so, but it did sound like an accretion disk outburst such as were then being invoked to explain the recurrent eruptions of dwarf novae.

My first thought was to look for the double-peaked absorption line profiles one would expect for a disk, but was having little success taking spectra at 5200 Å. Then Peter Petrov visited CfA and told me about some HIRES red spectra that he and Herbig had taken which showed double absorption lines in FU Ori as if it were a double-lined spectroscopic binary, but the lines didn't vary in radial velocity. I became very excited, and even had the nerve to cold-call George in Hawaii to tell him he had discovered the signature of an accretion disk. George was noncommittal; as you know, he never liked the disk model, and wrote papers with Peter trying to support alternative explanations. Anyway, we eventually got red spectra with the MMT echelle which showed the line doubling. We subsequently went to the Kitt Peak 4m FTS and obtained high-resolution 2 μm spectra which showed slower infrared rotation, as expected for a Keplerian disk." [25]

Hartmann and Kenyon and their collaborators published a long series of papers dealing with various aspects of the accretion disk model. Altogether, the disk hypothesis was soon adopted by most of the community as an attractive explanation for many of the peculiarities of the FU Orionis objects. But Herbig was not among its adherents.

5.4.2 The Herbig-Petrov Model

Herbig first voiced his concern about the disk model in a review presented at an ESO workshop near Munich (Herbig 1989a). Here he reviews what is known about the FUors, discusses the disk model, and concludes that *"I am not completely comfortable with the accretion disk hypothesis so eloquently put forward and elaborated in a series of papers by HK and their co-workers. At issue is not whether some kind of flattened circumstellar structures exist around FUors (and TTS), – that I regard as highly likely – but whether the observations* demand *interpretation of the FUor phenomenon in terms of Lynden Bell and Pringle-type self-luminous accretion disks. I believe that other possibilities have not been ruled out, given the present state of the evidence and the fact that the disk hypothesis is not without its own difficulties."*

Much of Herbig's ensuing work on FUors was done in an important longterm collaboration with Peter Petrov of the Crimean Astrophysical Observatory. Petrov recalls his first trip to the United States in 1984:

“The visit was arranged within the scientific exchange program between the USSR and USA academies of sciences. The mid of the 1980s was at the peak of the cold war, and I was very surprised to see how friendly Americans were to the Russian visitor, not only in a scientific community but also the people on the streets I met every day. The final point of destination was Santa Cruz and Lick observatory, where I worked with George Herbig during two months. George suggested to measure the photographic and CCD spectra of FU Ori, taken by him at Lick Observatory. He said there was something strange with the photospheric line profiles: most of the lines looked double, like in a spectroscopic binary consisting of two identical G-supergiants. Of course, the hypothesis of a binary was weak: only one star could flare up by six magnitudes, not both. After careful analysis of the spectra we ended up with two hypotheses: either there were emission components present at the bottom of the broad photospheric lines, or the lines are formed in a luminous accretion disk. That result was not published immediately, however, since we planned to take one more spectrum. On the way back home I visited CfA and talked to Lee Hartmann about this effect of line doubling. Lee has recently written about this in his reminiscences in Star Formation Newsletter 260.

The accretion disk model of FUors is based mostly on the spectral energy distribution over a broad wavelength range, which undoubtedly belongs to a self-luminous disk. The difference in the optical and infrared line widths indicates the differential rotation of the inner and outer disk areas. In the work with George Herbig we focused on the *optical* spectrum of FUors, which belongs to the central object, whatever it was - a star or the innermost region of an accretion disk close to the star. It is interesting to note, that originally the argument in support of the accretion disk model was the dependence of the photospheric line width on wavelength and excitation potential of a line, as it was expected for a differentially rotating disk with a temperature decreasing outward. However, using the best quality CCD spectra of FU Ori, we did not find such a dependence within 4500-8000 Å.” [26]

Following this visit, Herbig traveled in 1987 to Ukraine where Petrov hosted him at the Crimean Astrophysical Observatory and they continued their collaboration (Figure 68). Over a period of 17 years, Herbig and Petrov published three papers with high-quality data, dealing with their concerns about the disk model while refining their own interpretation.

In the first paper (Petrov & Herbig 1992), it was demonstrated that

> *“the double absorption lines observed in FU Ori and other members of the group, which have been claimed to be the signature of a self-luminous Keplerian disk, can be produced equally well by a [...] model consisting of an*

Figure 68: *Herbig with Roald Gershberg (middle) and Peter Petrov (right) at the Crimean Observatory in 1987.*

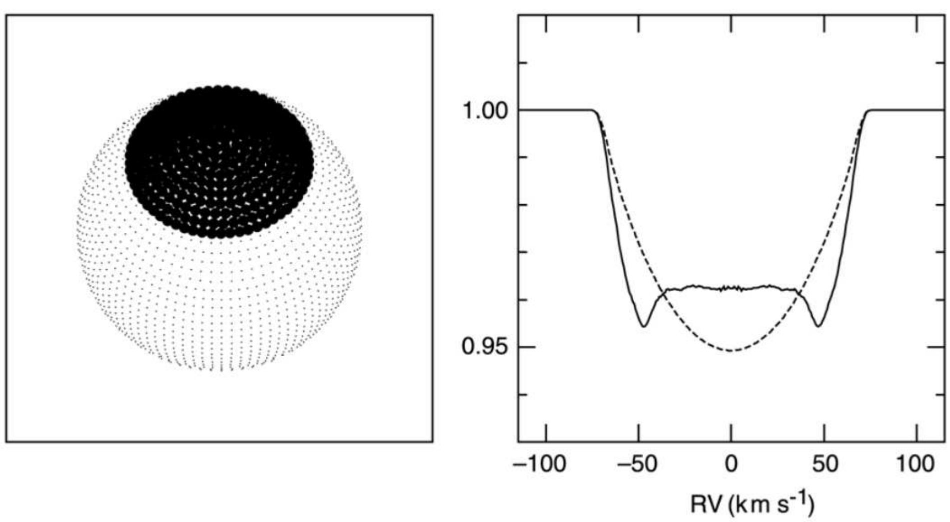


Figure 69: *(left): Model of a star with a black polar spot. (right): typical line profile of a star with (solid) and without (dashed) a polar spot. From Petrov & Herbig (2008).*

emission-line shell overlaid by a cooler absorbing layer, the two superposed upon a macroturbulent G-type supergiant spectrum. In this model, the appearance of line doubling is due to the appearance of weak emission cores in the metallic absorption lines, while curve-of-growth effects account for the observed dependence of reversal intensity upon absorption line strength."

On the observational side, direct support for this concept was provided by the existence of similar double lines in certain high-luminosity stars (e.g., ρ Cas and RW Cep), in which there is no reason to think that a disk exists. Theoretically, the idea of a bloated star as the source of the FUor characteristics was first proposed by Larson (1980), who suggested that the outer layers of a star could expand if they gained a thermal energy comparable to the kinetic energy it would have in rapid rotation.

In their second paper (Herbig, Petrov, & Duemmler 2003), a massive set of high-resolution spectra of FU Ori and V1057 Cyg was analyzed, and it was concluded that *"a rapidly rotating star near the edge of instability, as proposed by Larson, can better account for these observations. The possibility is also considered that FUor eruptions are not a property of ordinary T Tauri stars but may be confined to a special subspecies of rapidly rotating pre-main sequence stars having powerful quasi-permanent winds."*

In their third paper (Petrov & Herbig 2008), it was found that the flat-bottomed line profiles seen in numerous metallic lines in FU Ori could be reproduced with a star having a dark polar spot (see Figure 69). The spectra used in their study were all optical, so they asked the question: *"What is it that is seen in the optical region, a central star or an inner accretion disk?"* In summary they found that:

"(1) all weak photospheric lines have the same line width and profile, as expected for a rigidly rotating body, but in definite conflict with prediction for the self-luminous Keplerian disk model; (2) those profiles can be explained if the central object is a rapidly rotating high-luminosity star with a dark polar spot; and (3) there is no sign of the line doubling, or the dependence of line width on wavelength (in the optical region) that is expected for the disk model.

Do these results undermine the self-luminous accretion disk hypothesis in a significant way? No, but they do demonstrate that some modification is in order. It is remarkable that the hypothesis still stands even though two of the strongest observational arguments that were originally urged in its favor are now seen, in the case of the prototype, to be invalid."

Herbig continued to study other aspects of FUors, but did not again address the controversy over the interpretation of the nature of FUors. In his autobiographical notes, he refers to the divergence of opinions between him and Lee Hartmann:

> *"By 1989, many papers on the FUor phenomenon had appeared, especially by Lee Hartmann and Scott Kenyon and their associates at Harvard. I tried to review the situation as I saw it at a Munich workshop in that year, in particular expressing my reserve about the Hartmann-Kenyon proposal that the FUor spectrum originates not in a star at all, but in a self-luminous accretion disk. Of course, by 1989 the idea of disk accretion as a solution to all the problems of TTS had become almost a frenzy, and any skepticism was looked upon as heresy by the faithful. The pro-disk people were persuaded, for example, that an incipient doubling seen in the absorption lines of FU Ori and V1057 Cyg was indisputable evidence of an inclined Keplerian disk. I claimed at Munich, and later Peter Petrov and I (1992) pursued the argument in more detail, that such line doubling could be produced equally well in ways having nothing to do with an orbiting disk. In fact some high-luminosity G stars exhibit just such line doubling, and in those cases it is clearly an atmospheric phenomenon.*
>
> *My blood pressure is affected not at all by this controversy. All that I can usefully say has by now been put into print, and I have no intention of pursuing the matter any further, unless some new idea should strike me. This little war has been waged very politely on both sides, and of course both camps are quite unmoved by the arguments of the other. The issue will certainly be settled one day, if in no other way by the departure of one of the contestants (me) from the scene.*
>
> *I am certainly not against circumstellar disks: the nature of accumulation of material containing angular momentum into a small volume shows that some kind of flattened structure is inevitable. Perhaps I was the first, or one of the first, to argue that there is clear observational evidence for such a disk in the case of Minkowski's Footprint* [Herbig 1975b]*, and less directly in the case of VY CMa* [Herbig 1970a]*."*

5.4.3 A Hybrid Scenario

Controversies abound in science, and all too often they are accompanied by highly personal loathing. In contrast, the discussions, via numerous letters and emails, between Herbig and Hartmann were always carried out with the utmost civility. In fact, despite their inability to agree on the FUor phenomenon, the two had a warm personal relation (Figure 70), and Herbig often privately expressed his great admiration for Hartmann.

So who won the argument? There is little doubt that the disk hypothesis has been extremely successful in explaining a wealth of observations, and that it

Figure 70: *From right: Nuria Calvet, George Herbig, Lee Hartmann, and Bo Reipurth at the home of Herbig in 2003. Discussions about FUors between Herbig and Hartmann were always conducted in an amicable atmosphere.*

is widely accepted in the community. Yet the question may be inaccurately posed, since we still know far too little about the FUor phenomenon. The Indian parable of the blind men and the elephant comes to mind: "Six blind men were asked to determine what an elephant looked like by feeling different parts of the elephant's body. The blind man who feels a leg says the elephant is like a pillar; the one who feels the tail says the elephant is like a rope; the one who feels the trunk says the elephant is like a tree branch; the one who feels the ear says the elephant is like a hand fan; the one who feels the belly says the elephant is like a wall; and the one who feels the tusk says the elephant is like a solid pipe. A king explains to them: 'All of you are right. The reason every one of you is telling it differently is because each one of you touched a different part of the elephant. So, actually the elephant has all the features you mentioned'." [27]

Herbig and Petrov studied FUors with optical data while Hartmann and collaborators mostly studied them in the infrared. It is conceivable that some time in the future it will be found that both are right. Specifically, we know almost nothing about what happens to a star when it suffers the massive accretion of material that is dumped onto it from the inner disk edge. We know that accretion columns from a disk to a T Tauri star has clearly observable effects on the star, so it does not seem farfetched to assume that accretion on a vastly larger scale will expand the star greatly, making it much more luminous than the progenitor T Tauri star, thus resembling a bloated supergiant star. Indeed, recent calculations of episodic accretion onto low-mass protostars suggest that, for sufficiently high accretion rates, the central star may expand significantly, thus increasing its luminosity far beyond the expectation based on its mass and age (e.g., Hosokawa et al. 2011, Baraffe et al. 2012). And the injection of angular momentum from the disk will create a rapidly rotating brighter equatorial region, making the star appear relatively darker towards the polar regions, thus mimicking the polar spot suggested by Petrov and Herbig. In fact, for such a coupled system it may be almost a semantic question what is called a star and what is called an inner disk. So some kind of hybrid model, combining elements of both the Hartmann-Kenyon scenario and the Herbig-Petrov scenario, may in the future reconcile the two opposing views discussed here.

5.5 The Winds of FUors

FUors have powerful, cool winds, which manifest themselves as several hundred km wide absorption troughs at the lower Balmer lines, the Sodium doublet, the Calcium triplet, the H & K lines, and other strong lines. Herbig demonstrated that this is a characteristic of all FUors observed at high enough spectral resolution and clearly different from the outflows found in T Tauri stars.

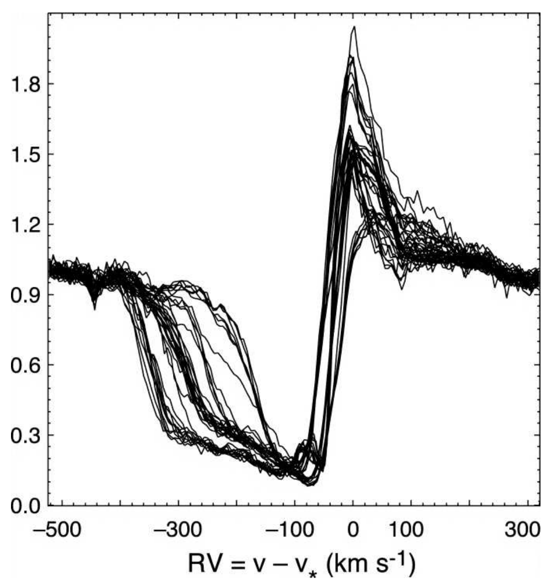


Figure 71: *Variability of the Hα line of V1057 Cyg in 1996-2001. From Herbig et al. (2003).*

Using the Keck I telescope with the HIRES spectrograph, Herbig obtained high resolution spectra of all known FUors, and in particular monitored FU Ori and V1057 Cyg (e.g., Herbig 2009a). In a major study, Herbig et al. (2003) found periodicities of 3.5 and 14 days in the outflowing wind in FU Ori. These periods were later confirmed by Powell et al. (2012), thus showing that the variability mechanism must be stable over at least a decade. Such data constrain the size of the wind acceleration region to $\sim$10 $R_\odot$.

Figure 71 shows a sequence of Hα line profiles of V1057 Cyg in the period 1996-2001 from Herbig et al. (2003). The terminal wind velocity is evidently strongly variable in the approximate range 150 to 350 km s^{-1}. This is highly supersonic, but Herbig-Haro objects are generally not found in association with FUors, suggesting that FUors in most cases have lost the collimation mechanism that can turn the winds from T Tauri stars into collimated shocked jets.

Modelling of line profiles allows the determination of FUor mass loss rates, which are found to be typically in the range 10^{-6} to 10^{-5} $M_\odot$ yr^{-1} (Croswell et al. 1987, Calvet et al. 1993, Hartmann & Calvet 1995), that is, several orders of magnitude larger than for T Tauri stars.

5.6 Triggering the FUor Outbursts

A number of ideas have been forwarded to explain the triggering of FUor outbursts, and they can be broadly divided into four categories. The first involves a throttle mechanism that controls the passage of gas through the inner disk (e.g., Hartmann & Kenyon 1996, Zhu et al. 2009). The disk receives gas from an infalling envelope, but it is not evident that the disk can transfer the gas inwards through the disk at precisely the same rate with which it falls in, thus leading to material piling up in the disk, and eventually a re-adjustment that leads to an eruption (Figure 72). The second is based on the assumption that the energy generated in a viscous disk must be balanced by radiative losses in order to remain in thermal equilibrium. When perturbations are applied to a disk that lead to higher disk temperatures then the disk may under some circumstances just radiate more and remain stable. But if the opacity of the gas in the disk rises sufficiently fast with temperature then heat becomes trapped within the disk and a runaway situation develops until the opacity dependence on temperature changes again. Such thermal instability models have been explored by many groups, including Bell & Lin (1994) and Armitage et al. (2001), and other types of instabilities have been invoked as well. The third mechanism to drive accretion involves a companion in an eccentric orbit that perturbs the disk at periastron (Bonnell & Bastien 1992, Reipurth & Aspin 2004a). Perturbations by a planet (Clarke et al. 2005)

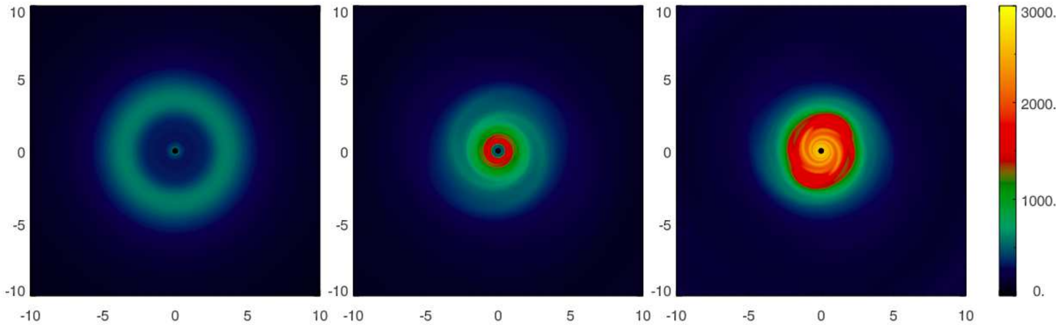


Figure 72: *Simulations of an accretion outburst in a disk. The figure shows the midplane temperature (color scale on right) during the quiescent phase (left), at the onset of the outburst (middle), and at the peak of the outburst (right). The figures are 20 AU across. From Bae et al. (2014).*

or with another member of a dense cluster (Pfalzner 2008) have also been considered. Finally, the fourth idea revolves around the accretion of a large body, e.g. a planet (Larson 1980) or a large 'gas blob' in a circumstellar disk (Vorobyov & Basu 2015), which would cause a major energy release.

We tend to simplify the interpretation of a complex phenomenon by assuming that all observed cases can be explained in the same way. But there is no particular reason why all FUor outbursts necessarily must be triggered the same manner. Once perturbed, the number of ways a disk can react is limited and in all cases will involve a brightening and subsequent decay. As Herbig already demonstrated in his 1977 paper, there are differences between the observed light curves of the known FUors, so one might envisage several different mechanisms at work leading to similar overall observational characteristics but with differences in their details. Only detailed studies of as many cases as possible are likely to resolve such questions.

In his 1977 paper, Herbig stated hopefully that *"not only should new examples erupt, but perhaps some past events that were overlooked can be detected in T Tauri-rich regions on old photographs."* With time, both of these predictions were borne out, but exceedingly slowly, and Herbig often wondered why more cases were not found. Finally, in the last few years of his life, he was gratified to see that many new FUors were discovered, mainly from a group that no one would have predicted, namely advanced amateur astronomers (Figure 73). With the emergence of cheap CCD cameras, many amateurs have taken to image large swaths of the Milky Way, and some compare their images with previous ones, allowing the occasional discovery of a new FUor. Herbig was thrilled when the young amateur Ian McNeil in 2003 discovered a FUor in Orion (Reipurth & Aspin 2004b, see Figure 74), the first of the amateur discoveries.

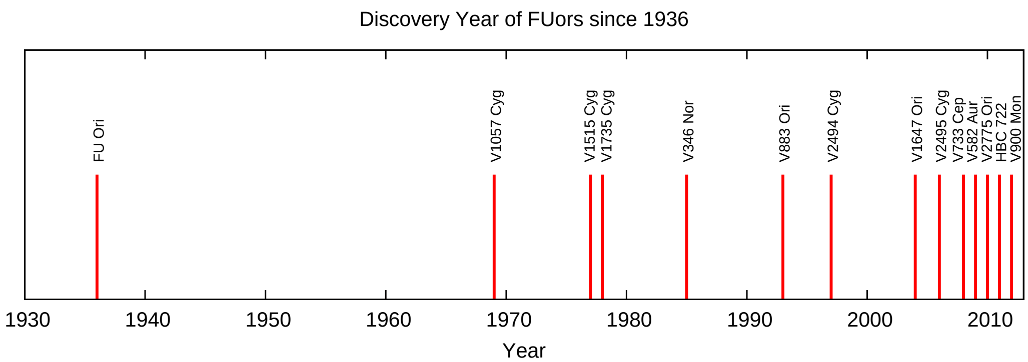


Figure 73: *The number of FUor discoveries has been increasing since the FU Ori outburst was observed in 1936.*

Figure 74: *The FUor V1647 Ori erupted in 2003, and was discovered by the young amateur astronomer Ian McNeil. Image taken with the Gemini 8m telescope. From Reipurth & Aspin (2004b).*

Evidently FUors may hold critically important clues to the way stars build up their masses, in fact it is conceivable that as much as half the mass of a star could be accumulated in eruptive events. Despite their rarity on human timescales, FUor outbursts may therefore hold the key to an understanding of how stars form and assemble their masses and thus define the initial mass function.

5.7 EX Lupi and the EXors

In his 1977 paper on the FUor phenomenon, Herbig asked the question: *"Can vestiges of the phenomenon be found in other stars?"* In reviewing the erratic variability of numerous T Tauri stars, Herbig singled out three stars, primary among them the unusual variable EX Lupi. The star was known for its occasional fitful outbursts, especially a major outburst in 1955-56 (Figure 75), and was suspected to be a nova. But already in one of his earliest studies, Herbig showed that EX Lup was likely to be an unusual T Tauri star, not a nova (Herbig 1950c). At minimum light (V∼13.2), EX Lup shows an M0 V absorption spectrum with an emission spectrum superposed with emission lines of H, He I, He II, Ca II, Fe II, etc. No spectrum exists from the 1955-56 eruption, and in 1977 Herbig concluded that while EX Lup could show eruptions with almost the same major amplitude as the FUors, albeit of much shorter duration, the step *"to claim that these relatively active small-range variables are driven by the same phenomenon that one sees on a larger scale in the FU Ori variables, cannot be taken."* Much more detailed studies would be needed.

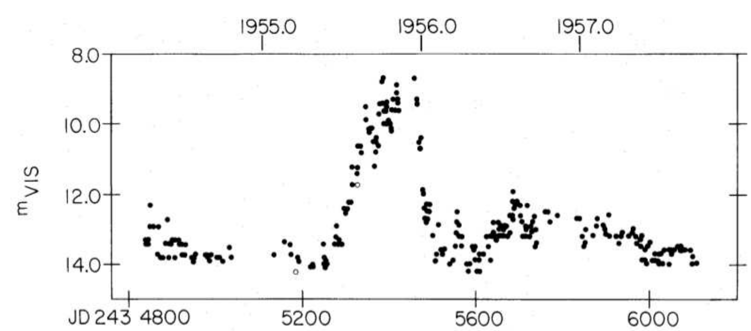


Figure 75: *The 1955-56 maximum of the EXor EX Lup. Visual estimates by Bateson & Jones (1957). From Herbig (1977).*

The 1955-56 outburst of EX Lup was discovered and charted through visual observations by the New Zealand amateur astronomer Albert F. Jones, who during half a century assiduously monitored this star. He and Herbig corresponded over the years, and both waited impatiently for the next outburst

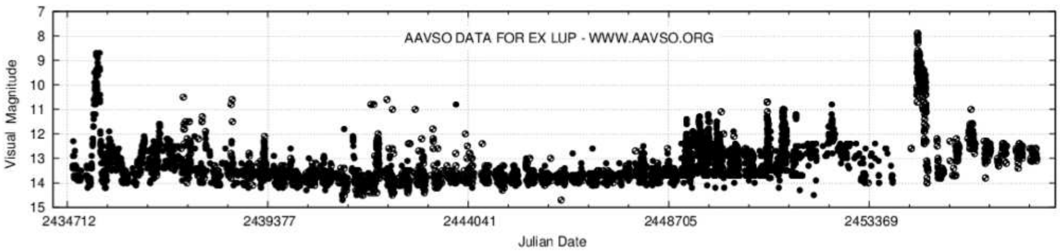


Figure 76: *The light curve of EX Lupi from 1954 to 2015 based on visual estimates by AAVSO observers.*

to take place. Eventually, in 1993-94 EX Lup was finally brightening again, although with only milder activity, and Herbig, Jones and collaborators assembled as much photometric and spectroscopic data as possible on this event, despite its relative weakness. At outburst, a blue continuum appeared which veiled the absorption spectrum and partly 'drowned' the emission lines (Herbig et al. 2001, see also Lehmann et al. 1995). But then on June 22, 1998, Herbig was notified by Albert Jones that EX Lupi again had gone into eruption, this time displaying much more activity (Figure 76). Herbig was able to get a high-resolution spectrum already the night after, thanks to his former student Ann Boesgaard who was observing with HIRES at the Keck I telescope. This was the first in a series of HIRES spectra that Herbig obtained of EX Lupi, although in the coming years the star would be fainter and less active.

The 1998 spectrum showed that

> *"a large number of narrow, slightly asymmetric emission lines of He I, He II, Fe II, Fe I, Ti II, Mg II, Cr II, and Si II were present. Notably, the [S II] lines at 6716 and 6730 Å, which are considered an outflow signature, were not detected on this or on subsequent HIRES spectra. The stronger Fe II and Ti II lines were clearly composite (Figure 77): the narrow component at the stellar velocity was superposed on a broader line [BC] displaced 10-20 km s^{-1} shortward. [...] Investigators of TTS spectra have suggested that the BC of the emission lines is formed by gas in the accretion funnel flow (Edwards 1997; Beristain et al. 1998; Najita et al. 2000). If so, the negative velocity shift of the BC (observed in EX Lup and in many TTSs) is puzzling; see the comments by Alencar et al. (2001). In the case of DR Tau, Symington et al. (2005) explain it as being produced by the in-falling gas on the far side of the star, the near side being concealed by the disk. [...] Longward of many of the stronger Fe II and Ti II lines on the 1998 spectrum are broad, asymmetric 'reverse P Cyg' absorption components with minima at +320 to +340 km s^{-1}. [...] In 1998 Hβ was flanked longward*

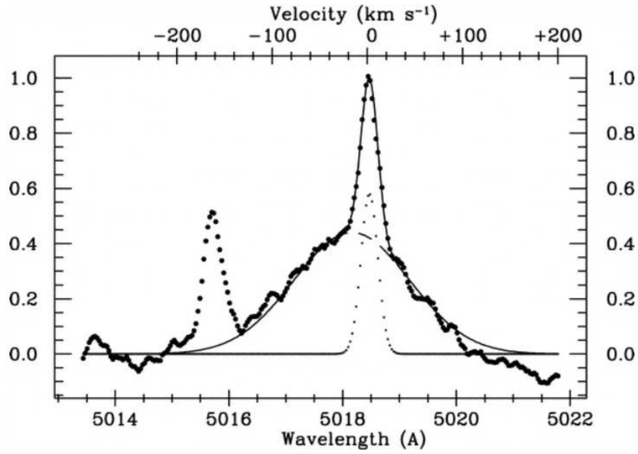


Figure 77: *Fe II λ5018 line in EX Lup on 1998 June 23, decomposed into two Gaussians. From Herbig (2007).*

> *by an absorption component at +340 km s^{-1} that had disappeared by 2002. [...] These displaced absorptions provide clear evidence of infall"* (Herbig (2007).

Despite the high-quality data Herbig was working with, he was dissatisfied that many issues remained unresolved, and concluded the paper with the self-deprecating comment that it *"is possible that the larger picture is only confused by observational minutiae such as those detailed in this paper. Certainly, the issue deserves more critical observations or deeper insight."*

In 2008, EX Lup underwent its largest outburst ever recorded, reaching a visual magnitude of 8, and lasting for 7 months (Figure 76). Herbig was pleased to find that this triggered great activity among a younger generation of astronomers, resulting in a flood of studies (e.g., Aspin et al. 2010, Kóspál et al. 2011, Goto et al. 2011, Banzatti et al. 2012, Teets et al. 2012).

While EX Lup is a particularly fine example it is by no means the only star with major eruptions that last for months to a few years. In 1989, when Herbig gave the previously mentioned review talk at an ESO workshop in Munich, he assembled a list of eruptive variables which had certain features in common with EX Lup, and which he consequently dubbed EXors, to distinguish them from the FUors while at the same time indicating that they also represent a phenomenon whose main characteristic is high-amplitude outbursts. The EXor class is somewhat heterogeneous, but in broad terms the members have a photometric behavior with outbursts typically lasting a year or less and optical amplitudes sometimes approaching those of FUors. These events are followed by periods of quiescence lasting from several years to several decades. Spectroscopically the EXors often show strong and rich emission line spectra during quiescence, sometimes also revealing a photospheric spectrum, but during outbursts both emission and absorption lines are weakened or drowned out by a luminous continuum. However, somewhat to the exasperation of observers, EXors not always follow this behavior, sometimes quiescent spectra are rather featureless, while rich emission appears during outbursts.

In the years following the Munich workshop, Herbig's work on EXors mainly focused on EX Lup itself, as discussed above, but in 2004 he embarked on a detailed study of 3 other EXors (Herbig 2008), namely NY Ori, V1118 Ori, and V1143 Ori, while eventually dismissing two other candidates as EXors: V1184 Tau and V350 Cep. This was the first high-resolution spectroscopic study ever of EXors other than EX Lupi. Two of the stars from the 2008 paper are briefly described in the following.

NY Ori. During his extended visit to Yerkes Observatory as a postdoc in 1948/49, Herbig examined archival plates obtained of the Orion Nebula between 1905 and 1919 with the 40-inch refractor. In addition to many known variables he also discovered a new variable which later became the famed EXor NY Ori. While subsequently observing at McDonald Observatory with Otto Struve (Section 1.6) he took a spectrum of this new star[28] and noted its strong emission in the Balmer lines and its heavy veiling (Herbig 1950b). In his 2008-study, Herbig used HIRES on the Keck-I telescope to study the line profiles of NY Ori. A faint early K-type spectrum was apparent, and superposed by a rich emission line spectrum. The most notable feature of the spectrum are redshifted absorption troughs at many but not all of the emission lines, spanning velocities up to 150 – 250 km s^{-1}. An example is shown in Figure 78. Evidently the star was at the time subjected to strong accretion.

V1118 Ori. This star is among the more active EXors, with rather frequent outbursts. Herbig obtained a HIRES spectrum of V1118 Ori while it was bright but not quite at maximum light, and noted a rich emission line spectrum of hydrogen and neutral and ionized metals. Evidence for supersonic outflowing neutral winds can be seen as blueshifted absorption troughs at the Sodium doublet lines (Figure 79). Herbig noted that if such outflowing material was in a shell it would be transient, since the absorbing column density at these high velocities would rapidly decrease on a time scale of days. The most amazing feature of the HIRES spectrum is that the lithium λ6707 line is in emission, as already discussed in Section 2.8 (see Figure 26).

EXors are increasingly attracting the attention of the astronomical community. The importance of obtaining spectra during both quiescence and outburst has

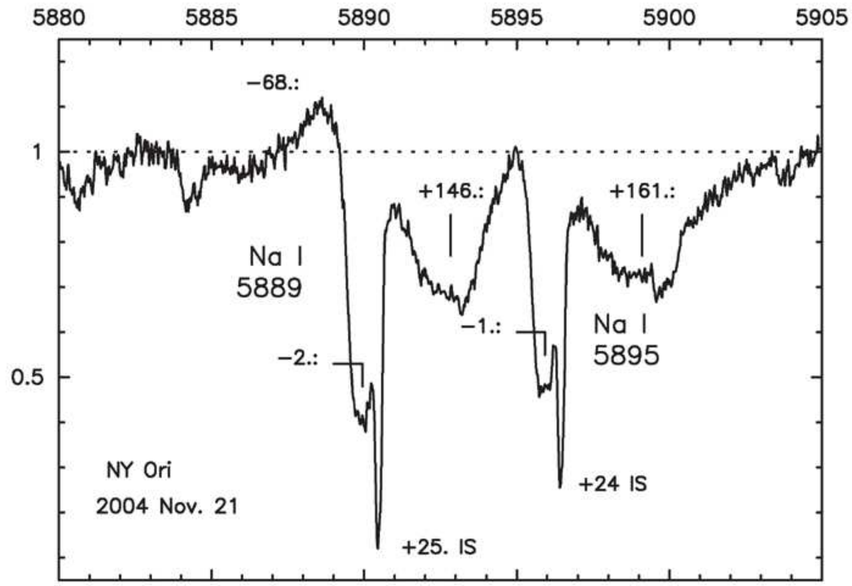


Figure 78: *The Sodium doublet in the EXor NY Ori. Pronounced redshifted absorption features are present, indicating an ongoing massive infall event. From Herbig (2008).*

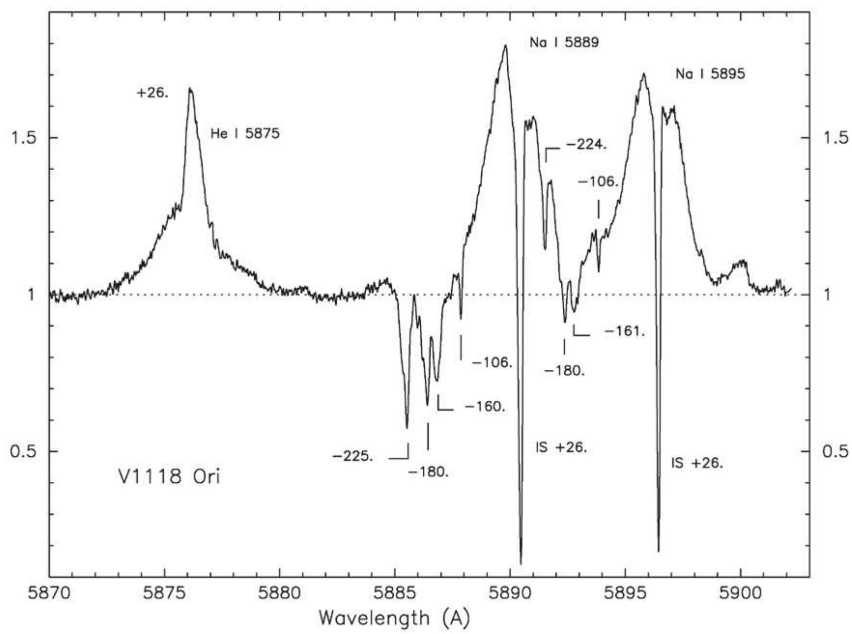


Figure 79: *The He I λ5875 and the Sodium doublet in the EXor V1118 Ori near maximum light. Blueshifted absorption features indicate that high-velocity mass loss is taking place. From Herbig (2008).*

been recognized, and optical and infrared spectroscopic monitoring is now being carried out (e.g., Lorenzetti et al. 2009, Sicilia-Aguilar et al. 2012), casting light on the variable accretion processes that drive these eruptions, which can be interpreted as more powerful versions of the magnetospheric accretion models that describe conventional T Tauri accretion (Figure 80). A particularly noteworthy comparison between quiescent and outbursting spectra was done by Ábrahám et al. (2009), who used the Spitzer Space Telescope to study the mid-infrared spectrum of EX Lup, and found that during the 2008 eruption the silicate line profile between 8 and 12 μm changed shape corresponding to a transformation of amorphous grains to crystalline grains. Specifically, it appears that forsterite, the Mg-rich form of olivine, dominates the crystal population. This is a transformation that cometary material is known to have undergone, and the observations of EX Lup suggest that it may have happened in comets via thermal annealing in the surface layer of the inner disk by heat from an EXor-like outburst.

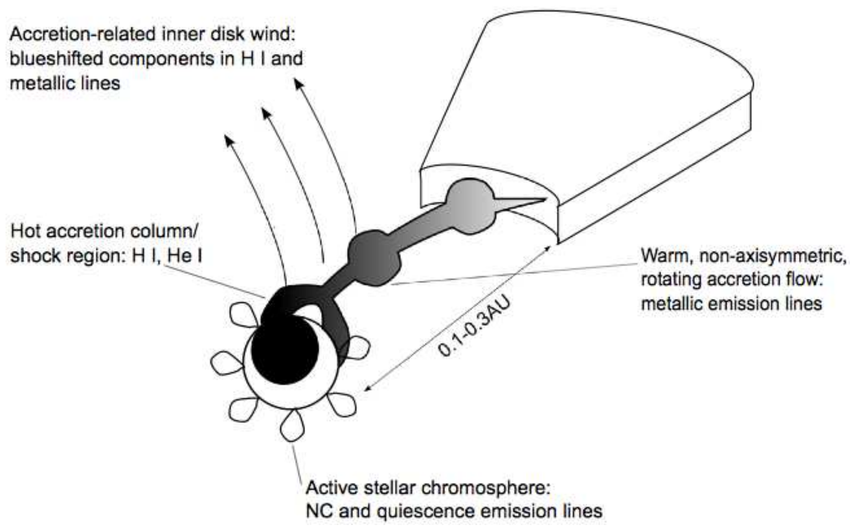


Figure 80: *A possible morphology for the accretion flow from the inner disk edge towards EX Lup, based on time series spectroscopy of the star. From Sicilia-Aguilar et al. (2012).*

The EXor class is heterogeneous and apart from the "classical" EXors (EX Lup, NY Ori, V1118 Ori, V1143 Ori), arguments for and against membership can be made for many other objects included in the category. Herbig himself was aware and concerned about this:

> *"The original list of candidates (Herbig 1989a) was simply a list of variables that exhibited large-range outbursts and displayed spectra like those of*

T Tauri stars (TTSs) at maximum light. At that time, only fragmentary information was available for some of these objects, so the defining characteristics of the class came, by default, to be dominated by what was known of the prototype, namely, that the outbursts of EX Lup are repetitive, its spectrum does not show the shortward-displaced outflow signature at Hα so striking in FUors, Li I λ6707 is prominent, and at minimum it is an M-type dwarf of modest v_{eq} *sin* i. *But that original list also included active classical TTSs (CTTSs) such as DR Tau, which are variable on both short and long timescales and clearly are not quiescent between occasional flare-ups, and so are not EXors in the sense of those criteria. It remains to be determined how many stars actually behave like EX Lup, and whether they can be recognized spectroscopically"* (Herbig 2007).

More candidate members of the class continue to be found (Figure 81), but also outbursting objects that do not readily fit into neither the FUor nor EXor boxes (e.g., Hodapp et al. 1996, Covey et al. 2011). The study of FUors and EXors and even their definition is a work in progress.

Figure 81: *The FUor V900 Mon was discovered by the amateur astronomer Jim Thommes. The left image shows a 10 × 10 arcmin field from the POSS-I atlas from 1953, and the right image shows Jim Thommes' discovery image taken in 2009. V900 Mon is the central object surrounded by a complex reflection nebula. From Reipurth, Aspin, Herbig (2012).*

6 CLUSTERED STAR FORMATION

Most stars are formed in clusters, small or large, and naturally Herbig would be attracted to such groups, even though much of his work dealt with more detailed studies of individual stars. Herbig got involved with the question of cluster formation in the late 1950s and early 1960s when he tried to argue against the then prevailing idea that stars in clusters would be coeval, having formed simultaneously in a cataclysmic event:

> *"It is proposed that [...] the formation of a cluster or association is a very gradual process in which less massive stars are formed over a long interval in a massive dark cloud, from which most are unable to escape. This gradual buildup of the lower and middle parts of the luminosity function within the cloud continues until a high-luminosity O or very early B-type star forms. The radiation of this star heats the cloud in its neighborhood so as to ionize the hydrogen, evaporate nearby dust, and induce a degree of kinetic and turbulent activity that largely puts an end to ordinary star formation in that volume, although it may trigger the formation of additional large-mass stars in the immediate neighborhood"* (Herbig (1962b).

Herbig envisaged that cluster formation could spread out over perhaps as much as a hundred million years, but this is much more than what is determined today, where age spreads for the majority of stars in clusters are found to be typically no more than a few million years, with a small tail-end of stars with ages up to 5-10 Myr, suggesting that star formation in a cloud is a rapid process (e.g., Elmegreen 2000, Hartmann 2001, Jeffries et al. 2011). But Herbig's idea that cluster formation is largely halted by the birth of massive stars is widely accepted.

6.1 The Orion Nebula Cluster

Following his early work on the faint red variables of the Orion Nebula Cluster (ONC), already described in Section 1.6, Herbig returned to this rich cluster in the early 1980s (Figure 82).

> *"My only serious venture into stellar photometry was made in collaboration with Don Terndrup, then a graduate student and my research assistant at Lick. Conventional spectroscopy and photometry is confounded by the brilliant H II nebulosity around the Trapezium stars, but it is possible to work effectively in some spectral windows between emission lines. Again, it was Walter Baade who drew my attention to this opportunity, although he in-turn picked it up from Trumpler's early work at Lick. Baade showed me his plates in yellow light, and with the then-exotic Kodak U emulsion, both of which worked in regions between the stronger nebular lines, and which*

as a consequence permitted exposures to be extended to much fainter cluster stars. Baade and Minkowski in 1937 had written a fascinating paper on the Cluster which foreshadowed much of what came later. I elaborated on this work with the aid of near-infrared[29] *direct plates that I had taken at the 120-inch prime focus. These confirmed the remarkably high star density of the Cluster; these results were reported at the Henry Draper Symposium*[30] *in 1982 [Herbig 1982]. Following this, in a slight elaboration of Baade's photographic technique, I ordered some special interference filters whose yellow and near-infrared passbands fit between nebular emission lines and also lay near the effective wavelengths of Cousin's V and R colors. With these, and a then-very-new CCD camera at the Lick Nickel (40-inch) telescope, Terndrup and I determined a V,V-I color-magnitude diagram for stars in the brightest part of the Orion Nebula."*[1]

The ONC is nowadays so well studied photometrically (and spectroscopically, for a detailed review of the ONC literature see Muench et al. 2008) that it is hard to imagine that prior to the study of Herbig & Terndrup (1986) there existed no accurate color-magnitude diagram of the cluster because the severe background problem had frustrated all observers until CCD arrays became available. Herbig and Terndrup proceeded to superpose onto the color-magnitude diagram new evolutionary tracks calculated by D.A. VandenBerg for ages of 10^6, 4×10^6, and 10^7 yr. After reddening corrections, they found that *"the majority of the cluster members fall youngward of the* 1×10^6 *yr isochrone, and most of the remainder have ages* $\lesssim 4\times10^6$ *yr. Furthermore, the slope of the reddening line is such that, regardless of the amount of their extinction, few of the remaining stars could be shifted into a region [of the diagram] that is oldward of the* 1×10^7 *isochrone."*

Considering only the area within the approximate boundary of the brighter nebulosity seen in images of the cluster (Figure 83), Herbig and Terndrup derived the remarkably high star density of $\sim$2200 stars pc^{-3} for stars brighter than an absolute I-magnitude of $M(I_C)=+6.0$. Such a star density is much higher than found for ordinary galactic clusters; however, both stellar evolution as well as dynamical evolution as a result of gas removal will eventually make the cluster members fainter and spread them over a larger cluster radius, making the cluster a much less spectacular object than today.

Herbig had previously pointed out (Herbig 1983) that *"the high star density in the Trapezium cluster means that close encounters between cluster members are relatively frequent, and that such encounters must affect the distribution of circumstellar material about such stars."* For realistic input parameters, it was found that after $\sim1.6\times10^6$ yr some 10% of the cluster members would have suffered at least one encounter closer than 100 AU. *"Clearly, many stars*

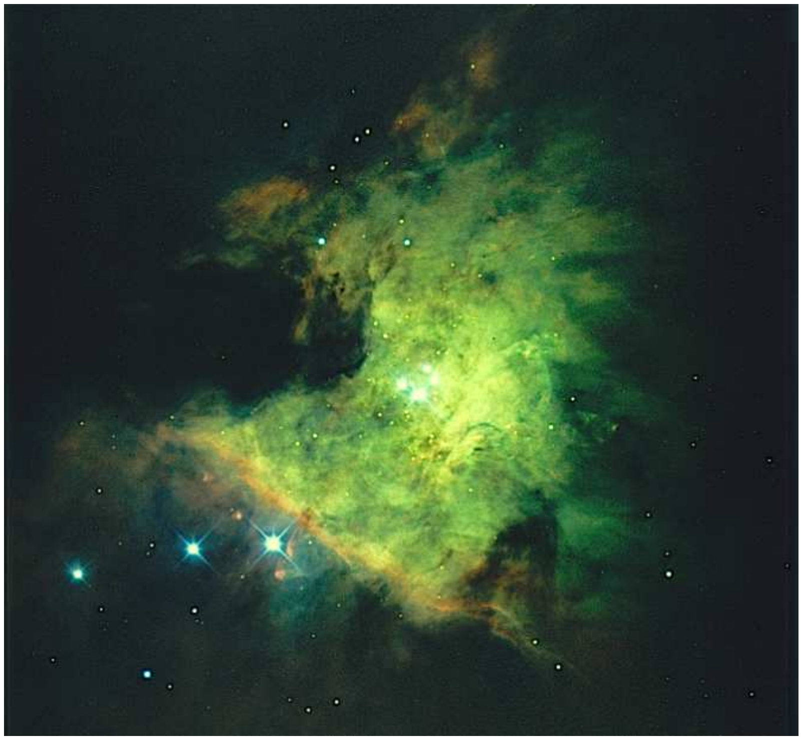


Figure 82: *The central region of the Orion Nebula surrounding the Trapezium based on interference filter photographic plates obtained at the prime focus of the Lick 120-inch reflector. North is up and east is left. From Herbig (1971b).*

Figure 83: *A near-infrared image of the central Orion Nebula Cluster obtained with J,H,K filters. These filters enhance the view of the embedded stellar cluster. The area shown corresponds to the area studied by Herbig and Terndrup. Courtesy ESO.*

that originate in such dense clusters and are subsequently released into the field will have had any residual circumstellar material that they might originally have possessed quite drastically rearranged." With modern computational techniques these results have been confirmed and refined (e.g., Vincke et al. 2015).

Herbig and Terndrup concluded their paper by stating that *"We wish to stress that we regard this investigation of the Trapezium cluster as a first reconnaissance, which shows the directions that future work must take."* Their work has indeed been followed by intense efforts in the past 30 years, culminating in major, detailed studies of the ONC with the Hubble Space Telescope (Robberto et al. 2013).

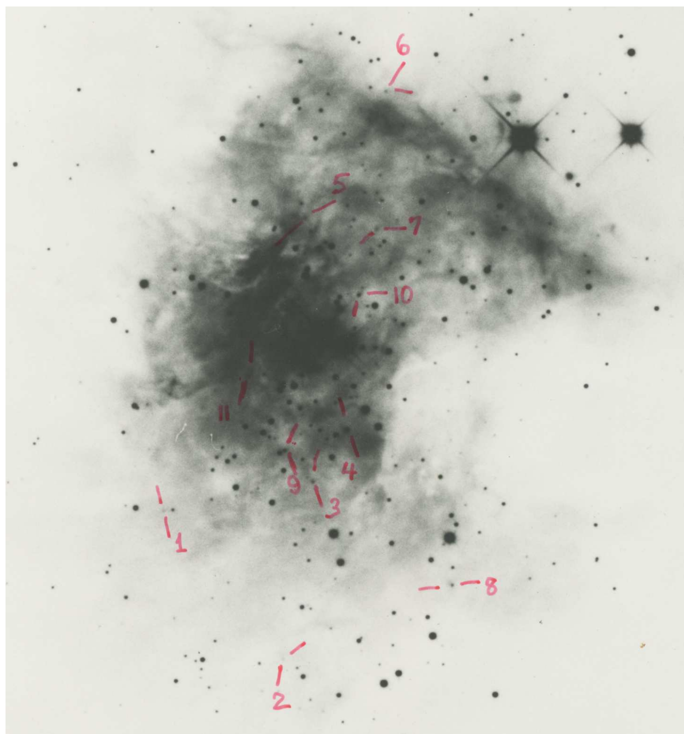


Figure 84: *A print of the center of the Orion Nebula found among the papers left behind by Herbig. This is from a photographic plate taken in the 1960s at the prime focus of the 120-inch reflector. Marked are 11 small nebulous objects, which include the brightest of what is now known as the Orion proplyds. North is down and east is right.*

The newborn low-mass stars that are closests to the Trapezium are subjected to brutal ultraviolet irradiation, especially from θ^1 Ori C. As a result their circumstellar environment gets photoionized, resulting in a luminous halo surrounding these nascent stars. The first such nebulous objects were detected by

Laques & Vidal (1979), although their true nature was not recognized at the time. It took the Hubble Space Telescope to reveal that they were young stars with photoevaporating circumstellar disks, dubbed 'proplyds' (for protoplanetary disks) by O'Dell et al. (1993) and O'Dell & Wen (1994). These objects have now been imaged in great detail and their structure and rapid evolution is well understood (e.g., Bally et al. 1998).

As a historical aside, among the voluminous documents Herbig left behind is a folder with a print from photographic plates that Herbig had taken in the 1960s with the 120-inch prime focus camera. Marked on the print are 11 small nebulous objects (Figure 84) together with notes that copies had been sent to the infrared astronomer Gerry Neugebauer in 1968 and to the German radio astronomer Peter Mezger in 1969. Evidently Herbig was curious about these objects, but realized that the equipment available at Lick would not reach such optically faint objects, and he must have concluded that they should be studied at infrared and radio wavelengths. Nothing came of this, and Herbig did not pursue the matter any further. From notes in the folder one can see that Herbig later realized that many of these objects are among the brightest of the Orion proplyds.[31]

6.2 IC 348

When Herbig was 78 years old, an age when most people are long retired, he embarked on a major systematic study of young clusters, soon to be joined by his student Scott Dahm, and clustered star formation was to be his prime interest for the following 14 years. The first in a series of five major papers dealt with IC 348. This is a small cluster with a radius of about 4 arcmin or 0.37 pc, partly embedded in the dense molecular filaments that also contains the well known young cluster NGC 1333. The brightest member of IC 348 is BD +31°643, which is also part of the Per OB2 association. Early on, Herbig (1954a) surveyed IC 348 for Hα emission stars, and found 16 such objects. That study *"played a significant conceptual role in the early history of star formation studies because it encouraged the belief that TTSs must also be young, in fact about the age of the OB association"* (Herbig 1998, see also Section 2.4).

In the new study, Herbig found 110 Hα emission stars, using the Wide Field Grism Spectrograph and a CCD detector at the 2.2m telescope on Mauna Kea (see Section 2.5). This setup readily detects Hα emission with equivalent widths down to about 3 Å. Using the conventional distinction that WTTS have W(Hα) less than 10 Å and CTTS have values larger than that, Herbig identified 58 WTTSs and 51 CTTSs (a few stars had variable equivalent widths), and their distribution is shown in Figure 85a. Herbig further ob-

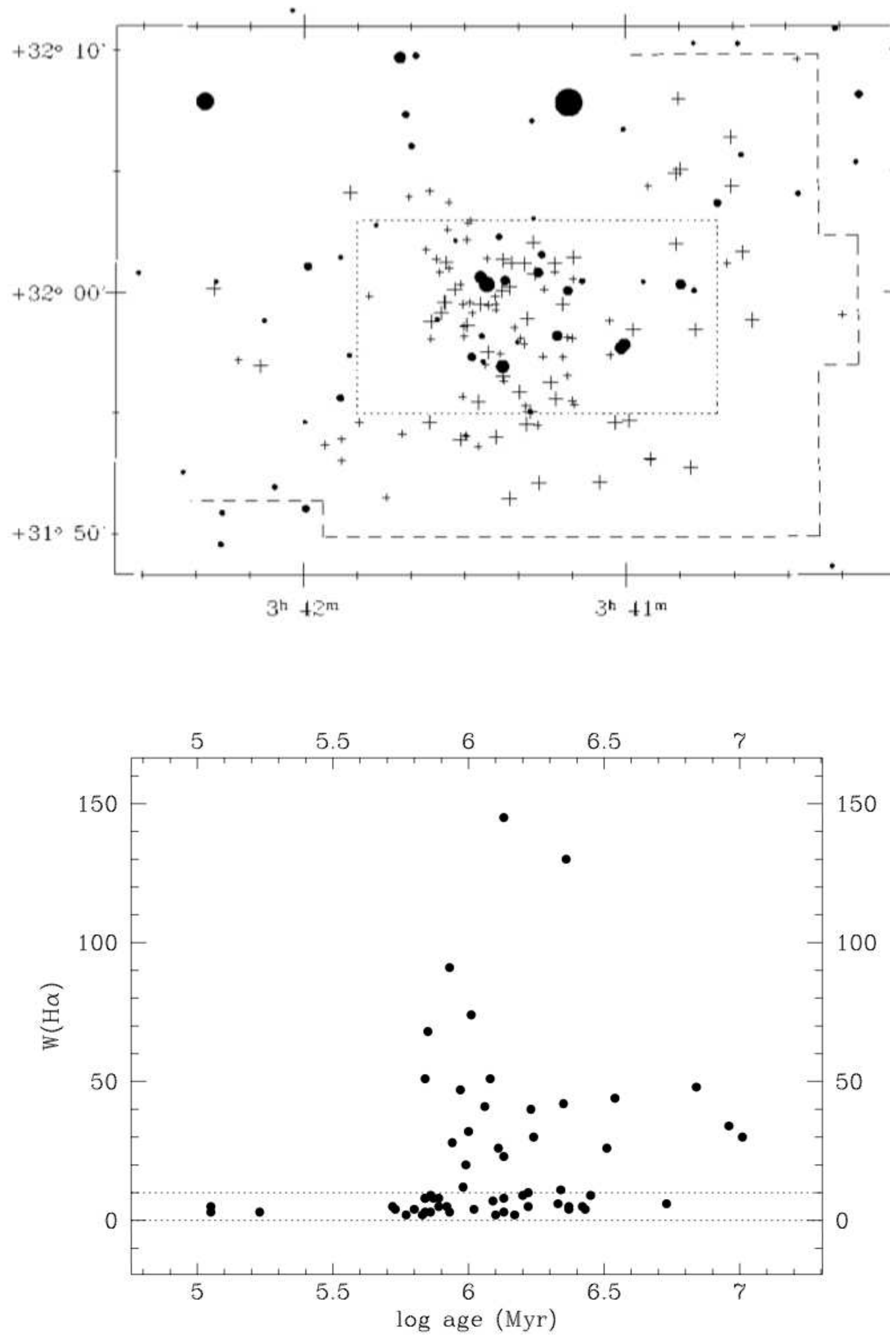


Figure 85: *(a) The distribution of CTTS (large crosses) and WTTS (small crosses) in IC 348. (b) A plot of W(Hα) of IC 348 members as function af age shows no dependence upon age. From Herbig (1998).*

tained BVRI photometry for about 260 stars in and around IC 348 as well as multi-object spectroscopy for 80 stars. Based on this material, he constructed a color-magnitude diagram and overplotted theoretical evolutionary tracks from D'Antona & Mazzitelli (1994), allowing the estimation of ages. Herbig concluded that (see Figure 85b):

> *"Most of the ages of about 100 stars [...] scatter between about 0.5 and 12 Myr. The emission-line stars, which are most likely to be members of IC 348, have a mean age of 1.3 Myr, but there appears to be a substantial spread around this value. Allowance for unresolved binaries would increase this age somewhat, but there is a firm upper limit at 2.95 Myr. There is no indication that the ages of the emission- line stars depend upon W(Hα): the IC 348 WTTSs as a population are not systematically older than the CTTSs. There is, however, a tendency for the WTTSs to be concentrated toward the center of IC 348, while the CTTSs are more widely distributed"* (Herbig 1998).

6.3 IC 5146

IC 5146 is located at the eastern end of a long filamentary dark cloud in Cygnus at an approximate distance of 1.2 kpc. The nebula is partly reflection and emission nebulosity and is centered on the B0 V star BD +46°3474 (star A in Figure 86). At the western edge of the nebula is BD +46°3471 (star B in Figure 86). The characteristic appearance of IC 5146 is likely the result of a cavity in the cloud which has opened up in our direction, allowing a previously embedded population of young stars to be observed optically. A summary of the numerous optical, infrared, and millimeter studies of the region can be found in Herbig & Reipurth (2008).

Herbig did a first survey for young low-mass stars in IC 5146 in 1960, and found 22 Hα emission stars (Herbig 1960b). Forty years later he returned to the region with his student Scott Dahm, and using the UH Wide Field Grism Spectrograph detected another 83 Hα emitters in two regions centered on BD +46°3474 and BD +46°3471. Additionally they obtained BVRI CCD photometry of 700 stars (to V=22), of which about half (including all the Hα emitters) were found to lie above the main sequence in a color-magnitude diagram, the rest being foreground stars, as expected for a cluster as distant as IC 5146. These data were augmented by JHK photometry (to K=16.5) of about 800 sources around the two B-stars, revealing a number of infrared-excess stars. Finally optical spectroscopy was obtained of about 60 stars.

The young stars were found to concentrate in two areas, surrounding each of the two luminous cluster members. The large majority is located east and

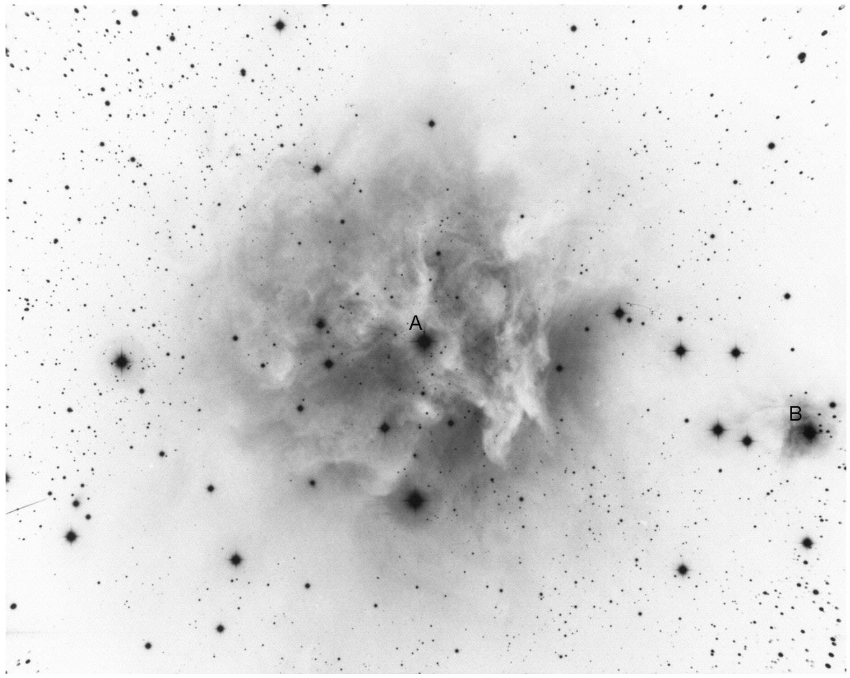


Figure 86: *A photograph of IC 5146 obtained by W. Baade at the 5m Palomar telescope. The stars marked A and B are the two young B stars BD +46°3474 and BD +46°3471. From Herbig & Dahm (2002).*

southeast of BD +46°3474, probably reflecting the structure of the primordial cloud giving birth to the low mass stars, but subsequently destroyed when BD +46°3474 appeared. Only about ten Hα emitters were found around BD +46°3471. Curiously, these two massive stars are very different:

> *"The two are about the same apparent magnitude, yet their spectra and local circumstances are very different. The source of the illumination of IC 5146, +46°3474, has a normal B0 V spectrum with very narrow lines (v sin i = 10 km s^{-1}), apparently a constant radial velocity, no obvious IR excess, and is the brightest of a cluster of over 100 stars. On the other hand, +46°3471 is variable in light, has a complex emission spectrum, a major IR excess plus a peculiar optical region color, rapid rotation (v sin i ∼180 km s^{-1}), and is accompanied by only a minor clustering of T Tauri stars. Why such a difference? It is possible that once +46°3471 reaches the main sequence some of its abnormalities will have disappeared, its temperature will have risen, and it might have some effect on the structure of the surrounding cloud. But why should a large cluster of lower mass stars already have formed around +46°3474 and only a very minor grouping at +46°3471?"* (Herbig & Dahm 2002).

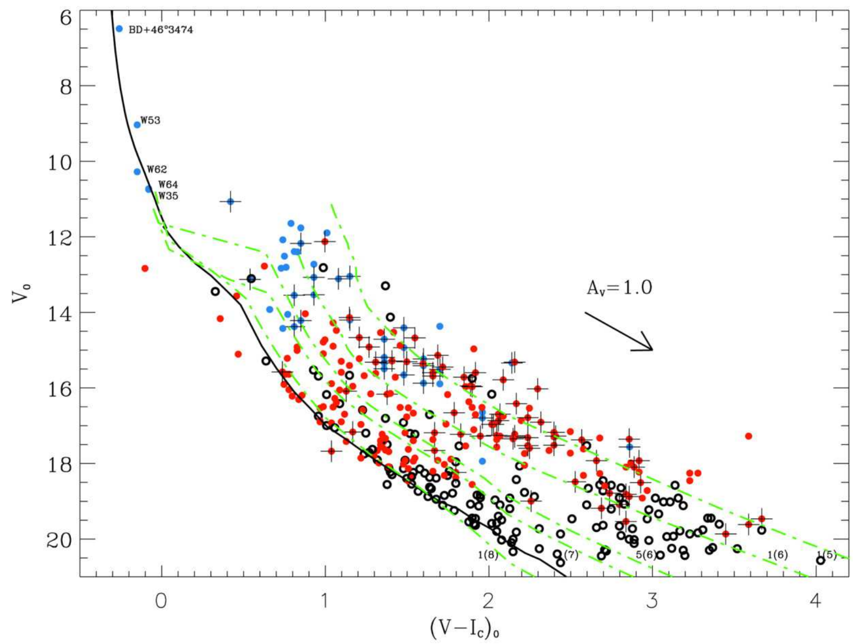


Figure 87: *A color-magnitude diagram of IC 5146. Hα emitters are marked by crosses. Blue points mark stars with known spectral types. Red points have unknown types and are corrected with the mean cluster extinction. From Herbig & Dahm (2002).*

With their extensive data, Herbig and Dahm could construct a color-magnitude diagram V_0 vs. $(V–I)_0$ for the cluster (Figure 87), calibrated with several sets of theoretical isochrones. The age distribution of the Hα emitters has been estimated by reference to several sets of theoretical isochrones. The different models show substantial disagreement, but the median age of the cluster does appear to be near 1 Myr.

Comparing the ratio of WTTS to CTTS in IC 5146 to their earlier determination in IC 348, Herbig and Dahm noted that *"there is a clear difference in the frequency distributions of W(Hα): the fraction of Hα emitters above the 3 Å detection threshold that are WTTSs is 0.52±0.12 in IC 348 and only 0.23± 0.06 in IC 5146"*, possibly a result of an age difference.

6.4 NGC 1579

The next cluster that Herbig studied, in collaboration with Sean Andrews and Scott Dahm, was in the region of NGC 1579 (Figure 88). The nebula is a reflection nebula illuminated by the peculiar high-mass star LkHα 101, which was the main focus of their study, as already discussed in detail in Section 2.15.1. The associated cluster is partly embedded and surrounds LkHα 101.

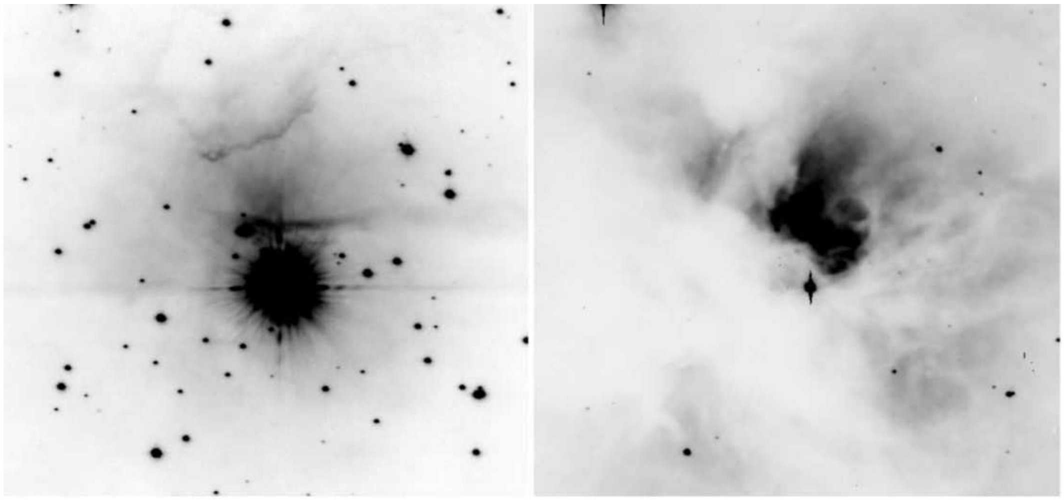


Figure 88: *The embedded cluster in NGC 1579 at K (left) and R (right). The bright star is LkHα 101. From Herbig et al. (2004).*

"About 35 much fainter (mostly between R = 16 and >21) Hα emitters have been found in the cloud. Their color-magnitude distribution suggests a median age of about 0.5 Myr, with considerable dispersion. There are also at least five bright B-type stars in the cloud, presumably of about the same age; none show the peculiarities expected of HAeBe stars. Dereddened, their apparent V magnitudes lead to a distance of about 700 pc" (Herbig et al. 2004).

6.5 Lynds 988

The molecular cloud complex Lynds 988 lies in the rich Cygnus-rift of the Milky Way, and although evidence of star formation was recognized, the region had escaped detailed study. Herbig & Dahm (2006) surveyed the northwestern periphery of the cloud for Hα emitters (see Figure 19 in Section 2.5) and found a rich concentration around the two HAeBe stars LkHα 324 and LkHα324SE, seen in the near-infrared image in Figure 89. Herbig and Dahm summarized their findings as follows:

"This study is devoted to the region of LkHα 324 and 324SE, on the northeastern edge of L988. To the east of this wide pair of bright stars is a small cluster of about 50 Hα emitters - presumably TTSs - between about V = 15 and 22. The distance is estimated to be 600 pc. Our VRI photometry and 2MASS JHK data result in an extinction-corrected color-magnitude diagram. The Hα emission stars are not distributed along a well-defined

pre-main-sequence; DM97 tracks and isochrones suggest a median age of 0.8 Myr. The surface density of Hα emitters around the cluster center is about 109 stars pc^{-2}, somewhat less than we have observed in other young clusters such as IC 348 and NGC 2264 (at its peak).

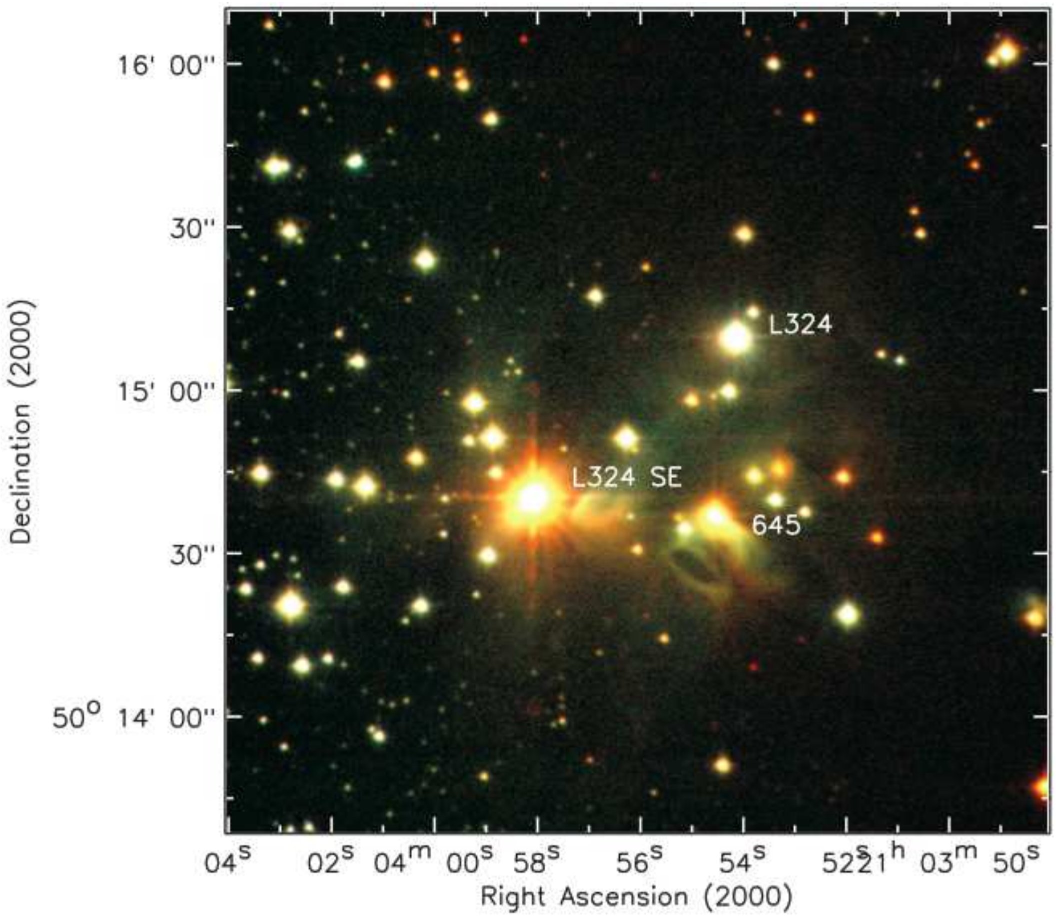


Figure 89: *A JHK colormosaic of the cluster of young stars surrounding the HAeBe star LkHα 324. This is the same region seen in Figure 19. From Herbig & Dahm (2004).*

LkHα 324 is a rapidly rotating star of type B6 or B7, with variable emission in its Balmer lines. LkHα 324SE is a more unusual object, with P Cyg-type structure at the Balmer and Na I lines and strong [O I] and [S II] emission. The star image is bar-shaped, with a forked dust fan at one end and a series of forbidden-line condensations at the other. These latter are apparently in the process of being ejected from the neighborhood of the star at velocities of up to –200 km s^{-1}, possibly through a cone-shaped volume inclined to the line of sight."

Herbig and Dahm noted the presence of several other luminous young stars associated with L988, and in particular commented on the chemical peculiarities detected in one of those (see discussion in Section 4.3). More recently, L988 has been found to have numerous Herbig-Haro objects distributed across the cloud surface (Walawender et al. 2013), indicating the presence of a distributed population of embedded young stars.

Figure 90: *The IC 1274 star forming region forms a cavity about 5 arcmin in diameter which appears to have been carved out of the L227 molecular cloud by several B-type stars. Image from the CFHT by J.-C. Cuillandre. From Dahm, Herbig, Bowler (2012).*

6.6 IC 1274

Simeis 188 is a complex of several weakly ionized HII regions within a few degrees of M8 and M20. One of these HII regions is IC1274, whose morphology gives the impression that the ionized gas has carved out a near-spherical cavity in the adjacent L227 molecular cloud (Figure 90). Near the center of IC 1274 is the B0 V star HD 166033, which appears to be the dominant ionizing source. In an early study of the region, Herbig (1957b) identified six faint Hα emission stars in and around IC 1274. In a detailed study, Dahm, Herbig, & Bowler (2012) acquired deep BVRI CCD photometry of IC 1274 together with slitless grism Hα spectroscopy to reveal the faint T Tauri population in the region. Over 80 Hα emission stars were identified, more than half of which lie within

IC 1274. Also, a number of infrared-excess stars were found in the region (Figure 91). Photometry of the early-type stars in the region yielded a distance of 1.82±0.3 kpc. From a color-magnitude diagram with theoretical isochrones a median age of ∼1 Myr was derived, but with a significant dispersion. *"Notably absent from IC 1274 are bright Hα emission stars that could be intermediate-mass Herbig AeBe or classical Be stars. Given the relative youth of the cluster, the presence of Herbig AeBe stars would be expected"* (Dahm, Herbig, Bowler 2012).

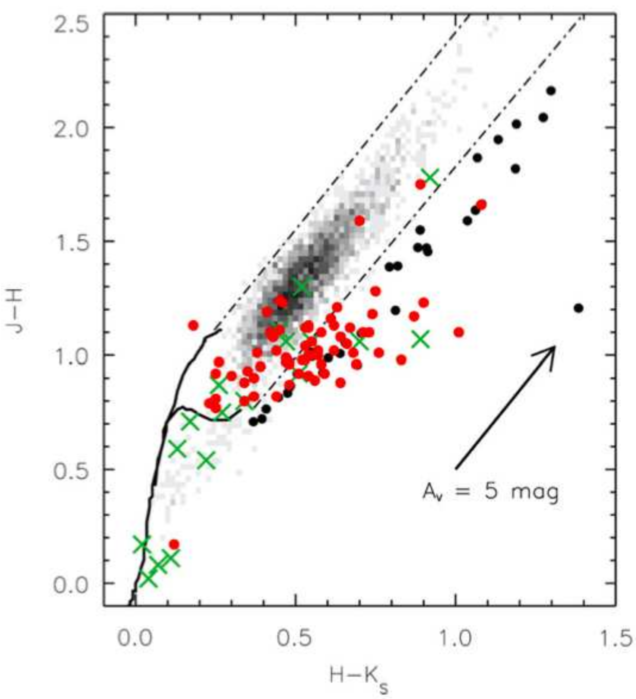


Figure 91: *A number of infrared-excess stars are found in the IC 1274 region. Red dots are Hα emission stars, green crosses are X-ray sources, and black dots are 2MASS sources with excess not already identified as Hα emitters or X-ray sources. From Dahm, Herbig, Bowler (2012).*

7 THE INTERSTELLAR MEDIUM

Herbig is most famous for his work on early stellar evolution, but his interests ranged much farther afield, and throughout his career he focused his attention on many other subjects. In particular, he developed a strong interest in the interstellar medium, and published a series of papers on diverse aspects of it. In his autobiographical notes he recalled:

> *"I had become an interstellar spectroscopist about 1960, when the 120-inch coudé spectrograph became available, because it seemed a highly appropriate field for that instrument. Also, I had always been fascinated by the pioneering work of Dunham and Adams with the Mount Wilson 100-inch coudé, and by Strömgren's 1948 theoretical paper on the interpretation of interstellar lines. And furthermore, it seemed to me that if stars were being formed out of interstellar material, I ought to know more than I did then about the interstellar medium."*

7.1 The Diffuse Interstellar Bands

Besides young stars, no other topic engaged Herbig as much as the intractable problem of the origin of the diffuse interstellar bands (Figures 92, 93). In the years between 1963 and 2000 he wrote 12 papers regarding the diffuse interstellar bands, including his 1995 Annual Reviews article, which for decades stood as the main statement on diffuse interstellar bands (Herbig 1995a). In his autobiographical notes, Herbig summarized his attempts to understand the DIBs:

> *"I'm not sure when I became seriously interested in the diffuse interstellar band (DIB) problem. I know that Billy Bidelman and I talked about them in the pre-120-inch days, and I recall that Father Patrick Treanor, a Jesuit priest who spent some time at Lick in the 1950's, tried to detect polarization structure in one of the DIBs at the 36-inch refractor. I built a small grating spectrograph for use at the 36-inch, and one of the things we tried was to observe in HD 183143 the DIBs that had been reported by Mount Wilson observers about 20 years earlier. Nothing much came of this, but of course I was to return to HD 183143, again and again, with the 120-inch and other coudés.*
>
> *My first DIB paper* [Herbig 1963]*, in a series that to date has grown to nine, was not even an observational effort: it was the attempt to identify DIBs with unresolved structure of bands having as the lower state $c^3\Pi_u$, the lowest triplet electronic level of the H_2 molecule. Of course, there were several serious problems with this proposal even at the outset, and it never survived, particularly after Herzberg in a paper in* Science of Light *produced*

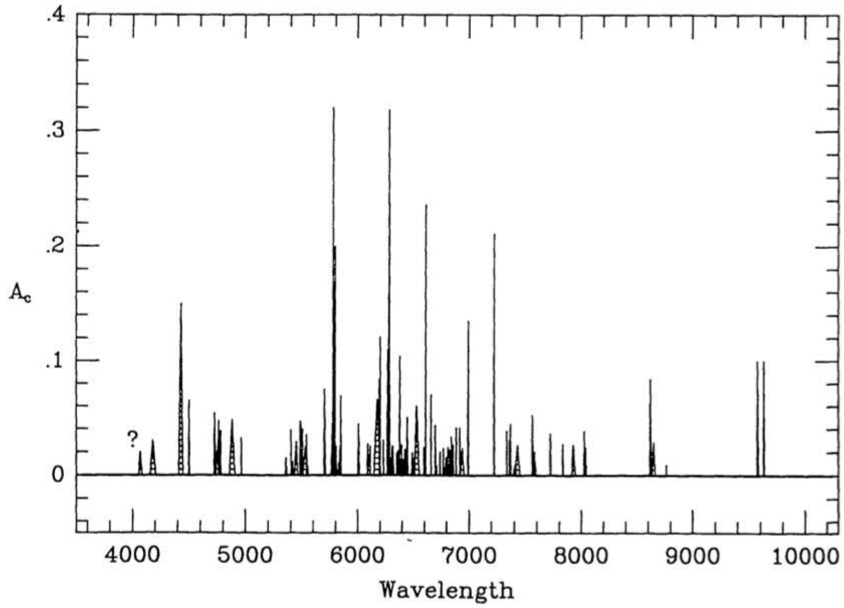


Figure 92: *The central depths of the optical DIBs known at the time of Herbig's Annual Review article. From Herbig (1995a).*

those band spectra in a laboratory discharge. This showed, on top of all other difficulties with the idea, that even the band structure was not what the hypothesis required.

I measured the profile of the 4430 Å DIB in HD 183143 on coudé plates in 1966 [Herbig 1966b]. *This demonstrated that there was no discernible fine structure in 4430 Å but left open the question whether there was any significance to the location of that DIB very near the kink in the interstellar extinction curve, a question which remains unanswered. This was done when the IBM 1620 was new at Lick, and punched cards were the medium of data storage, and I recall how exhilarating it was to be at the forefront of data-processing technology! But it was indeed a big improvement on point-by-point reductions by hand on graph paper.*

Over the next 8 years I continued to accumulate coudé spectrograms of reddened OB stars, as well as of other objects that I felt might be relevant: novae, the outer planets, the rings of Saturn. It was a major effort to microphotometer and reduce all this material, but I had several temporary assistants to help with the drudgery, and it all was worked up in 1975, in paper 4 of the series [Herbig 1975a]. *That was the last of my DIB papers based on photographic material. Despite the limitations of photographic spectroscopy,* *the presence of systematic errors at the weakest DIB strengths and in the 6284 Å DIB which is confused by an atmospheric* O_2 *band, there is still much worthwhile in that 1975 paper, and it is still referred to with some respect.*

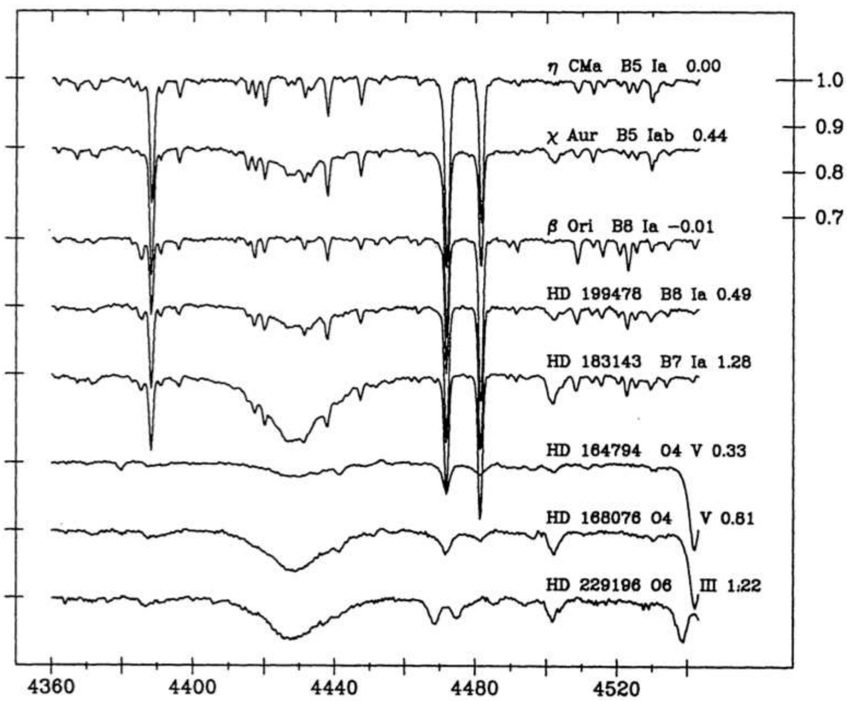


Figure 93: *The most prominent DIB in the blue spectral region is the λ4428 feature, seen here in stars of different reddenings (spectral types and E(B-V) are listed to the right of the star names). From Herbig (1995).*

Paper 5 appeared in 1982, with Dave Soderblom (who was then employed by me as research assistant while he worked toward a thesis) as co-author [Herbig & Soderblom 1982]. *This reported high-resolution spectroscopy of several DIBs obtained with the image-intensifier scanner in the 120-inch coudé. This device, built with NSF funds, was a double-pass Littrow system that fed a 40-mm intensifier chain whose output was scanned by an image dissector, the output then to magnetic tape. The optical design was my responsibility, with help from Soderblom and Doug Duncan, while the electronics were by Lloyd Robinson and Joe Wampler. With such digital data, it was possible to retrieve two new DIBs from the complex water-vapor structure in the red, and to show clearly that in at least one DIB, the same double structure is present as in the interstellar K I lines. I.e. at least that one DIB originates in the diffuse clouds. Furthermore, none of these DIBs showed any sign of* *internal fine structure at that high resolution.*

Before leaving Lick in 1987, I had accumulated still more DIB data at the 120-inch, both with a CCD detector and with Steve Vogt's Reticon system. I worked up this material in Hawaii: paper 6 dealt with a series of weak DIBs that I had discovered near 6800 Å [Herbig 1988]. *There is an intriguing uniformity of spacing of these features which may have deep significance, although I was not able to make anything of it. Paper 7 (1990) was a description of a search (made at Lick in 1986) for DIBs in the absorption spectrum of Comet Halley as it transited two early-type stars: results were negative* [Herbig 1990a].

Paper 8, coauthored with 'KD' Leka (1991), contained all the Lick Reticon results for the 6000-8650 Å region in many stars, but particularly HD 183143 [Herbig & Leka 1991]. *We found some 22 new DIBs, raising the total to slightly over 100. Most of these were extricated from behind atmospheric water-vapor structure. No support was found for the idea that H^- is responsible for some DIBs, nor were any convincing vibrational sequences found among the multitude of DIBs known by then. It was concluded, not for the first time, that the DIBs must be produced not by a single species, but by a family of carriers.*

Paper 9 (1993) was the result of a major effort to determine how, or if, the strengths of the two DIBs at 5780 and 5797 Å correlated convincingly with the abundance of any other interstellar species in the same lines of sight [Herbig 1993]. *The material was mostly pre-1988 Lick CCD and post-1988 CFHT coudé Reticon spectra, for a total of 93 stars. I concluded, among other things, that the carrier of those DIBs was not a product of the processes involving H_2 that produces the carbon diatomics, but in fact was most closely correlated with H I. Furthermore, DIB strength was not correlated with Ti depletion, thus ruling out the hypothesis that the DIBs are formed somehow on or in coated grains. Nor do the DIBs in the Pleiades respond to CH^+ column density, indicating that they are unaffected whether the gas has been shocked or not. My final conclusion was that 5780, 5797 Å behave as if their carrier is a free neutral species in the gas, which responds to the ionization level of the gas as if its ionization (or dissociation) threshold is somewhat higher than 5 ev.*

I expect, and hope, that someday soon there will be a breakthrough in this field: some laboratory investigations will crack the problem open, and then the astronomical observations can focus sharply on real issues, rather than pursuing what sometimes seems to me to be an almost mindless blundering about in the spectra of reddened stars."[1]

After the above notes were written, in 1993, Herbig published three more papers directly or indirectly related to DIBs. In 1995 he summarized all he had learned about DIBs in the previously mentioned article in Annual Reviews (Herbig 1995a). The second was a (negative) search for DIBs in Comet Hale-Bopp (Herbig & McNally 1999, see Chapter 8). The third paper (Herbig 2000) dealt with a search for "buckminsterfullerene", neutral C_{60}, which, although not a carrier of DIBs, might be present in diffuse clouds; C_{60}^{+} was suggested to be responsible for two DIBs (Foing & Ehrenfreund 1994). However, no reliable detection of C_{60} was found in the optical region.

Herbig's by far most cited paper on DIBs is his 1975 paper on DIBs in the region 4400-6850 Å. Alexander Tielens has commented on the impact of this paper on the field:[32]

"Herbig's 1975 paper represents a seminal study of DIBs. This paper meticulously sums up the observational characteristics of the DIBs as known at that time. In this study, Herbig classified the bands – 39 at that time – in terms of certain or probable DIBs. There are now of course hundreds of DIBs known but I still consider that the field should focus on identifying the strong bands found by Herbig in this study. The paper also stands out in its rigorous statistical analysis on correlations with E(B-V). Photographic studies of that time of course have their limitations, but Herbig was able to realize that the correlation with E(B-V) is not perfect. From his data, Herbig concluded that the DIBs are internally well correlated. The former point has been well confirmed in later CCD studies and the latter point was only proven incorrect when sensitivity had improved so much that sight-lines with individual clouds could be examined.

Another one of Herbig's key findings was that there are regional variations in the behavior of the DIBs with color excess. He connected this to the behavior of the so-called knee in the interstellar extinction curve. This was later studied in more detail and the classification of DIBs in two classes – those that are strong in sight-lines with σ Sco or ζ Oph type of extinction curves, respectively – is now well established. This is now thought to be connected to the behavior of the extinction curve in the far-UV and thus to the abundance of small grains – as surmised by Herbig – but rather than a direct connection to dust grains it may just reflect that a strong radiation field is required to prepare the DIB carriers into the 'right' state.

Herbig's search for regularity in the DIB spectra were inconclusive - 'unrewarding' was the word Herbig chose to describe his efforts. A word later echoed by many a graduate student. He concluded from this that the carrier is either a single polyatomic species of forbidding complexity or multiple carriers, and/or – I paraphrase here – we do not fully understand the molecular physics involved. Some 40 years later, all of these conclusions are still very much ascribed to by the field.

In his 1975 paper, Herbig discusses the carriers in terms of dust particles and he goes into some detail in refuting the various arguments put forward against this hypothesis. While the dust conclusion and the supporting arguments are no longer accepted by the field, it should be remembered that hindsight is 20/20. Indeed, at the writing of the 1975 paper, Douglas had not yet published his paper on the importance of internal conversion in large molecules and which ascribed the DIBs to long chain carbon atoms (Douglas 1977), and dust was still widely considered a reasonable possibility in the dust community and beyond. Nevertheless, in a prescient discussion, Herbig connected the DIBs to small grains responsible for the far-UV rise in the extinction curve and makes a link to Platt particles (now generally recognized as PAHs).

As a young graduate student, I remember analyzing Herbig's 1975 paper and in particular his detailed description of each of the 39 bands that he qualified as certain or probable DIBs, and I considered studying the slightly asymmetric profile of some DIBs, notably the 5780 Å band. However, I abandoned this project rather quickly because it wasn't clear to me that dust carriers were implied (the premise insisted on by my then supervisor). I still think that that is one of the smartest moves I made as a scientist. Indeed, until very recently, I told my students who are lured by dreams of glory that DIBs may be the fastest way to end a career. That is no longer the case and I actually believe we are zooming in on the identification issue. The connection of C_{60}^{+} to the pair of DIBs around 9600 Å is particularly convincing. In many ways, this progress was only possible by the pioneering study by Herbig that lead the way towards systematic studies of the DIB characteristics."

Herbig's hope to see the solution to the DIB problem in his lifetime was not to be fulfilled. While the field has moved forward in terms of more observations and more theoretical work, the fact remains that the DIB problem has not yet been cracked. It is widely accepted that the DIBs are the signatures of highly complex molecules. But the hopes for clear correlations between DIBs have been dashed, and it is now believed that rather than forming one family, there are multiple families where bands within one family may correlate well, but not with other families. Numerous potential candidates for the carriers of DIBs exist, with much attention focused on hydrocarbon chains, PAHs, and fullerenes.

Recently the IAU Symposium No. 297, *The Diffuse Interstellar Bands*, was held in The Netherlands.[33] The proceedings, which were dedicated to the memory of Herbig, provide an overview of the current state of the field (Cami & Cox 2014). Alexander Tielens summarized the meeting and concluded the following:

"The most important step forward has been that we have realized the enormous complexity of the issue of the DIB carriers; much more complex than a single scientist can solve by himself. Solving the DIB problem will require the close cooperation of astronomers, molecular physicists, astrochemists, and spectroscopists – each contributing their pieces of the puzzle. Spectroscopists will have to study the visible spectroscopic signatures of relevant carriers as well as the general photophysics of these species. In order to keep the molecular zoo to be studied tractable, these studies will have to be guided by astrochemists who can identify those species that might be particularly relevant. Their models will have to explore the inherent non-steady-state conditions of the interstellar medium, including aspects of the global cycling associated with star-death and star-formation as well as the transient chemistry of, for example, turbulent dissipation regions. Laboratory studies of key chemical rates will have to be measured in the laboratory in order to make these astrochemical studies realistic. As the excitation conditions in laboratory settings will differ from those in the ISM, molecular physicists in close collaboration with astrophysicists will have to develop models for the excitation processes relevant for the interstellar environment and evaluate the line profiles based on a deep understanding of the photophysics and using the molecular constants measured in the laboratory. Astronomers will have to play a key role in guiding these studies, evaluating the results, and comparing calculated and measured spectra. [...] It is my expectation that, with such a concerted program, we can indeed expect to cash in on the promise of the DIBs and to identify the full extent of the molecular Universe" (Tielens 2014).

7.2 Absorption Lines of Interstellar Gas

Another substantial study of the interstellar medium was a 1968-paper on the line-of-sight to ζ Ophiuchi, which exhibits a rather strong interstellar line spectrum with a particularly fine showing of molecular lines. The paper was published in the German journal Zeitschrift für Astrophysik, because Herbig for a few years was a co-editor of that journal together with Albrecht Unsöld, and so published several papers there. ζ Oph is an O9.5 V runaway star (Figure 94), a member of the Sco OB2 association, and about a million years ago it was located near the ρ Oph clouds. The star is a very fast rotator, so there is no confusion between stellar and interstellar lines.

Herbig obtained spectra with the Lick 120-inch coudé, which with its fresh aluminum surfaces and a properly blazed grating was quite efficient, especially

Figure 94: *The runaway star Zeta Ophiuchi heats the complex interstellar medium around it, and also creates a magnificent bow shock as the star ploughs through the interstellar medium (from lower right to upper left), as seen in this image from the WISE mission. Blue and cyan represent light at 3.4 and 4.6 μm, and green and red represent light at 12 and 22 μm. Courtesy NASA/JPL-Caltech/UCLA.*

in the ultraviolet down to the atmospheric cutoff. Herbig carried out a major study, and summarized his results as follows:

> *"The optical interstellar lines in ζ Oph are double (at –15, –29 km s^{-1}) on ordinary spectrograms. The stronger component at –15 km s^{-1} has been analyzed to obtain homogeneous data on the atomic and molecular concentration in a specific interstellar volume. A curve of growth study yielded* N*, the total number of absorbers cm^{-2} for Na I, Ca II, K I, CH and CN [...]. Correction of the atomic data for ionization was performed by evaluating the photoionization and recombination coefficients in the combined radiation field of ζ Oph [...] and that of the galaxy (an advantage of ζ Oph is that due to the concentration of the interstellar material in the vicinity of the star, the stellar radiation field largely dominates the ionization equilibrium, so that in ionization calculations there is less dependence on the general galactic field with its uncertainty arising from the imperfectly-known law of interstellar extinction in the far ultraviolet). Reduction of the* N*'s to concentrations* n *(in cm^{-3}) was based on a model for the distribution*

> *of interstellar material between ζ Oph and the Sun, beginning with an H II region of* n_e*=3 cm*$^{-3}$ *centered on the star. It was argued that the –15 km s*$^{-1}$ *spectrum must largely be formed in a dense H I region which lies somewhere between 15 and 50 pc from the star, and is succeeded by a tenuous H I region of* n*(H) ~0.1 cm*$^{-3}$ *extending to the Sun"* (Herbig 1968b).

Herbig went on to derive the properties of the H I layer, and concluded that the abundance of K is normal, but found the astonishing result that Ca is deficient by about a factor 1400, and Ti by at least 100 relative to solar system values. He further measured or searched for molecular lines of CH^+, CH, CN, OH, and NH, and discussed the different ideas for how diatomic molecules might be forming in the relatively dense H I layer. At the end of his paper, Herbig emphasized that *"explanation of these deficiencies is a major and pressing problem"*. We now know that the missing elements are locked in dust grains (see next section).

A side-product of the above investigation was a determination of the C^{12}/C^{13} abundance ratio from the CH^+ λ4232 line (Augason & Herbig 1967).

It is now known that ζ Oph is ionizing an elliptical $7^\circ \times 10^\circ$ density-bounded H II region, corresponding to ~18 pc × 26 pc at a distance of ~140 pc. Large-scale CO maps have determined the properties of the denser gas towards and around the star. And the location of cool dust in the area has been observed with the WISE spacecraft (see Figure 94).

Herbig's analysis was the first detailed study of the line-of-sight to ζ Oph. Yet he realized that significant progress could be made from future satellite-borne equipment, and strongly advocated such missions (Herbig 1970c). Indeed many detailed spectral studies have since then been performed from spacecraft like Copernicus, IUE, and HST, and the line-of-sight towards ζ Oph has become the prototype for studies of interstellar gaseous abundances and depletions in diffuse clouds and is used to test detailed chemical models.

7.3 Formation of Interstellar Dust

As mentioned earlier, Herbig and Harold Urey met from time to time to discuss issues in common to star formation and cosmochemistry (Section 2.14). During one of Urey's visits to Santa Cruz in the late 1960s

> *"... we were talking about meteoritic solids in the solar system, and the subject of solid particles in interstellar space came up, and I must have expressed some puzzlement as to where all that dust came from, and he blurted out: why didn't it come from the stars, why wasn't it merely leftover debris from the formation of planetary systems?*

I was fascinated with this idea, and pursued it vigorously for a time. Perhaps unfortunately, because the speculation deserved to be drawn properly to the attention of a wider astronomical audience, I published my thoughts only in some rather obscure places. I wrote up the idea as Introductory Remarks to a Liège Symposium [Herbig 1970a]*, and in an article (in German) in Sterne und Weltraum* [Herbig 1971b]*, and then talked about it in a Sigma Xi lecture that I gave around the south and southwest that was published under the title 'Interstellar Smog' in the American Scientist* [Herbig 1974a]*. A corollary of the idea was that chemical condensation processes in a cooling gas of a cosmic composition ought to follow the sequences described by Grossman in the early 1970s; condensates ought to form in descending order of binding energy so that titanates and silicates would freeze out of the gas first, followed by less tightly bound compounds, provided that the gas continued to be well stirred. This of course would account for the disappearance of Ti and Ca from the interstellar gas, which I had discovered in 1968 in the analysis of the interstellar spectrum of ζ Ophiuchi* [Section 7.3]*."*[1]

Today the favored mechanism for the formation of interstellar dust is of course due to AGB stars and supernovae. However, Herbig continued to surmise that dust production as a by-product of the formation of stars and planets through Galactic history was an important contributor to the dust of the interstellar medium.

7.4 Globules

Bok & Reilly (1947) and Bok (1948) drew attention to small dark nebulae, which they called globules, and which formed the smallest known entities of the interstellar medium. They were divided into small globules, which were found only in connection with HII regions, and the large globules, also known as Barnard objects and first recognized by Barnard (1919). Bart Bok speculated that these objects might be 'proto-protostars', a natural intermediate step in the condensation of material from diffuse interstellar material towards newborn stars (e.g., Bok 1977, 1978).

Herbig was skeptical that globules could be an important pathway for star formation, since virtually all T Tauri stars were found in association with much larger cloud complexes:

"My own opinion is that the 'globules' which we can see optically cannot be [a starting point for star formation]. Star formation must usually begin with the condensation of dense subclouds deep within the cool interiors of large dark nebulae, and these very requirements militate against their detection at optical wavelengths" (Herbig 1974b).

Figure 95: *The Rosette Nebula shows a fine collection of small globules in the northwest quadrant of the nebula. The globules face the central cluster of OB stars. From a red Lick 120-inch plate (Herbig 1974b).*

Nonetheless, Herbig proceeded to investigate the problem, and focused on the irregular clouds first noticed by Minkowski (1949) in one corner of the Rosette Nebula. He based the study on deep prime-focus plates he had taken at the Lick 120-inch reflector (Figure 95), which provided the first detailed look at such structures (Herbig 1974b):

> *"The small dark globules seen against the nebulosity in the northwest quadrant of NGC 2237-2244 [...] have an elongated, tear-drop form with the symmetry axes and sharper edges directed toward the central star cluster. This orientation is shared by the well-known elephant trunk structure, which in general lies farther from the center than these isolated dark spots. Examples of globules still connected with large dark masses by dust filaments are also present. It is suggested that these globules represent a late stage in the pinching-off and dissipation of elephant trunks as the central cavity of the HII region expands into the peripheral dust clouds, and that these globules are not protostars. It is estimated that the age of a typical isolated globule in this region of NGC 2237-2244 is of the order of 10^4 years."*

Herbig's conclusion that the small globules in HII regions are not sites of star formation still stands today. His suggestion is now widely accepted that they are shortlived structures resulting from dynamical break-up at the interface between ionized gas and cold neutral gas. It is also clear that the large globules are not common sites of star formation, although some globules have been found to form a small number of stars (e.g., Bok 1978, Reipurth 1983, Keene et al. 1983).

Figure 96: *The runaway O-star AE Aur is moving across an interstellar cloud and illuminates the reflection nebula IC 405. The figure shows a WISE image of the region. Blue represents light at 3.4 μm, cyan at 4.6 μm, green at 12 μm, and red at 22 μm. Image credit NASA/JPL-Caltech/UCLA.*

7.5 AE Aurigae

In the early 1950s, Blaauw and Morgan published two studies of the massive runaway stars AE Aur and μ Col, which move away from the Orion association in opposite directions (Blaauw & Morgan 1953, 1954). AE Aur lies north of the Orion Nebula 350 pc distant and moves with a space velocity of about 128 km s^{-1}, indicating that the star was ejected about 2.7 Myr ago. The star currently has a chance encounter with an interstellar cloud, and illuminates the extensive nebula IC 405, which covers more than half a degree on the sky. AE Aur has a spectral type of O9.5 V, and will therefore ionize hydrogen but light will also scatter off dust where it is present. Images of IC 405 in different filters show that the reflection and the emission nebulosity have completely different structure. This intrigued Herbig, who took a series of long-slit spectra of different parts of IC 405 to understand better the distribution of ionized gas and reflected light (Herbig 1958b). Figure 96 shows a modern image from WISE of AE Aur and IC 405, indicating the extent of the reflection nebula (green), and also showing a region surrounding the star where the dust is heated and re-emits radiation (red). Forty years later, Herbig returned to AE Aur, this time asking the question whether any changes would be discernible in the interstellar spectrum of the star as it moves through the cloud at a speed of about 4 AU per year. None were found, but Herbig listed his measurements for comparison with spectra that will be taken sometime in the future (Herbig 1999).

7.6 Merope and IC 349

The Pleiades are surrounded by the finely structured reflection nebulosity well-known from numerous images of the cluster. The nebulosity results from the chance encounter between the stellar cluster and a small cloud fragment of the Taurus-Auriga molecular cloud complex, and is not remnant material from the formation of the cluster (e.g., White & Bally 1993). In 1891, E.E. Barnard studied the Pleiades visually through the then new Lick 36-inch refractor when he noticed a small, bright nebulous patch 36 arcsec southeast of the B6 IVe star Merope (23 Tau) and remarked that "... It is about 30″ in diameter [...] and very cometary in appearance". The nebula is shaped like an arrowhead pointing towards 23 Tau, with a bright nucleus at its apex.

Herbig was fascinated by the opportunity offered by this fortuitous encounter to study the dissipation of a cloudlet by the radiation field of the nearby star. In 1995 he gave the Petrie Prize Lecture (Herbig 1995b) in which he discussed his ideas about Barnard's Nebula, also known as IC 349, followed the next year by a formal paper with full details of his analysis (Herbig 1996). Here he derived the relative velocity vector from the mean proper motions and radial velocities of the cluster members, and the CO radial velocity of the nearby Taurus-Auriga clouds, while the proper motion of IC 349 itself was inferred from T Tauri stars associated with the nearby clouds (Jones & Herbig 1979). Altogether, it was found that IC 349 is moving almost directly towards Merope. This is roughly perpendicular to the assumed motion of the Pleiades through the cloud that was deduced by White & Bally (1993) who suggested that a cavity through the CO cloud is a 'wake' from the cluster motion.

As a starting point to settle this discrepancy, Herbig noted that the *"ejection*

Figure 97: *IC 349, also known as Barnard's Nebula, is a small dusty cloudlet having an accidental encounter with and being dissipated by the radiation field from Merope in the Pleiades (to the upper right). From Herbig & Simon (2001).*

of dust from a nonstellar object in the neighborhood of a star is reminiscent of the situation of a comet near the Sun, where the comet's nucleus is warmed to the point that frozen volatiles evaporate, and in escaping carry dust with them". He then calculated the temperature of the nucleus of IC 349 for different separations from Merope, and found temperatures in the range from 65 to 98 K for realistic silicate dust grain sizes. At these temperatures, it is possible that evaporation of CO ice could drive the outflow of dust in IC 349. Herbig noted that *"the motion of very small silicate particles launched from the nucleus of IC 349 will be controlled by the radiation pressure from 23 Tau, by the gravitation of both the nucleus and 23 Tau, and by drag from the material of the ambient Pleiades nebulosity"*, and proceeded to calculate particle trajectories for the two competing directions of motions of IC 349. If the direction envisaged by White & Bally (1993) was adopted, IC 349 would take a distinctly curved appearance, in clear contrast to its actual appearance.

The above scenario assumes that IC 349 is a high-density condensation belonging to the Taurus-Auriga clouds, and it is the surface layers that are being swept away. However, the thermal velocity of escaping gas would be less than 1 km s^{-1}, while to reproduce the observed opening angle of the fan of IC 349, Herbig had to assume an ejection velocity of 9 km s^{-1}. An alternative scenario could be that there is a young star deep inside the IC 349 clump, which might drive the ejection of dust. However, no evidence for an embedded source has been found (Barentine & Esquerdo 2003).

Herbig returned to IC 349 5 years later after obtaining exquisitely detailed multi-filter images with HST (Herbig & Simon 2001). The new images (Figure 97) allowed the accurate aperture photometry at many locations of the nebula and the derivation of colors. The range of observed colors set stringent limits on the radii of particles (assumed to be silicate and graphite) to 0.1 – 1.0 μm, with the smaller particles generally located further away from 23 Tau than the larger, suggesting that the linear streaks seen in the HST images represent size sorting of the dust grains by radiation pressure from the star. The chance encounter by the Pleiades with an otherwise small anonymous cloud has thus offered the opportunity to study interstellar material under unique circumstances.

8 MOLECULAR SPECTROSCOPY

Already as a student, Herbig distanced himself from the classical astronomy that dominated work at Lick observatory when he arrived there in 1943. Instead he eagerly dove into the literature on the new field of astro-physics, which he read voraciously. As a graduate student he had participated in a laboratory study of the alpha system of TiO at the LeConte Hall spectroscopic laboratory at Berkeley, under the aegis of Francis Jenkins:

> *"Karl Strauch, a physics graduate student and later a professor at Harvard, and I packed the pole pieces of a carbon arc with commercial TiO_2 powder and focussed the flame on the slit of a 21-foot concave grating spectrograph in Jenkins' lab. The rotational structure of the 4954, 4804, 4761 Å bands (as I recall) was fully resolved on these plates, which I measured, and extracted the various branches from this mess. (These plates, identifications, etc. are buried in the plate vault at Mount Hamilton. They are at best only of historical interest, because John Phillips later carried out a complete rotational analysis of the alpha system.) Knowing the masses of the Ti isotopes, it was then possible to predict the positions of the isotopic branches and band heads."*[1]

Upon graduation in 1948 Herbig received a 1-year National Research Council fellowship, and armed with the results from his earlier laboratory study he decided to first spend the summer in Pasadena, where he had been given the opportunity to browse through the collection of spectra, with the intent to investigate Ti isotopes in M stars.

> *"I tried to pick out the isotopic features on the coudé spectrograms of M stars that I found in the Santa Barbara Street files. There was no attempt to photometer these plates, but to work from eye estimates, and the results were not very firm. I avowed (1948) that no gross departures from the terrestial Ti ratios were apparent, but it was a shabby job, and I am not very proud of it"*[1] (Herbig 1948).

One thing that turned up during that Pasadena summer was more successful:

> *"Merrill had found on his coudé plates of S stars a molecular band head at 3682 Å that was partially resolved, but which no one was able to identify. I had been given the opportunity to browse through the collection of spectra of various atoms and molecules that had been obtained over the years in the Mount Wilson spectroscopic lab by the elder (Arthur) and the younger (Robert) King, and found the 3682 Å band was present on spectrograms, I think of a Zr arc in air. It turned out that 3682 Å is the 0-0 band of a new singlet system of ZrO, which I wrote up for the ApJ"*[1] (Herbig 1949).

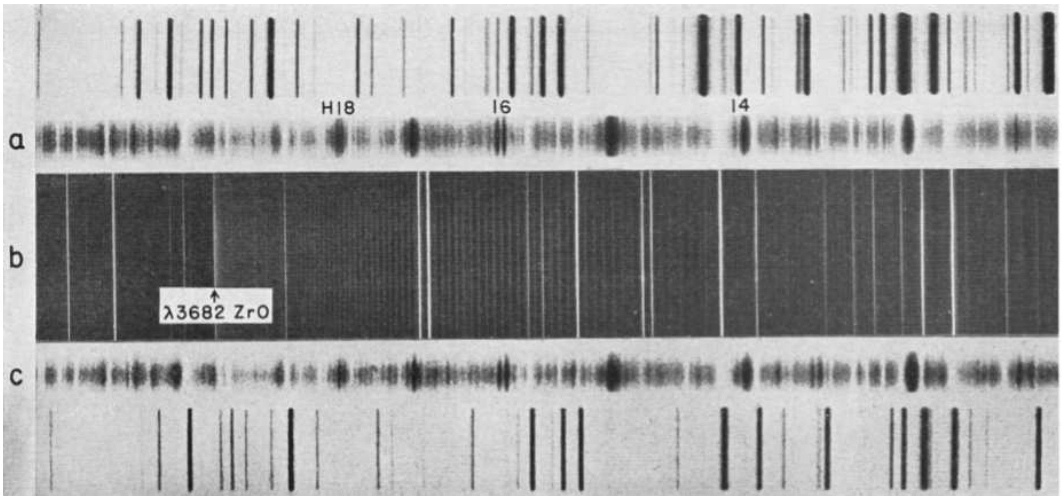


Figure 98: *The zirconiumoxide band at λ3682 in (a) o Ceti, (b) laboratory spectrum of a zirconium arc in air, and (c) χ Cygni. From Herbig (1949a).*

These experiences with TiO and ZrO (see Figure 98) kindled Herbig's interest in molecular spectra, to which he would be returning again and again. But first he would be fully occupied with the study of T Tauri stars and Herbig-Haro objects before he 7 years later returned to molecular spectroscopy.

> *"My next serious venture into molecular spectroscopy was in 1956, when I stumbled across the identification of the peculiar series of emission lines that had been found by Merrill in the long-period variable χ Cyg near minimum light. I often mused about some of the unidentified lines found in such stars (some of which remain so) and one evening, sitting in our living room on Mount Hamilton, mulling over Herzberg's book on* Spectra of Diatomic Molecules*, it dawned on me that Merrill's lines were just short sections of the band branches of the 0-0 band of AlH, and that this selectivity is a consequence of the way that Al and H atoms combine, a process (called inverse predissociation) that had been observed in the laboratory* [Herbig 1956b].
>
> *I followed this by an effort (1958), with low dispersion at the Crossley, to observe as many long period variables (LPVs, now usually called Mira's) as possible near minimum light, to see if there was anything systematic about the occurrence of AlH emission. The conclusion, from observations of about 70 stars, was that AlH was detectable only in S-type LPVs, and of those, only in the stars having periods longer than about 370 days. I never was able to make anything of this result* [only a meeting abstract was published, summarizing these results (Herbig 1958c)]. *Much later (1968), Zappala and I published a short follow-up paper on the subject, and as far as I know the*

> *subject remains there today* [Herbig & Zappala 1968].
>
> *It should be mentioned that these observations of LPVs near minimum light turned up several having either close optical companions or showing the unresolved spectrum of a hotter companion. I discussed these results, as well as the fact that R Aqr remained the only star among the M's and S's that I had observed which exhibits a hot emission line spectrum, at the 1965 Bamberg meeting"*[1] *[Herbig 1965b].*

Once the 120-inch with its coudé spectrograph became available, Herbig became still more immersed in molecular spectroscopy, applying intense efforts to the impenetrable problem of the diffuse interstellar bands, previously discussed in Section 7.1.

As already mentioned in Chapter 1, one of Herbig's early assignments when he started as an assistant at Lick Observatory in 1943 was to take astrometric plates of comets and derive orbital elements from the data (Herbig & Hansen 1944, Herbig 1945). But Herbig had no serious interest in that work. Eventually, however, he got involved in spectroscopic work on comets, and that fit well into his interest in molecular spectroscopy. In his autobiographical notes he writes:

> *"In the early days – i.e. pre-120-inch times – at Lick, I was a tireless observer, amply provided with curiosity and stimulated by the ready availability of telescope time. I observed the spectra of every interesting transient object that came to notice, which included bright comets. This was more to my liking than the comet astrometry, but at first, it was to no real scientific purpose. It became more focussed later when I developed an interest in interstellar molecules and the early solar system. When Comet Kohoutek was found in 1973, there was a huge amount of publicity (followed by public disappointment when it did not become as spectacular as advertised) and I took a number of coudé spectra, one of which showed the peculiar double-headed bands that Herzberg and Lew shortly thereafter identified with H_2O^+. That identification was written up in a joint paper with them and with Peter Wehinger and Susan Wyckoff* [Wehinger et al. 1974].
>
> *Largely on the strength of this paper, and I suppose on account of my custodianship of the Lick collection, I was asked to write a review of cometary spectra for a NASA colloquium on comets* [Herbig 1976]. *In the process, I learned more about the subject, and was stimulated to observe other bright comets as they came along, although it was always a sideline. As Comet Halley approached in the 1980's, I did become involved in the Steering Group of the International Halley Watch, and attended numerous planning meetings on what to do. My part of the Halley program was primarily to get*

high-dispersion coudé spectra of the nucleus and coma, which I did (and contributed the results to the IHW archives), but also to attempt something which I thought could be interesting: to get spectra of the ion tail in the thought that Doppler shifts ought to show if the moving structures represented real material motion, or only travelling plasma waves.

I received a NASA grant to build a CCD camera fed by a short-focus lens (mounted on a 12-inch Cassegrain reflector which someone had presented to Lick), and set up a program for on-the-spot astrometry of the CCD images which this would produce of Halley's tail. The idea was that the observer at this telescope, erected near the 120-inch dome, could almost immediately determine the coordinates of any interesting structure in the Comet's tail (photographed through an interference filter centered on a CO^+ band) and telephone them to me, standing by at the coudé auxiliary telescope (CAT), which feeds the 120-inch coudé spectrograph. I would then (so went the plan) set the CAT on those coordinates and get a spectrum of the invisible knot or streamer in the tail with a delay of only a few minutes. Rick Pogge, a graduate student at Santa Cruz, worked with me on this and did much of the hard work. But it all came to naught: when Halley became accessible again at Lick after perihelion, the weather was totally cloudy and we got nothing.

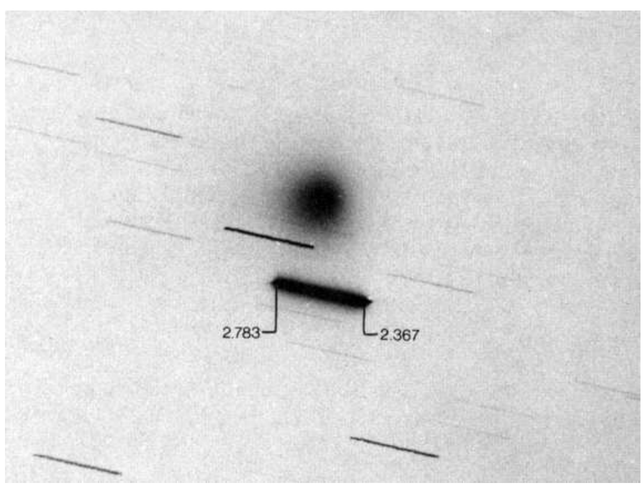


Figure 99: *Comet Halley during the τ^1 Ari occultation on 1985 November 19. The ends of the star trail are marked with UT times in decimal hours of the beginning and end of the exposure. From Herbig (1990a).*

I did measure up the coudé spectrograms of Halley, and found what seemed to be systematic streaming motions of the molecular gas out of the nucleus and away from the sun. These differential velocities amounted to about

> *7 km s^{-1}, and so are almost an order of magnitude larger than expected from theory and from indirect evidence. They are, I think, the only high-angular-resolution Doppler measures of the kind, and although more accurate Fabry-Perot and radio velocities are available, those integrate over such an angular area that they are not directly comparable to the coudé results. Of course I remembered my problems with image-intensifier velocities on other occasions, and so was nervous about this conflict with expectation. I tried every check that I could think of, but the results would not go away"* (Herbig 1990b).

Already mentioned (Chapter 7.1) was Herbig's attempt to determine whether some of the diffuse interstellar bands would appear in absorption as comet Halley transited a bright early-type star (Figure 99, Herbig 1990a), and a similar attempt with comet Hale-Bopp (Herbig & McNally 1999). Derek McNally recalls their joint work on comet Hale-Bopp: "George and I shared an interest in whether or not comets might also carry whatever produced the diffuse interstellar lines, and we collaborated on Comet Hale Bopp - using the Keck telescope and its digital detectors. Together we drew a blank! No sign of any enhancement of the diffuse lines was observed. This rather backed up a weaker conclusion from my earlier Lick photographic work that the carriers of the diffuse interstellar absorption were destroyed in the warmer parts of the ISM. But one strong lesson I learned from George was 'do not exceed the observed EVIDENCE'. A good principle!"

9 VARIABLE AND EXOTIC STARS

As already mentioned, Herbig had a seemingly insatiable appetite for stars with unusual spectra and variable stars behaving unusually. He was early on exposed to such objects when he, as a young, newly hired assistant at Lick Observatory, had the opportunity to study two new bright novae:

> *"The outburst of Nova Aql 1945 and the recurrence of T Pyx in 1945 and of T CrB in 1946 happened during this period. These events, taking place as they did almost before my eyes when I was the only one at Lick with the interest and energy to pursue the opportunity, turned me to serious reading of the literature on the spectra of novae and of odd emission-line stars. This was also the time when the series of papers on the spectra of peculiar stars by Struve and Swings was appearing in the Ap.J., and I now realize how much my interests and tastes were shaped thereby. And of course, nova spectroscopy had been a tradition at Lick, begun by Campbell but pursued in most detail by Wright and Wyse. So Moore allowed this callow, untutored but oh-so-energetic youth to go ahead and observe the novae on every occasion and with all the weapons at hand, which meant mainly the 36-inch refractor with all the combinations of prisms and cameras that (it seemed) only I knew how to put together. The papers that I wrote on those two novae reflected the spectroscopic lore that I had picked up from the pages of Struve, Swings, Bowen, ..."*[1] (Neubauer & Herbig 1945, Herbig & Neubauer 1946).

In the following, a selection of the numerous papers that Herbig wrote on stars of various notoriety are discussed in some detail, ordered chronologically. Some generated Herbig's passionate engagement, others were observed *"not because I was intensely interested in such systems, but because I always felt strongly that it was the duty of observers at a real observatory to work their telescopes as hard as possible. In those primitive times there were plenty of interesting objects in the sky that seemed to demand attention: peculiar variables, novae, supernovae, comets, ... And of course in those times the tyranny of theory did not weigh so heavily upon us, nor were we cowed by the arrogance of telescope assignment committees."*[1] All of the stars discussed in the following have in common that they are optically bright and many have gone on to become important objects within their respective fields. Most of Herbig's pioneering observations discussed in this chapter were done at a time when X-ray observations and even infrared observations were far in the future, and yet it is remarkable how many of his conclusions still hold today.

9.1 R Coronae Borealis – A Double Degenerate Merger

This star is the proto-type of the group of hydrogen-deficient, carbon-rich supergiants that are characterized by occasional, dramatic declines in brightness ascribed to the formation of carbon dust. Less than 100 R CrB stars are known in the Galaxy. They are hypothesized to form either when a double degenerate binary merges without reaching the Chandrasekhar limit, thus failing to become a supernova, or when an asymptotic giant branch star undergoes a final helium flash and expands to a supergiant. The discovery that R CrB stars have extremely low $^{16}O/^{18}O$ ratios supports the merger scenario, since no overproduction of ^{18}CO is expected from a helium flash, but could result from partial helium burning in a double degenerate merger (Clayton 2012).

Very little of this was known when in the winter of 1948, just as Herbig spent three months with Struve at the McDonald 82-inch telescope, R CrB started fading. He eagerly monitored the descent with a series of spectra (Herbig 1949b, Figure 100), although the very low elevation of the star as it emerged in the early-morning sky meant he had to balance the telescope by hanging the heavy observing ladder on the back of the telescope, as described in Section 1.6.

> *"As R CrB dropped about 4 magnitudes below maximum light during the winter of 1948-49, the McDonald spectra showed that emission cores appeared in the H,K lines and then as the continuum went down, a weird emission spectrum appeared, dominated by the D lines of Na I, H and K of Ca II, and a line at 3888 which must be due to He I, although no other He I lines were present. The rest of the spectrum was full of bright lines of ionized metals, but no H lines appeared. R CrB returned to maximum brightness after I returned to Lick in the summer of 1949, but the spectroscopic equipment at the 36-inch refractor was so inferior that although I took more spectrograms, they could contribute little new."*[1]

Herbig maintained his interest in R CrB and when, shortly after the 120-inch coudé was completed around 1960, R CrB again went into a minimum, he was well equipped to study the event and obtained much new spectroscopic material. Although he measured up these plates, he did not publish the results, since at that time he was deeply embedded in the study of lithium evolution, so later he handed over the material to his student N. Kameswara Rao, who wrote a thesis about R CrB stars (Chapter 10).

> *"I continued my interest in R CrB stars, I suppose partly because of a simple fascination with their bizarre spectra. Billy Bidelman was at Lick in those years, and his interest in the same subject, and our frequent discussions on this and other lively topics in stellar spectroscopy, certainly helped keep my own attention alive. The concentration of R CrB stars toward the galactic bulge provided an incentive to look for more such objects among the irregular variables that had turned up in the Harvard surveys for faint variables in*

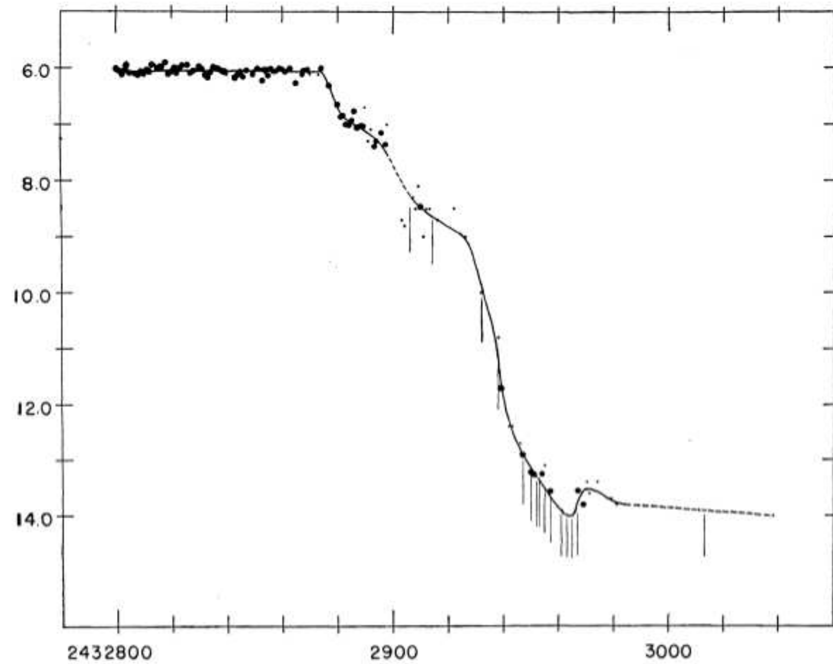


Figure 100: *An AAVSO lightcurve of the descent of R CrB into the winter 1948 minimum. The vertical lines indicate when Herbig obtained spectra with the McDonald Observatory 82-inch telescope. From Herbig (1949b).*

> *that direction. In this way I came across V348 Sgr* [Herbig 1958d] *and MV Sgr* [Herbig 1964]*, two stars that remain lively topics for research today.*
>
> *Also in the galactic bulge: Haro and his co-workers had over the years discovered a number of Hα emission stars in that area, I suppose while looking for novae and new planetary nebulae. On a visit to Mexico in 1961, I made finder fields for many of these discoveries from the Tonantzintla plates, and later took low-dispersion spectrograms of many of them at the Crossley. Most turned out to be symbiotic stars; the results were published in the Proc. Nat. Acad. Sci."*[1] (Herbig 1969b).

9.2 S Sagittae – A Cepheid Binary

Another part of Herbig's work as a newly hired assistant at Lick Observatory was the continuation of radial velocity measurements of long-period binaries with the Mills spectrograph on the 36-inch refractor. The results were gradually written up over the years by a number of people, including Herbig:

> *"I myself assumed responsibility for a large investigation begun by Moore of the 8-day Cepheid S Sge, which is also a spectroscopic binary with a period of*

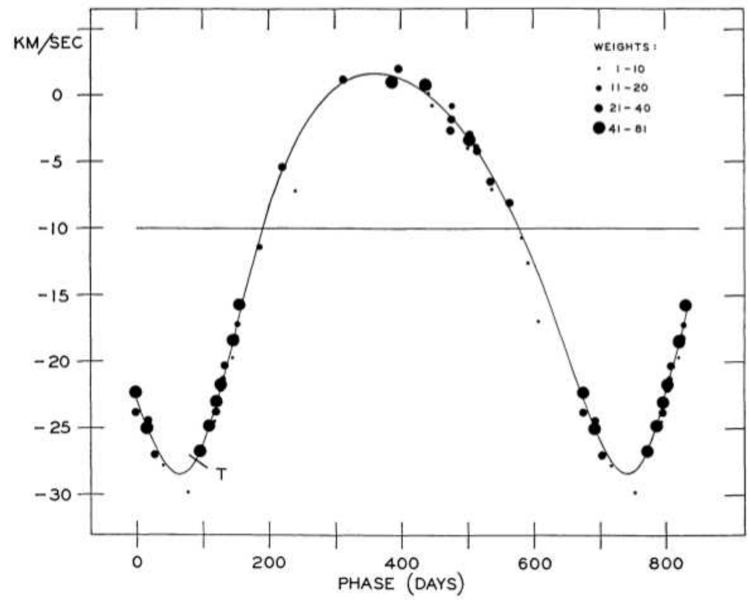


Figure 101: *The long-period velocity-curve of the Cepheid binary S Sagittae after careful subtraction of the Cepheid velocity variations. From Herbig (1952c).*

676 days. It took many days and evenings of trial and error and to-and-froing, but finally the two velocity variations were satisfactorily disentangled [Figure 101]*, and the results published (in 1952, after Moore's death) under our joint authorship* [Herbig & Moore 1952]. *A by-product of this (described in Paper II)* [Herbig 1952b] *was the discovery, on Mount Wilson coudé plates of S Sge that I took in an effort to detect a hot companion in the ultraviolet, of the transient appearance of Ca II emission on the ascending branch of the Cepheid light curve.*

It turned out that the same phenomenon had been seen in several other Cepheids by others, but not much had been made of it. I followed up by observing a number of other Cepheids of different periods, although this had to be done at Lick with the 36-inch refractor, whose transmission at H&K is very low, and pitifully low dispersion. It turned out that this emission seemed to occur in all Cepheids (at a level detectable with that equipment) having periods longer than about 5 days, and always on the rising branch of the light curve [Herbig 1952c]. *Later, Bob Kraft in his thesis went after this phenomenon in much more detail in both Cepheids and long period variables. At coudé dispersion, similar emission is detectable in Hα; it is now believed to be due to the emergence of a shock-heated compressional wave at that particular phase of the pulsation cycle."*[1]

The observed velocities are the sum of the pulsational and orbital velocities, but Herbig and Moore succeeded in separating the two and derived accurate orbital elements for the binary system, which turned out to change very little when Evans et al. (1993) more than 20 orbits later added observations and refined the orbital elements. Nancy Evans and collaborators also did a search for the companion using the IUE satellite; a flux excess was detected in the ultraviolet, suggesting that the companion is of spectral type between A7V and F0V. But the mass of such a companion, 1.5 to 1.7 $M_\odot$, is smaller than the derived minimum mass (2.8 $M_\odot$), suggesting that the companion is probably itself a binary, making S Sge a triple system (Evans et al. 1993).

9.3 VV Puppis – A Cataclysmic Variable

Through his correspondence with the South African astronomer A.D. Thackeray, Herbig had been alerted to the unusual variable VV Puppis, which Thackeray et al. (1950) had been following photometrically.

> *"VV Puppis was another star that upon discovery appeared to be just another short-period variable with a period of about 100 minutes but, unusually, with*

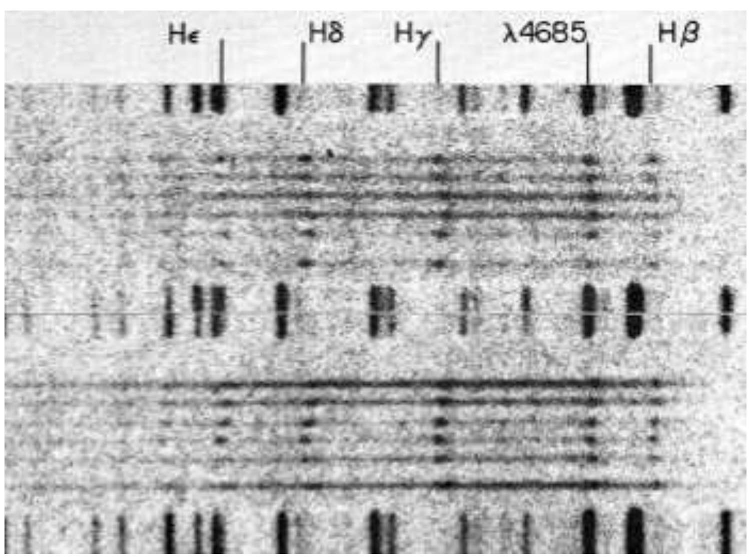


Figure 102: *Two spectroscopic runs on the cataclysmic variable VV Pup, a typical polar, each covering slightly more than one full 100-minute cycle. Each exposure is about 20 minutes. The upper series is approximately centered on maximum positive velocity, the lower one on maximum negative velocity. Both velocity and brightness variations are clearly seen. From Herbig (1960c).*

large variations in mean brightness. At times, the short-period variation apparently went away. I found all this tantalizing. It was possible to observe the spectrum with short exposures at the Crossley nebular spectrograph [Figure 102]*, and these showed immediately that VV Puppis was no RR Lyrae star: it had bright lines of H and He II, from which I discovered that the star is actually a single-line spectroscopic binary having the 100 minute period. I left it there: others have since shown that VV Pup is an accreting white dwarf and X-ray source, with a powerful surface magnetic field."*[1]

VV Puppis is now classified as a cataclysmic variable, more specifically as a Polar, where the white dwarf's powerful magnetic field causes the mass transfer stream to impact directly onto the white dwarf's magnetic poles without forming a disk. The development of observing techniques over the past half century has allowed very detailed observations, see e.g., the VLT spectra of VV Pup by Mason et al. (2008), and obviously X-ray observations with Chandra and XMM-Newton have provided unique insights into such systems.

9.4 V Sagittae – A Super-Soft X-ray Source

Herbig was not convinced that his many studies of peculiar stars constituted an important advance in astronomy, but believed an exception might be his study of V Sge:

"I think the most enduring result was authored by a consortium consisting of George Preston, Joe Smak, Bep Paczynski and myself (1965). We found that the rapidly irregular variable V Sge, under all its erratic activity, is a double-line eclipsing variable with a period of about 12 hours. I think that, in that zoo of peculiar binaries, V Sge is as bizarre and interesting as any."[1]

In their paper (Herbig et al. 1965), they noted that V Sge has defied classification despite much attention from photometric observers since its discovery in 1902. On the basis of time-resolved spectroscopy and new detailed UBV lightcurves (Figure 103) they found that

"... the complex light variations have been resolved into three apparently independent activities: (i) a strictly cyclic variation produced by an eclipsing binary of period 0.514195^d; (ii) an occasional major and very sudden brightening by as much as 3 mag; (iii) minor fluctuations with a time scale of a few days. [...] The spectrum of V Sge contains broad, hazy emission lines of H, He II, O III, O VI, N IV, N V (much as in a WN5 star) on a hot continuum, but also exhibits the unusual feature of sharp fluorescent lines of O III at λλ 3132,3444. These latter lines are double, and the two components oscillate (180° out of phase) in the period of the eclipsing binary and with semi-amplitudes of K_1=320 km s^{-1}, K_2=85 km s^{-1}, where

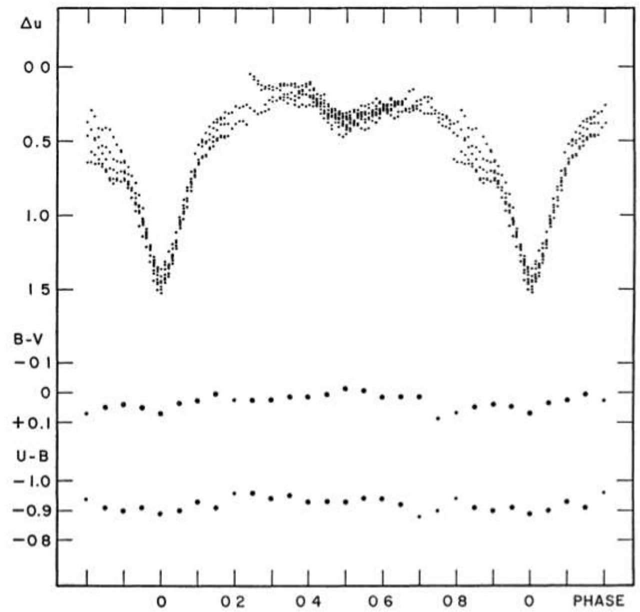


Figure 103: *The super-soft X-ray source V Sge is a 12-hr eclipsing binary, the light curve seen here is in the instrumental u-band. From Herbig et al. (1965).*

> *component 1 is the star of lesser mass and radius, and of higher surface brightness, that is eclipsed at primary minimum. The hazy O VI lines and the absorption reversals in the H and He II emissions are apparently produced by detached material in the binary system. Analysis of the light-curve and colors indicates that component 1 lies very near its limiting Roche surface while component 2 lies well within its lobe. [...] The observational data can be interpreted as the explosive ejection from component 1 of a semi-opaque shell of hot material that quickly, at an expansion velocity of 400-500 km* s^{-1}*, envelops the entire binary system. [...] The masses of the two stars are estimated to be* M_1*=0.74 and* M_2*=2.80 solar units, and the black-body temperatures as* T_1*=44000° and* T_2*=22000° K. [...] Presumably V Sge represents an advanced stage in the evolution of a close binary system."*

Evidently the Herbig et al. (1965) paper was ahead of its time, since for more than 20 years their model of V Sge was the only one and very little attention was given to V Sge. But then in the late 1980s V Sge was discovered as an X-ray source, and numerous studies began to appear (see Smak et al. 2001). Today V Sge is identified as one of the rare super-soft X-ray sources, systems with a very high mass transfer rate onto the white dwarf.

9.5 FG Sagittae – A Thermal Pulse in a Post-AGB Star

> *"Another star that rose from obscurity – a phenomenon that seems to have engaged a disproportionate amount of my time – and that has since become famous is FG Sagittae. Certainly no pre-main sequence star, it is now believed to represent a process that occurs in post-main sequence evolution and which, in a later stage, brings s-process material to the surface. I was involved with two early publications on FG Sge. The first, which I think was responsible for drawing initial attention to the object, was published in 1968 by Alexander Boyarchuk and me. Boyarchuk had come to Berkeley to work with Otto Struve, but because of Struve's departure from the institute he had transferred to Mount Hamilton. FG Sge had slowly brightened by about 4 magnitudes over a period of 70 years, and as the Lick material accumulated from 1960 to 1967, when the star was near maximum brightness, its type changed from a B- to an A-type supergiant. I measured up the Lick spectrograms while Boyarchuk did the curve-of-growth analysis on the coudé plates, and our paper appeared after he had returned to the USSR."*[1]

After the Herbig & Boyarchuk (1968) paper, Herbig went on to other studies, but Langer et al. (1974) continued the spectroscopic monitoring of FG Sge with the 120-inch coudé and, remarkably, found that a host of s-process lines (Y, Zr, rare earths) began to appear in the spectrum. This indicates that material has been dredged up from below due to a thermal pulse of a helium-burning shell, allowing a rare glimpse of stellar evolution in action. Since 1980, the cooling has ceased, and the star remains for now a yellow supergiant.

> *"Even the earliest observations had shown the star to be the center of a faint planetary nebula, and in 1973 Brian Flannery (then a graduate student at Santa Cruz) and I published a note on the expansion of the nebula, inferred from the doubling of its emission lines on image-intensifier spectrograms I had obtained at the 120-inch coudé."*[1]

Flannery & Herbig's (1973) expansion velocity of the planetary nebula surrounding FG Sge combined with its size and distance show that the nebula must have started forming about 6000 yr ago, indicating that the star must have left the asymptotic giant branch at that time. According to Schönberner (2008) it is now believed that FG Sge is a post-AGB star of 0.6 $M_\odot$ which experienced a thermal pulse about 150 years ago while it was very hot, perhaps as hot as 100,000 K. While much better spectra can be obtained today, the data of Herbig and Boyarchuk remain unique in providing information on this brief and rare phenomenon. As noted by Jeffery & Schönberner (2006), the equivalent widths measured by Herbig & Boyarchuk (1968) are invaluable as they permit further analysis using modern model-atmosphere techniques.

9.6 VY Canis Majoris – A Disk around a Massive Young Star

Among the many unusual stars in which Herbig took an interest, he was particularly fascinated by the very young and very massive star VY CMa, located near the edge of a molecular cloud (Lada & Reid 1978). This is a red supergiant (M5 Ia) at a distance of 1.2 kpc with a very high luminosity of $3{\times}10^5$ $L_\odot$. It suffers major mass loss ($\sim 3{\times}10^{-4}$ $M_\odot$/yr), sometimes in bursts which create an irregular, knotty reflection nebula several arcsec across (Figure 104, Humphreys et al. 2007). Its original mass was around 25 $M_\odot$, which by now has decreased to about 17 $M_\odot$. The star is expected to explode as a supernova. At a meeting in Liège, Belgium on pre-main sequence evolution during the summer of 1969, Herbig gave the introductory talk, and among other things stated (Herbig 1970a) that *"Our subject in the past has been one in which the speculative mind could wander freely and far, with only the most general restraints imposed by demonstrable fact. [...] The volume of observational information is now so great, however, that I think it is time to make an effort to match up the domains of theory and observation in a more satisfactory manner."* He proceeded to analyze the available data on VY CMa, with today's eyes perhaps an unusual choice given its evolved state, but due to its brightness much more information was accessible for VY CMa than for other young stars. Following the meeting Herbig was a guest at the Max-Planck-Institute for Astronomy in Heidelberg, where he could concentrate on modeling the data on VY CMa and benefit from the computing facilities at the nearby Rechenzentrum. At that time near- and mid-infrared photometry had become available for VY CMa, showing a major infrared excess. Herbig now modeled this energy distribution, and concluded that it was well described by a dusty circumstellar disk (Herbig 1970b). He solved the transfer of radiation through this environment, separating the continuous spectrum into one scattered in the disk and another from thermal emission by solid gray particles. This appears to be the first time that a disk structure was calculated around a young star, a subject that would soon bloom into an important tool for understanding young low-mass stars. Two years later Herbig addressed the conflicting observations of the presumed companions B,C,D,E,F reported by early visual observers around VY CMa (Herbig 1972). In this paper he started out noting that *"I have looked at VY CMa on many occasions since 1948, often in good seeing, with the 82-inch (McDonald) and 120-inch reflectors, and the 36-inch refractor. The image of VY CMa usually did not appear entirely stellar or round [...] but certainly no convincing sign of B, either as a duplicity or an asymmetry of the image of A in 180°–210°, was ever observed."* To settle the nature of these variable components Herbig did photographic polarization measurements, and found that the knots *"were radially plane-polarized in amounts up to 70% [...] and*

Figure 104: *The young red supergiant star VY CMa suffers copious mass loss and eruptive episodes that result in an irregular reflection nebula seen here in an HST image (Humphreys et al. 2007).*

hence must be structure in the nebulosity, not faint stars." Evidently what the early visual observers saw were knots ejected or condensing in the environment of the heavily mass-losing star. Herbig's last effort on VY CMa was a spectroscopic study (Herbig 1974d), in which he *"was especially intrigued by the fact that in its spectrum the band heads of ScO (in the 6000 Å region) appear in emission. It was possible to infer the rotational temperature from the band profiles (it was very low, about 800 K), a result that as I recall was confirmed by Phillips much later, and also by Lambert. Wallerstein has since pursued this subject, finding also emission of TiO in the same star, but no one has been able to capitalise on this odd phenomenon to tell us something new about VY CMa."*[1] In the 1974 paper, Herbig noted that the ScO emission features in VY CMa are sharply peaked, almost linelike, which he showed is due *"to the crowding of rotational structure near the band heads, on account of a very low rotational temperature; values of about 380° K in 1962 and 820° in 1966 were obtained by comparing the relative intensities of the 6036, 6079 Å peaks with theoretical prediction."*

9.7 IX Ophiuchi – A High-Velocity Interloper in Ophiuchus

B59 is a molecular cloud seen against the Galactic bulge and located in the vicinity of the more famous ρ Ophiuchi cloud and near the edge of the Sco OB2 association (Alves et al. 2008). It is associated with embedded newly born stars as well as some Hα emission stars. A few Hα emission stars are located outside its northwestern edge, and among these is IX Oph. Herbig had taken note of this star already in the 1970s and 1980s and took some spectra with the Lick 120-inch. After moving to Hawaii, he obtained a series of high-resolution spectra at the Keck I telescope, from which he prepared a detailed study. He determined that the spectral type

> *"... is about type G, with many peculiarities: all lines are narrow but abnormally weak, with structures that depend on ion and excitation level and that vary in detail from month to month. It could be a spectroscopic binary of small amplitude. Hα and Hβ are the only prominent emission lines. They are broad, with variable central reversals. However, the most unusual characteristic of IX Oph is the very high (heliocentric) radial velocity: about –310 km s^{-1}, common to all spectrograms, and very different from the radial velocity of B59, about –7 km s^{-1}. There is no detectable Li I λ6707 line. There is reason to believe that IX Oph is actually a background object, only aligned with B59"* (Herbig 2005).

If not a young star originating in the B59 cloud complex, then there would be several possible interpretations of the spectral features of IX Oph:

> *"(1) It is unlikely that it is a high-velocity ejectee from the Upper Sco or Upper Cen-Lup associations (the lack of detectable λ6707 shows that it is not the product of a very recent event, and the proper motion points in the wrong direction) or that it was born in or ejected from one of the distant high-velocity CO clouds at this longitude (l = 357°). (2) A stronger possibility is that it is simply a metal-poor high-velocity G- or K-type giant (but such stars are not irregularly variable in light and do not have such strong Balmer emission lines). More likely, (3) IX Oph is a member of the high-velocity, low-metallicity SRd class of semiregular variables found in the field and in some globular clusters. At some phases, those stars show Hα emission like that found in IX Oph and, in one example, emission lines of neutral metals and double absorption lines as in IX Oph"* (Herbig 2005).

9.8 UV Aurigae – Intercepting Shells from a Carbon Star

Carbon stars produce copious mass loss, which has primarily been investigated through single-dish millimeter observations. But if a carbon star has an early-type companion, then with fortuitous geometry the envelope material from the primary can be studied against the continuum of the secondary. UV Aurigae is such a carbon Mira star with a late B-type companion, and Herbig (2009b) found complex high-velocity structure flanking its interstellar Na I lines (Figure 105a). This is absent in two nearby background stars, and is therefore assumed to be produced by material ejected from the carbon star. The ob-

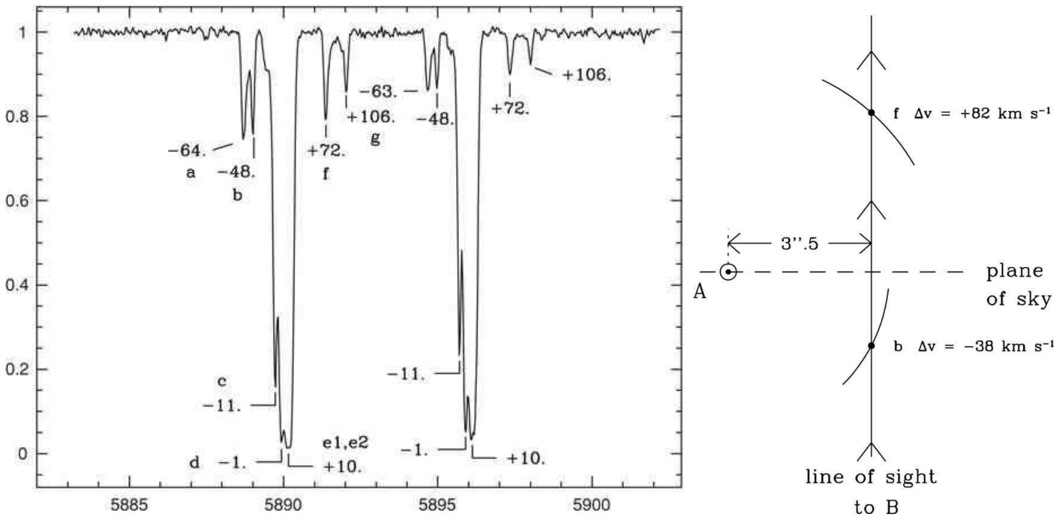


Figure 105: *(left) The Na I $D_{1,2}$ lines towards the early-type star UV Aur B show complex high-velocity structure suggesting they originate in expanding shell segments from the adjacent carbon star UV Aur A. (right) Illustration of the line of sight to the early-type companion intercepting two shells from the carbon star. From Herbig (2009b).*

served features can be interpreted as foreground and background sections of two expanding shells (Figure 105b).

Herbig further noted that, since the carriers of diffuse interstellar bands are believed to be a family of carbon-bearing polyatomic molecules, it is conceivable that they could be produced in the atmospheres of late-type stars. If so, UV Aur B provides the *"opportunity of separating foreground DIBs from DIBs in the ejecta because of the velocity offsets seen at the Na I lines."* However, while DIBs are clearly seen in the spectra, no convincing features were found at the velocities of the shell structure.

10 FROM ASTRONOMER TO PROFESSOR

Lick Observatory had for many years been part of the University of California, and the director of the observatory reported directly to the president of the university. Around 1960, Clark Kerr, a that time a new president of the university, launched a study of the organizational structure of the university, which already in those days consisted of many campuses at Berkeley, Los Angeles, San Diego, Santa Barbara, etc, with more to come. Kerr became aware that Lick Observatory was a research organization disconnected from any campus. He decided that Lick should be affiliated with a campus, and that the Lick astronomers should be taking part in the teaching of students. It was initially decided that Lick should be part of the Berkeley campus, but the Lick astronomers feared that they would have difficulty preserving their identity as part of an already well established astronomy department, and so the idea arose that the Lick astronomers could form their own astronomy department in a newly planned campus in Santa Cruz. George Preston recalls: "Herbig and I became the principal proponents of a move to Santa Cruz as a way to maintain some degree of independence. This was a matter of intense debate among the staff, most of whom detested the notion of moving to a college campus and teaching students. Herbig, as the most respected astronomer on the mountain, led the charge to Santa Cruz over all objections." [34] This was finally approved, and in 1967/68 the Lick astronomers moved to their new environment at the Santa Cruz campus.[35]

For Herbig this meant a major change of life. He and his family had lived on top of Mt. Hamilton for almost 20 years, with all the advantages and disadvantages this implied. Now they moved down to a house in Santa Cruz. From being an astronomer at Lick he was now a professor at the Santa Cruz campus, which involved teaching a variety of courses as well as supervising student projects (Figures 106, 107). The latter was merely a continuation of what he had already done for many years, because he had been advising and mentoring a number of students, who had fellowships at Lick Observatory and, until the move to the Santa Cruz campus, got their PhDs from Berkeley. In the more formal atmosphere of those days, students would address Herbig as 'Dr. Herbig' until the day of their PhD defense, when they were told that they could now call him 'George', a transition that many students found very difficult.

In the following each of the PhD theses that Herbig guided are described, together with reminiscenses from some of his former students.

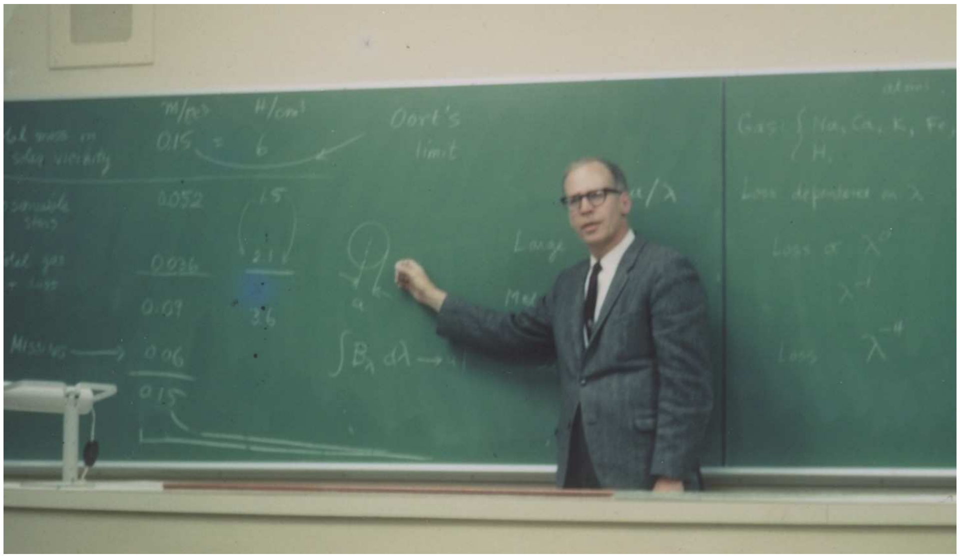


Figure 106: *Herbig giving classes at UC Santa Cruz in the 1970s.*

Elizabeth Roemer. PhD 1955: *The System of Polaris* (Roemer 1965).

When Herbig was first hired at Lick as a young assistant, one of his tasks was to use the Mills Spectrograph on the 36-inch refractor to continue long-term radial velocity programs of unusual spectroscopic binaries. After he became a staff member at Lick, Herbig maintained an interest in these observations:

> *"The 'Mills program' had been a major preoccupation at Lick from Campbell's time until about 1928, when the main results were published as Lick Publications Vol. 16. Observations with the 'New' Mills spectrograph on the 36-inch refractor continued thereafter at a more leisurely pace, now largely of spectroscopic binaries that had been discovered during the main program. Somehow I was persuaded (perhaps by myself, because I had some fondness for the Mills legacy) to see that some of this unique material was worked up. [...] New Mills observations accumulated steadily, after I had corrected some serious temperature-control problems with the Mills spectrograph that the early observers had managed to live with. One by one the orbits came out, usually under the names of various assistants that spent a year or two at Lick in the 1950's. Probably the biggest was the Ph.D.-thesis study of Polaris by Pat Roemer, who measured and worked up all the hundreds of Mills spectrograms that had accumulated since the 30-year binary period (superimposed on the 4-day Cepheid variation) was discovered at Lick in the 1890's. The Mills program finally dwindled away, partially because Shane (then the Director) felt that the return was too slim for the effort required, and because my own interest diminished."*[1]

Beverly T. Lynds. PhD 1956: *Spectra of White Dwarfs* (Lynds 1957). This thesis project was jointly supervised by Otto Struve and Herbig.

"George encouraged me to select the topic of white dwarfs – he was tickled to have somebody besides Jessie Greenstein working on white dwarfs – he said that Jessie had cornered the market and needed competition.

I worked for a year at Lick Observatory as an assistant before starting my graduate work in Berkeley, so I was already good friends with George, Nick Mayall, Gerry Kron, and Donald Shane when I started graduate work. George's 'administrative' responsibility then was overseeing the library and I helped him with that. I assisted with his observing program with the Mills Spectrograph, getting radial velocities of select stars (George included me as coauthor on a paper about 12 Coma Berenices [Herbig & Turner 1953]).

George and I hit it off because we were both avid Gilbert and Sullivan fans and knew most of the lyrics to the operettas. Our senses of humor seemed to fit well with Gilbert's. We also liked to share a beer during midnight lunch. For many years George would send me labels he had peeled off of beer bottles somewhere around the world.

Struve and George both were dedicated to their science – but George was totally focused on his research to the exclusion of almost everything else and resisted efforts to get more heavily in administrative duties. Struve chose to give up his research time to become an administrator – at Chicago, at Berkeley and then because the newly-established National Radio Astronomy Observatory desperately needed an internationally recognized astronomer as director, Struve agreed to take the position and it was at great personal and professional sacrifice. Struve spent a lot of time writing popular articles for Sky and Telescope, and wrote an Introductory textbook in astronomy, while George spent essentially all of his time writing scientific papers. Struve was a remarkable man who endured much to escape from Russia. He was a formal old-school type of person whose only recreation that I knew of was going to the movies. Yes, there was a world of difference between the two and the science needs both types to prosper. I was fortunate in being good friends with these two who I think were leaders in the field." [36]

Robert P. Kraft. PhD 1956: *The Calcium II Emission in Classical Cepheid Variables* (Kraft 1957).

One of Beverly Lynds class-mates was Bob Kraft, who had been admitted to the astronomy graduate program in Berkeley in September 1951. He had the good fortune to land an assistantship with Otto Struve, measuring radial velocities of stars on plates from the Mt. Wilson 60-inch reflector: "But it was more than just a job. It provided the opportunity to work with Otto Struve, the world's foremost stellar spectroscopist, to see how he carried out research, to follow his example, and to witness his hard work and dedication. I was part of a team that turned out several papers on β CMa stars (e.g., Struve et al. 1952). [...] Struve could be harsh in his criticism of science he thought to be slapdash, but he could also be kind and helpful. A man of formidable visage, tall, with a gait and bearing suggesting that of a military officer, he was not given to socializing and glad-handing. [...] I had been awarded a Lick Observatory Fellowship in 1953 and began thesis work on the Ca II emission in classical Cepheids under George Herbig's direction, based on small scale spectrograms obtained with the 2-prism spectrograph attached to the 36-inch refractor. This required many trips to Mt. Hamilton, sometimes even for half-night runs. I spent the summer of 1953 in residence on Mt. Hamilton, separated from my family except for occasional weekends. The Fellowship was a great boon both scientifically and financially: Our second son Kevin was born in Oakland's Kaiser Hospital on August 26, 1954. The Ph.D. thesis was completed in 1955 and I was awarded the degree" (Kraft 2009). Many years later, Herbig recalled: *"I have known Bob Kraft since the early 1950's, when he was a graduate student at Berkeley. His thesis topic, on emission lines in cepheids and long period variables, was suggested by me because I was interested in such phenomena at that time, but I think that Struve was technically his thesis advisor."*[37] Kraft was only 7 years younger than Herbig, and they got to know each other well, especially when Kraft later returned as a staff astronomer to Lick Observatory, where he was director from 1981 to 1991.

George W. Preston. PhD 1959: *A Spectroscopic Study of the RR Lyrae Stars* (Preston 1959).

Preston did a PhD on RR Lyrae stars based on spectra taken with Mayall's nebular spectrograph at the Crossley reflector.

"As thesis adviser, Herbig acted as my advocate in bi-weekly time-allocation meetings held at a table in the Lick library reading room. Stan Vasilevskis (36-inch refractor) and Nick Mayall (Crossley) made schedules for the telescopes based on verbal requests from astronomers who stood around the table. Give and take about needs led to final schedules. I, the only student in residence on the mountain, was not allowed to participate. I stood nearby while Herbig made requests on my behalf. I vividly recall one episode, when a request for Crossley time that I desperately needed was ignored by the astronomers (I was running out of money to support my wife and 2 children - I had returned to school after a stint in the US Army - so I needed to finish my thesis quickly). Overcome by grief, I retreated to the library stacks, but Herbig followed me, saw my condition, then returned to the reading room and later told me 'You got the time'. He had acted on my behalf: he had a heart.

Only one time did I see consternation on Herbig's face. In order to classify Crossley spectra I needed spectra of standard stars. W. W. Morgan's standard stars were *de rigueur* and the faintest of them were too bright - a hundred times too bright for conventional observing with Mayall's spectrograph. Herbig had devised a way to observe them by defocussing the telescope (20 arc sec-image on entrance slit), then running this huge image back and forth along the slit rapidly with guide motors. This procedure produces widened, beautiful uniformly exposed standard spectrograms (these were the days of photographic spectroscopy) - but they possessed one terrible defect! When the telescope is used in this mode, the entrance slit becomes an aperture stop, most of the collimator is unfilled, optical aberrations are greatly reduced, the point spread function becomes much narrower - resolution of the spectrograph is greater, and SPECTRAL ABSORPTION FEATURES BECOME DEEPER - A LOT DEEPER. As a consequence, when my faint target stars - observed in the normal way - were compared to Morgan standards observed by the out-of-focus technique, they *all* appeared to be 'weak lined', i.e. metal deficient. Finding weak-lined stars was the substance of my thesis, and I had become suspicious when I could find no normal faint stars. When I showed Herbig my evidence he was distressed, to say the least; he had given his student bad advice!

Upon completion of my graduate work I applied for the only two positions I knew about at that time - an assistant professorship at Indiana University and a Carnegie Fellowship. Indiana made an offer first and wanted an immediate reply. I was sorely tempted because I needed money. I talked to Herbig. He viewed my interest in Indiana with what I can only describe as contempt, telling me that I should turn down Indiana and wait for a reply from Carnegie - because it offered immensely greater career opportunity. I reluctantly did so, and I did receive a Carnegie Fellowship, which propelled me to a successful career." [38]

Following the Carnegie fellowship, in 1960 Preston was offered a staff position at Lick Observatory, and he and Herbig became colleagues. The 120-inch telescope had just gone into operation, and Herbig had completed the new coudé spectrograph (see next chapter) of which he was very protective. Hence Herbig strongly objected to the then director Whitford's policy of allowing experimentation with various electronic detectors at the coudé. Preston recalls:

"Merle Walker had installed a Lallemand image tube at the focus of the fastest (20-inch) Schmidt camera. The tube was cooled by glycol circulating through small rubber hoses, and once one of them burst, spraying the camera mirror with this sticky stuff. Repair required removing the whole camera from the coudé room – a lengthy difficult process. George was in charge of the coudé, and his policy disagreement with Whitford came to a boil one day when George flung open the door of my office and shouted to me '*Will you take over responsibility for the coudé?'* I replied something like 'Well, George I ...' and he shouted again '*Will you?'* I said 'Well, I suppose ..' and he left slamming the door shut behind him. Soon thereafter, Whitford appeared in my office to ask what was going on. Herbig later, in a moment of relative calm, informed me that as far as he was concerned I could fill the entire coudé room (with all the camera optics he had so carefully designed and brought into operation) - fill it with chocolate sauce! [Long after, Preston got the final word in that discussion when he on the occasion of Herbig's 80th birthday sent him a crate with 24 cans of Hershey's chocolate sauce, much to Herbig's amusement.]

In our professional lives we had little intellectual overlap. He studied young stars. I studied old stars and magnetic stars, both of which made his 'eyes glaze over' (his words to me). Nevertheless, we had a strong friendship, based in part on our mentor-student relationship, in part our shared views about the goals and future of Lick Observatory, and in part our mutual interest in professional football. To close: I have (mostly) fond memories of George Herbig. He was a startling, wonderful, immensely complex man." [39]

Leonard V. Kuhi. PhD 1964: *Mass Loss in T Tauri Stars* (Kuhi 1964).

Kuhi was the only of Herbig's students who did a thesis specifically on young stars, an interest he maintained, and which later led to the famous Cohen & Kuhi (1979) spectroscopic study of about 500 young stars.

"I would say that George was not a hands-on graduate adviser, but interactions with him were always productive. I first worked for him as a summer student at Lick on Mt. Hamilton. He had taken a series of photographs of the NGC 2068 region with the slitless grating spectrograph on the Crossley reflector. A filter of about 400 Å centered on Hα allowed one to find emission-line stars. He showed me how to search the plates for such stars, but basically left me alone to do the work. We would meet once a week or so to discuss the project, new results etc., but he was the astronomer and I was the assistant. The paper published in 1963 reported on 45 new H-alpha emission stars that were T Tauri stars. That was the only paper we wrote together, although I recall that he did most of the writing [Herbig & Kuhi 1963].

My thesis work was done on Mt. Hamilton in 1962-63. I lived on the mountain at that time as did everyone else. Summer students all lived in a dormitory just below the old observatory building and the newer extension. They came from Berkeley and UCLA. I and my wife were fortunate to move into a small cottage (long since demolished) for my thesis year.

I think that George was very loath to take credit for his students' thesis work. He felt that the dissertation was the student's project and he just provided some guidance along the way. Sometimes he might have suggested a possible topic or direction of research but he would not be a co-author unless it was truly a joint research project. He was very modest and unassuming. Again he instructed me in the use of the coudé spectrograph on the 120-inch at Lick and then left me pretty much alone to make the observations and do the work. During my thesis work we did meet semi-regularly and he usually had good suggestions to make and questions to ask. But he did not insist on controlling the research.

One thing that really impressed me about George was his meticulous attention to detail, especially in the use of the telescopes and spectrographs at Lick. Everything was spotless and tuned to maximum performance. That included me!" [40]

Ann Merchant Boesgaard. PhD 1966: *The Abundance of Lithium in Early M-type Stars* (Merchant 1966).

"In the summer of 1964 I went to work for George as a summer assistant on a project about beryllium in solar-type stars. I wanted to do a thesis with him, about Li, but we worked on this project that summer. To see if we 'could work together' (i.e., if I was good enough?) Apparently, I passed that test.

So then I worked on Li in evolved, cool giants and supergiants. There were some late-type stars which showed wallopingly strong Li lines. Over-abundant Li or just an effect of ionization of the Li I atoms which had low ionization potentials? This involved taking spectra with the 36-inch refractor, basically 2 nights a week, for what seemed to be endless weeks! And I was beset not only with rats infesting the dome and showing up for 'midnight lunch', but also with some fierce nights of ice and snow. I remember one night when it was crystal clear outside, in the depths of the Mt Hamilton winter, when I called Don Miller: 'Can you clear off this ice and snow?' We tried, but had to give up. It also involved taking high resolution spectra at the coudé of the stars which showed strong Li. So I got to assist George at the coudé about once a month for 2-4 nights. I had a generous amount of his time for my thesis observations. Some nights it was a star for him, a star for me.

I knew that developing those photographic plates was as much art as science. So I was surprised that, after much instruction, that task fell to me. No one is much thrilled by the smell of those chemicals. But the haunting, oily smell as you walk into the 120-inch dome is still with me today.

Life on Mt Hamilton was pretty rigid: work 8-12, 1-5 + evenings for students. Meals at 7:30, 12:15, 5:30. Sometimes I slept in the basement of the Preston house, sometimes in the old dorm, sometimes in the new dorm; George intervened on my behalf for the comforts of the new dorm. I did enjoy my weekends in Berkeley away from the fixed schedule.

One of my fond memories was helping George and Hans[41] in the alignment of the five mirror system for the coudé. George was in the coudé room and Hans was up on the fork on the arch where the fifth mirror was. My role was as a messenger, in the slit room, shouting the words of one of them to the other. The most common commands seemed to be "go the OTHER way."

Figure 107: *Herbig with his student Ann Merchant Boesgaard in June 1972.*

George taught us all not to lose one photon and not to lose a moment of observing time. In part this sprang from competing with the 200-inch. The 120-inch could do as well, and it did, until they responded to the challenge by cleaning up their act. The long-term effect of this tense photon- and minute-saving attitude was not only that I did this myself, but also that I suffer anxiety dreams still. I am at the telescope, the sun is going down, and I am not ready. There have been a number of different themes as to why I am not ready in these dreams: the plates are not warmed up from the freezer, I don't have the coordinates for the star, etc.

My first draft of my thesis was typed on yellow paper, triple-spaced to have room for his comments. Those pages seem to have as much of his penciled suggestions and corrections as they do of my text." [42]

Robert R. Zappala. PhD 1971: *The Abundance of Lithium in Galactic Cluster Stars* (Zappala 1972).

"In 1967 I was excited to be part of the inaugural class of graduate students at the beautiful new campus of UC Santa Cruz. I had been working with Al Hiltner at Yerkes on the newly discovered polarization of long-period variable stars and decided to extend that work for my PhD thesis. With the help of Joe Wampler and the Lick shops, a polarimeter for the 36-inch Crossley reflector was put into operation in about a year and I began work.

My work on the Crossley was moving ahead, although the ancient telescope was certainly no pleasure to use, when suddenly several papers on the polarization of long-period variable stars appeared in print and it became obvious that there was no clear path to a thesis topic for me in that direction. I talked things over with George and he suggested that I work for him and extend lithium depletion studies to the lower-main-sequence stars of nearby open clusters. More specifically I would obtain spectrograms of F to K main-sequence stars in the Hyades, Pleiades, and Praesepe clusters, and of still contracting stars in the NGC 2264 cluster, allowing the study of lithium depletion over time. This would necessitate designing and constructing an image-tube camera for the coudé spectrograph of the 120-inch reflector.

From then on I would meet with George in his office 2-3 times a week and, as well as engineering the new camera, we discussed astronomy and many other topics. I had a broad range of interests outside astronomy and was surprised to find that George did too. He had even published some science fiction (under a pen name) in his younger years! He also often exhibited a wry sense of humor that was quite entertaining. I remember discussing that my wife and I were smitten with the new little BMWs and were considering buying an orange 1602. We ultimately opted for a Datsun 510 instead, deciding that discretion was best for graduate students. Several months later George wore his best crocodile grin as he showed me his brand new dark-green BMW 2002!

After several months George and I carried the completed camera to Mt. Hamilton and installed it on the 20-inch camera of the 120-inch coudé spectrograph. After a brief debugging period we found that the camera worked quite well (at least for a pre-CCD device.) After working with George for several nights I began to get my own time on the 120-inch during the bright run and to pursue my thesis observations. Many of my nights were scheduled during the holiday periods when demand for telescope time by the Lick staff and UC faculty was low. I usually stayed in the dormitory taking meals at the observatory dining room, but occasionally Katy and I would stay in one of the apartments and ward off the aggressive raccoons!

Later I assisted George with the construction of an image-tube guider for the coudé focus that allowed us to acquire very faint objects such as the strong infrared emitter IRC+10216, which our image-tube spectra revealed to be a highly reddened carbon star. It was always a pleasure to observe with George, an extremely efficient worker who was able to massage the equipment and get the best out of every night."[43]

W.R. Alschuler. PhD 1974: *Observations of lithium dilution and rotational velocity decay in F and G giant stars* (Alschuler 1975).

"A few years after I arrived in Santa Cruz (1967), I decided to ask Herbig if he would take me on for a thesis and he agreed. I first expressed interest in doing a Hubble telescope based project, but he did not expect it to orbit for a number of years, and told me to steer clear. He was right, of course. He then suggested as a topic the problem of lithium in the F and G Giants, presumably first-time crossers of the Hertzsprung gap. I was happy with that, and not long after it occurred to me that my spectra would be suitable also for rotational velocity determinations in addition to lithium abundances, and this would give me a two-handed grip on the properties of the stars' convection zones and at the same time the structural changes due to radial expansion. That worked. George asked questions, always good ones, as I proceeded, but left me mostly on my own. I did the observations and some minor adapting to models supplied to me by Icko Iben and Peter Bodenheimer to make the theoretical predictions for comparison. In the end Herbig and the rest of my thesis committee approved my thesis and I got my degree in 1974.

George's manner was rather cool, I thought, and I rarely saw flashes of humor. He always had something clear and important to say, or he did not speak. George did not really have much tolerance for wasted time. I think he was one of the best organized observers I knew, with an excellent eye for project design, skill and care in observation, and extreme caution in not going beyond the data in reaching conclusions. He also could see where the field was going. In all these areas he set a high standard and I was proud to meet it in my work with him."[44]

N. Kameswara Rao. PhD 1974: *A study of the spectrum and colors of R Cor Bor at minimum light* (Rao et al. 1990).

"I was fortunate to get both admission and a fellowship at UC Santa Cruz in the fall of 1969 which enabled me to study in USA. George Herbig was giving us a course in interstellar matter during the fall quarter. He was already a famous man. During a chance encounter at the campus one foggy morning, we got to talk and I expressed my interest in young stars, and he told me about the new results on infrared excesses from circumstellar material around the T Tauri stars. I think some time in the fall of 1970 I approached George, asking whether I could work with him on T Tauri stars, and this led to my work on what was to become the Herbig-Rao catalog of young stars [see Section 2.6].

I think I was very fortunate to have had George Herbig as my advisor and guide. He was my thesis adviser too – I worked on minimum spectra of R Cor Bor for my thesis – nice 120-inch coudé spectrograms which George obtained in 1962 at 16 A/mm dispersion. I did not get back to T Tauri stars afterwards. For the facilities available to me in India at that time, T Tauris were much too faint for any meaningful spectroscopic follow-up investigations." [45]

David Soderblom. PhD 1980: *Rotational velocities and ages of solar-type stars* (Soderblom 1982, 1983).

"George and I spent a lot of nights together on Mount Hamilton in the 1970s: George would be on for 3 or 4 nights each month at the 120-inch coudé, and after I started my thesis I would be on the CAT for my own observing for a week or two in addition. This made it almost impossible to achieve any real progress, since you were always either getting ready for a run, or recovering from the last one. George was always supportive through a period longer than it should have taken anyone to do a thesis, and I wondered at times why. It wasn't as though we had long talks about the meaning of life in the middle of those long, cold, December nights with dome air being sucked down onto your lap by the exhaust fan that he thought improved the seeing. On the contrary, I suspect the lack of conversation was to his liking.

During his run we would usually use his Varo tube on the back of the 20-inch camera to get spectra of T Tauri stars; it was cooled by vapor from a dewar of liquid nitrogen, boiled off with a resistor heated by a variable voltage. On some nights we'd get 50 spectra, and that meant I got lots of exercise running down into the coudé room from the slit room, pulling off the plate holder, loading a fresh plate, and replacing it on the back of the Varo tube. I got pretty good at it, and managed to avoid leaving my blood and hair on the many sharp protrusions in the coudé room. After a few exposures, I would head into the darkroom so we could keep up and see what we had. I sure don't miss the smell of chemicals on my hand one bit.

'So what do people look at near eleven hours [RA], anyway?' he asked one night. In the spring there was a dead time of the night after Orion set and before the summer Milky Way was up, that time of the year that our extragalactic colleagues cherish. That dead time allowed for more adventurous observing, the kind you really wouldn't want to have to justify to a Time Assignment Committee. For those occasions George would collect odds and ends of variable stars to observe, just to see if something interesting popped up. One of those nights, with little to do, we stopped dead and spent several hours just puttering with the coudé optics to align them. On another, we spent a few minutes to get a spectrum of a star that had been a nova about ten years earlier: HR Delphini. Because it was pretty faint, we decided to trail the plate halfway up and down the slit instead of the full trailing we would use on T Tauris. The plate turned out to show evidence for an expanding shell in nebular emission lines. This was true serendipity at work: HR Del had to lie in an otherwise uninteresting part of the sky or George would never have observed it at all. It had to be just faint enough to force us to trail it half way because if we had used full trailing we wouldn't have seen the structure in the emission lines that stuck out past the stellar spectrum, yet it had to be bright enough to observe at all. And we were lucky enough to catch it at a position angle where the structure was evident. Without all these ingredients, nothing interesting would have shown, and with that plate (and additional spectra) we were able to deconvolve the structure of the ejected material." [46]

Douglas K. Duncan. PhD 1981: *Lithium Abundances, K Line Emission, and Ages of nearby Solar-Type Stars* (Duncan 1981).

"I approached George to do a thesis on Li Abundances and Ca II Emission in solar type stars because Olin Wilson had come to UC Santa Cruz to spend a month (around 1976), and he gave lectures including his discovery of sunspot cycles on other stars. Olin was quite a character and the science was very exciting to me. He also pointed out that no Ph.D. candidates that he knew were studying stars like the sun. (At almost the same time the Einstein X-ray satellite was launched, and Bob Rosner as a theorist and Sallie Baliunas as an observer began studying solar-type stars. I ended up working with both.)

George was much lower key. He accepted me first as an assistant, and gave me an assignment to try and detect weak interstellar features. The great advance of the time was an image intensifier in front of the small photographic plates installed on one of the shorter focal length coudé cameras. George took many of these of the same hot star. I traced them on a microphotometer and programmed the phone-booth sized PDP-8 computer to add all the spectra to smooth out photographic grain and noise. I eventually discovered that fixed pattern noise in the image tube limited the S/N no matter how many plates were added. (Hurrah for CCDs!). He must have thought that I did a good job, and he accepted me as a thesis student. George was a very hands-off advisor. We typically met once a month, not too much more. He gave good advice, but sparingly." [47]

Geoff Marcy. PhD 1982: *Observations of Magnetic Fields on Late-Type Stars* (Marcy 1981, 1984).

"George took me observing at the 120-inch telescope every month for four years. He patiently taught me spectroscopy and he led me through many projects. Among them were studies of the binary nature of the central stars of planetary nebulae, the hydrogen emission-line variability of T Tauri stars (on the Crossley telescope), Zeeman measurements of Sun-like stars, and the binary frequency of T Tauri stars. During the first three years he was my thesis advisor, but when he went on a sabbatical he suggested that Steve Vogt take over for the remaining year.

In my weekly meetings with George, he always wanted me to explain exactly what work I had done, including what worked well and what didn't work and why. He was very attentive to details, and driven to find a technical approach that might be better than previous techniques. For example, he directed me to digitize the photographic plates of spectra of T Tauri stars he had taken for 10 years, looking for binary stars among them. I dutifully used a new photographic plate measuring engine equipped with a photomultiplier tube to measure the transparency of the plates on the spatial scale of the silver halide grains. George directed me to measure the radial velocities of stars using the digitized photographic plates, hoping to reduce the errors from the common 1 km s^{-1} down to perhaps 0.5 km s^{-1}. After a year, I didn't make much progress, so George had me drop the project. I never forgot how frustrated he and I were that the errors in radial velocities didn't diminish despite digitizing the plates. Obviously, the source of errors in the radial velocities occurred before the detector.

Later, at Mt. Wilson, that puzzle bugged me more, leading to my careful guiding of the star on a narrow entrance slit at the Mt. Wilson 100-inch telescope. Eventually this puzzle led me to use iodine gas at the focal plane, as suggested by solar physicists David Bruning and Bob Howard, to track the errors in radial velocity due to off-center guiding of the star. This led to an RV precision of 1 m/s, 500x better than George's 'dream precision'.

I remember the intensity in research that George demanded of me. One day while driving back from Lick Observatory I mentioned to George that the atmospheric term 'Greenhouse effect' was a misnomer because greenhouses trapped heat by confining the convective motions to the housing, while the Earth's atmosphere traps heat by the various gases that absorb mid-IR light. He heard me, and didn't respond. Eventually he said, 'You know, Geoff, you really should be spending your time thinking about the radiative transfer in stars, not greenhouses'.

I know that the overarching message George taught me was to work carefully, to double-check all measurements, and to draw physically meaningful interpretations that don't stray too far from the data. George's approach to research influenced all of my work." [48]

Scott Dahm. PhD 2005: *The evolution of young clusters* (Dahm 2005).

"Shortly after I arrived at the Institute for Astronomy as a graduate student in August of 1998, I attended a seminar that George, then 78 years old, gave to the first year graduate students. George's lecture reviewed his then recent work in IC 348, the first of the young cluster papers produced at the Institute for Astronomy. He also touched upon a search for T Tauri stars in the Cygnus OB 2 association that he had recently begun using the slitless grism spectrograph on the University of Hawaii 2.2 meter telescope. The issues he raised concerning post T Tauri stars, isolated star formation and the initial mass function remain open questions to this day. This one lecture convinced me to explore the issue of star formation in more detail. After a couple of weeks had passed, I cautiously knocked on his office door on the second floor of the Institute for Astronomy. George turned away from his Sun workstation – aptly named Orion – and invited me to sit down in the chair that I would subsequently sit in countless more times over the course of the next six years. He had a project in mind for me and walked over to his filing cabinet where he drew forth a manila folder with a tab titled 'IC 5146'. From this he pulled out an image of the beautiful emission-reflection nebula that Walter Baade had taken with the Hale 200 inch telescope. Baade had given the print to him decades ago and his handwriting was on the back of the print. It struck me at the time that I was handling a historical document. Through George I was reaching back to the early giants who built the foundations of astronomy, most of whom were now long deceased.

As an advisor, George was extraordinarily generous with his time, never once turning me away the countless times I visited him in his office. Even if in the middle of measuring an equivalent width or writing code, he would invite me in, turn his full attention to my question, and then work to resolve it.

Although we observed with Keck I on several occasions, I observed with George from the summit of Mauna Kea only once. It was a two-night run with the now long decommissioned HARIS spectrograph on the 2.2 meter telescope. Weather conditions on the summit were poor when we arrived at the midlevel station, Hale Pohaku, but late at night, well after midnight, our telescope operator came in to see George and I in the reading room just above the dining area. Conditions on the summit had improved enough to where he thought we could open. We drove up the gravel road at a frantic pace, opening around

2 am. George was 79, and observing from 14,000 feet is not easy even for the young. But there he was eagerly waiting for each read-out of the CCD and producing line cuts across the spectra and identifying for me various absorption lines. That night and the following we observed several OB stars in NGC 2362 and a handful of other young clusters.

George's knowledge of the sky was exceptional and probably rooted in his teenage years as an amateur astronomer. One night he glanced up and without hesitating commented to me that Mira was near minimum. Numerous times I would bring to him images of star forming regions or embedded clusters while piecing together my thesis outline. He would glance at them briefly and say something to the effect of, *"ah, yes, that is IC 1274 – extraordinary, isn't it? The dark cloud to the east is Lynds 227. The central B star in the nebula is HD 166033. I surveyed that region at Lick and found a handful of Hα emitters..."* His memory of papers was legendary and in conversation he could recall not only the principal results of a paper, but the author, journal and year of its publication. He read preprints and reprints daily and spent many hours in the library at the Institute for Astronomy reviewing the literature.

George always emphasized that when examining a problem, one must look at the larger picture to understand what processes are at work. We would often walk into the copy room at the Institute for Astronomy where the large negatives of the Palomar Sky Survey were retained. Before studying a given star-forming region, he would familiarize himself with the field, examining features that lay several degrees away from the star-forming region that we were interested in. It became a habit for me in the years that followed. With the availability of the Digitized Sky Survey, this technique is now all but lost. There is something missing, however, when one is constrained to less than two degrees of the sky.

When I graduated from the Institute for Astronomy in 2005 (Figure 108), George felt that it would be good for me to move – away from 'west coast astronomy', as he termed it. Ultimately, however, I stayed on the west coast, moving instead to Pasadena for three years before returning to Hawaii and W. M. Keck Observatory. There I would assist George on a handful of occasions as his support astronomer, helping him with his favorite instrument (and mine) – the High Resolution Echelle Spectrometer (HIRES). George and I would talk through the night, discussing papers during long exposures. He was a patient and careful observer. Even in his late 80s, he would arrive in the remote operations room with echelle and cross-disperser angles for HIRES long established. His motions with the control software were deliberate and exact – as those are of most instrument builders, who understand that, downstream of the software are moving mechanisms."[49]

Figure 108: *Herbig's student Scott Dahm defended his PhD at the University of Hawaii in 2005. Dahm was his last student since, at 85, Herbig decided that it was time to stop supervising students.*

In an interview[50], Herbig was asked about the people who had influenced him most as a student, to which he replied Otto Struve and Alfred Joy, and he then added:

> *"I cannot believe that I played a similar role in influencing the careers of any of the students that I advised or worked with at Lick. I suspect that those who went on to notable careers would probably have done just as well with guidance from someone else.*
>
> *Personally, I would have no hesitation in choosing astronomy as a career again. As to advising graduate students, I always tell them that if there is nothing else that would satisfy you or make you happy, go ahead toward astronomy as a career. But be warned: you will be in competition with a lot of bright people, especially those coming from physics, so you should have some special talent or insight or idea with which to make your mark. It is not enough to turn the same old crank that your thesis advisor has been turning."*

11 INSTRUMENTS AND TELESCOPES

Herbig was recognized as an extraordinarily careful observer, with a deep understanding of what occurred inside the many instruments he was using throughout his long career. Less well known is the fact that he was also a first-class instrumentalist, who through his career built many of the instruments he needed for his research. Of course, the instruments and techniques he had access to or developed, especially in the early years at Lick Observatory, have little resemblance to what is available today. It is worth keeping in mind that much of the fundamental work Herbig did in the 50s and 60s on T Tauri stars, Herbig Ae/Be stars, FUors, Herbig-Haro objects, etc., was done with techniques and instruments that have all but vanished. Here are some recollections that Herbig late in life wrote about observing at Lick during his early years there:

> *"As about the last surviving Lick/Mt. Hamilton old timer, I thought that there might be some value in an account of how spectroscopy was done at Lick in the 1940's, and particularly after 1943 when my own experience began. It is incredible to me, now immersed in the CCD giant-telescope era, how we managed to accomplish anything worthwhile, considering the difficulties with which we then (unknowingly) had to cope.*
>
> *In my early years at Mt. Hamilton the main spectroscopic instrument was the 36-inch refractor, about f/18 and of course visually corrected (i.e. minimum focus at about 5500 Å). For many years it had been devoted to the radial velocity survey of the stars brighter than m(vis) = 5.5, with the so-called New Mills Spectrograph, 3 prisms in a temperature-controlled box, covering the region about 4400 to 4600 Å at 11 Å/mm. Although the 36-inch refractor had originally been provided with a large photographic correcting lens (that had to be inserted at the top of the tube), it was never installed in my time, so for the Mills and other spectrographs working in the 'photographic' blue-violet region, a small (about 2-inch) photographic correcting lens had to be inserted about a meter inside the focus. This lens was mounted in an x-y stage that was controlled by knobs accessible from below, so the first task of the night was to set on a bright star and adjust the lens position so that the colored halo around the blue core looked symmetric. Because of flexure in the telescope tube, as the pointing changed, the telescope axis moved with respect to the lens center, so the observer had to re-check this adjustment after moving very far in the sky.*
>
> *The Mills required other kinds of attention as the telescope focus changed with temperature, and one had to fuss with the heating system to be sure that the temperature inside the box didn't change an unacceptable amount*

during the exposure.

With the faster photographic emulsions that became available in the 1950's, an exposure time of about an hour sufficed at mag 5.0 for the Mills, of course hand guided by the vigilant observer at the eyepiece who kept the star on the slit via push-buttons and handwheels, who also had to rotate the dome, watch the windscreen, and adjust the floor level.

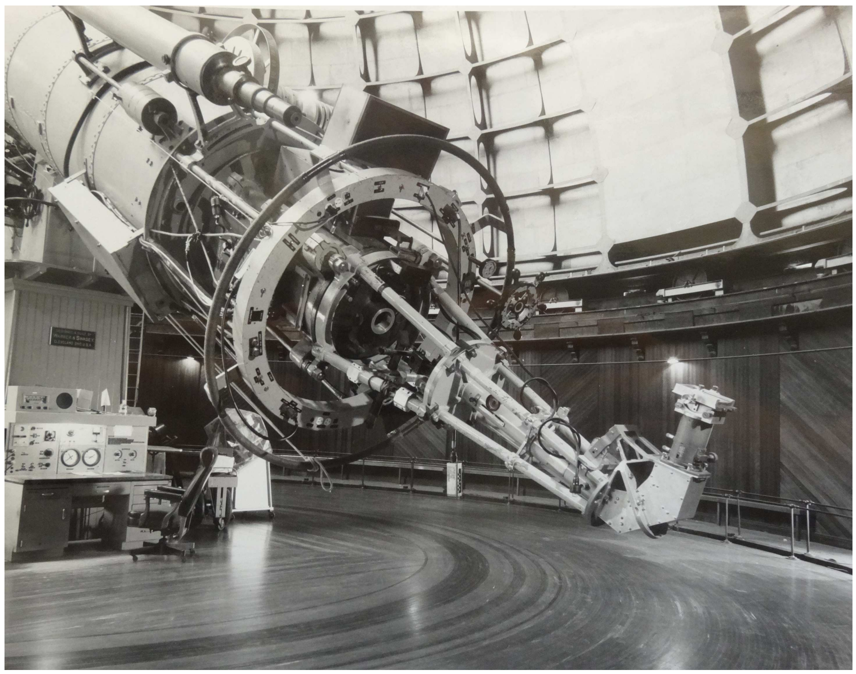


Figure 109: *The 'Original' Mills spectrograph mounted on the 36-inch refractor. Herbig used this instrument extensively in his early years at Lick Observatory.*

Of course I was interested in stars fainter than mag. 5, for which one had to turn to other prism- and camera combinations that could be bolted on to the frame of the 'Original' Mills spectrograph (Figure 109). Camera focal lengths from 3.5- up to 32-inches were available, together with 1- 2- and 3-prism assemblies of light flint glass (for the shorter wavelengths) and of dense flint (for the longer), as well as collimator lenses corrected for the blue-violet and for the yellow-red. Some of these combinations required the camera axis to protrude at an angle of 60 degrees or more with respect to the collimator axis, so to stabilize the camera against flexure, a series of steel bars were provided, to form the hypotenuse of the camera-collimator triangle. There was a pivot point at the prisms, the theory being that as the dome temperature changed (this spectrograph was not thermostatted) and the index of refraction of the prisms changed, the steel bars would shorten *or lengthen by the amount required to keep the spectrum from moving in the focal plane. I was never sure if this really worked in practice. Also provided were one or two thin metal wedges that could be inserted between the prism boxes to change their angle of minimum deviation.*

In the late 1950's there was interest in spectroscopy at longer wavelengths than these prism assemblies could deliver, so we built a small reflection-grating spectrograph to attach to the 'Old Mills' slit-and-collimator unit, the camera being a Kodak Aero-Ektar lens of 7-inch focal length, from Air Force aerial cameras then appearing on the war-surplus market. For this device, Frank Ross designed a correcting lens to move the focal curve of the 36-inch refractor from its minimum near 5500 to somewhere near 8000 Å. This arrangement was not used very extensively because soon thereafter the 120-inch coudé spectrograph came into operation.

In those days, the only detectors available were photographic. One sees on pre-1943 plate envelopes the names of long-forgotten brands of photographic emulsions, the best and fastest then available on the commercial market: 'Imperial Eclipse 950' and 'Cramer Hi-Speed'. I don't know when Kodak became interested in the astronomical market: I have heard that C.E.K. Mees, then a big wheel at Kodak and an amateur astronomer, got the Kodak Research Laboratory into the business of custom-tailored astronomical emulsions. One could order plates of any size, with color sensitization from type O (ordinary blue-violet) through G (about right for visually- corrected refractors) and N (near-infrared to about 8800 Å) and M (to about 1.2 μm), and speed and graininess from type I (the fastest and grainiest) to type V (very slow, very fine grain and high contrast). Later they developed type 103 (speed of I and graininess of III) and 103a (same, but designed for astronomical use at low light levels) and IIa-O. How a giant organization like Kodak put up with piddling astronomical orders of a few dozen odd-size plates I can't imagine.

There were endless attempts to increase the speed (or lower the reciprocity failure) of these emulsions, such as baking, flashing, ammoniating and exposure to mercury vapor. How unthinkable by present standards was our practice of having a bottle of liquid mercury on hand in the darkroom for this purpose!

At the 36-inch, the practice was to buy plates in the 3 1/4 $\times$ 4 1/4-inch size and slice them in half to fit the spectrograph plateholders, so we became adept at the use of wheeled glass cutters in the dark. When the 120-inch became operational, things changed. The focal planes of the shorter cameras at the coudé spectrograph were curved, so plates were obtained on thin glass

(0.8 mm thick as I recall) that could be bent. At the 20-inch camera, these plates were stressed near the limit and all too often at the end of an exposure the plate was found to be in two pieces, despite the procedure of pre-stressing them in a bending-box in the darkroom.[51] *This thin glass was cut with a diamond glass cutter mounted in a precision cutting table bought from the Mt. Wilson & Palomar Observatories, which were usually ahead of Lick in such matters.*

In the photographic era, every dome had its refrigerator for storage of plates, and a darkroom for developing the output. Grateful am I that all that is behind us: the mixing of chemicals, the debate of whether D-19 or D-76 or DK-50 was the best developer, the hand-magnifier examination of dripping-wet plates at the light-box over the sink, ... the unforgettable smell of those darkrooms.

Before the 120-inch, time on the 36-inch and Crossley was parcelled out every Thursday afternoon at an open meeting of the observers in the Library. The 36-inch night was divided in halves, and observers were required to install their own equipment, so the second-half observer often had to remove what he found on the telescope, and put on his own. This was not a trivial task for spectroscopists: it entailed tieing down the lower end of the telescope, sliding the spectrograph and correcting-lens unit up a sloping carriage, bolting them on, and rebalancing the tube. Of course there was no one to do this except the observer.

At the Crossley, the observer was also completely on his own. After the telescope was firmly clamped, the spectrograph or the double-slide plateholder (for direct photography) had to be lifted from its box, lowered into its supporting brackets at the top of the tube, bolted down, and the tube re-balanced. No help at all, of course. When I first used the Crossley, the RA drive was not via a single worm-and-wormwheel to drive the telescope continuously, but worked through a system of two pie-shaped sectors that took turns in driving the telescope in RA for some fifty minutes, at the end of which there would be a warning bell so one could close the shutter and wait for the other sector to resume the drive, which happened after much clanking of relays. Then the observer had to pick up the star again. When the sectors were replaced with a conventional 360-degree worm wheel, there was much rejoicing. Although observing at the Crossley was hard work, cold and windy, I enjoyed the experience of standing on the platform (which ran on tracks up and down the shutter arch), almost in the open, with nearly the whole sky above. One got used to being careful in the dark: it was a long way down to the dome floor. In those days the Mt. Hamilton sky was very dark. Often when I trudged wearily home with a heavy box of plateholders, I would *stop and admire the morning zodiacal light coming up in the east, and the gegenschein – quite apparent if it fell away from the Milky Way. If Venus was bright in the east, its outline of the open shutter on the opposite side of the dome was very obvious."*

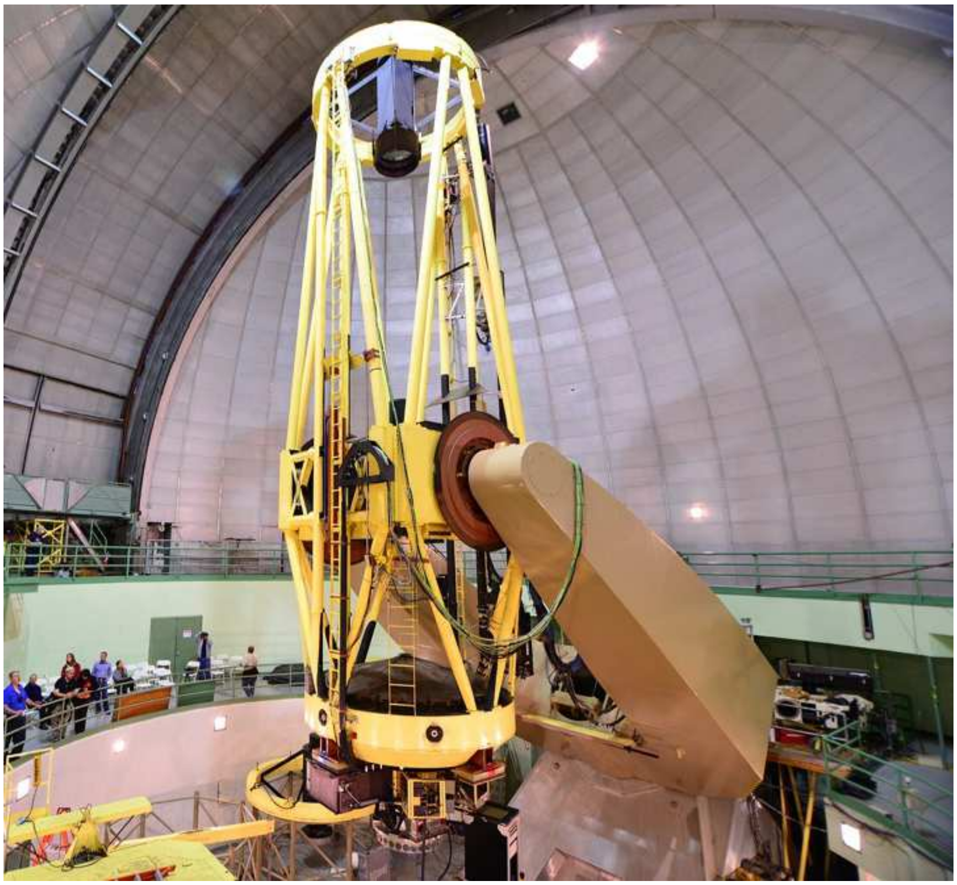


Figure 110: *Lick 120-inch Shane telescope.*

After the 5 meter Palomar telescope went into operation, it became increasingly clear that Lick Observatory could not remain competitive with only the two ageing 36-inch telescopes, but that a new large reflecting telescope would be needed. Plans were drawn up for a 120-inch reflector (Figure 110), and after funding had been secured, design and construction took place during the 1950s. The first spectrum recorded in the logs of the new telescope was obtained by Herbig on the night of October 22/23, 1959: a 22 minute exposure of χ Cygni. When the 120-inch at Lick Observatory went into operation, Herbig had the second-largest telescope in the world at his disposal. Osterbrock in his book 'Eye on the Sky' about the history of Lick Observatory, writes:

"It was Herbig who insisted that the 120-inch could not be completed as a bare-bones telescope equipped for research with only a prime focus. During two weeks of each month, when the moon is near full, the sky is too bright for research on very faint stars, which would be done at the prime focus. High-disperson spectroscopy of bright stars could be done near full moon, but little else. Many discoveries remained to be made in this field, Herbig argued, as the astronomers at Mount Wilson and Palomar were continually proving. It would be foolish not to build a coudé focus and thus to foreclose the possibility of making discoveries at Lick. His arguments won the day and the coudé was added, together with a superb spectrograph that Herbig designed and had built."

Figure 111: *The observer's end of the coudé spectrograph designed by Herbig for the Lick 120-inch telescope. In the early days, the observer would guide the telescope by patiently monitoring the position of the star on the slit. Autoguiders were later installed. The Lick engineer Hans Boesgaard is at the eyepiece.*

Herbig's coudé spectrograph (Figure 111) was to be housed in a giant concrete box at the south side of the 120-inch building, partly underground. While this would seem to be a fairly simple structure it ended up causing a surprising amount of trouble due to a number of curious issues, described by Herbig as follows:

> *"The concrete box was a separate structure from the cylindrical main building, deliberately so that vibration from the turning dome would not be transmitted to the spectrograph (Figure 112). The two were separated by a gap of about an inch, filled with felt. This was fine until a few years later, when the chief engineer (Bill Baustian) was replaced by Larry Berg, who was probably unaware of the issue, and decided that that gap should be filled with liquid concrete. Once that was done, it was discovered that as the dome turned, the*

concrete dome wall was slightly compressed when the section containing the heavy shutter machinery passed by overhead, and that this movement was now transmitted to the upper support structure of the spectrograph, resulting in a small but very perceptible movement of the spectrum in the focal plane of the long-focus camera. This was of course intolerable, and the problem was solved by Hans Boesgaard, who changed the top support from the original in which the spectrograph was connected rigidly to the building at the top through the A-frame that carried the weight of the upper end. Instead it was suspended by a short flexible cable from the A-frame, and so the dome movement was not transmitted.

Figure 112: *Herbig's coudé spectrograph was housed in a concrete box on the side of the 120-inch building, with the Coudé Auxiliary Telescope (CAT) located to the right.*

From the beginning it was realized that, in order to keep dust out of the spectrograph room, it was necessary to maintain a small positive air pressure therein, so that dust would be blown away from any gap or crevice. I had other thoughts on how to make the spectrograph better. One was my concern that since the room was not temperature-controlled, there might be a problem that, as the temperature drifted, the consequent change in the index of refraction of the air and grating space would cause a shift in the spectrum. Fortunately, the fantastic scheme that I dreamed up to deal with these concerns was not pursued.

To monitor thermal problems, I hung a number of laboratory thermometers around the coudé room, and discovered that solar heating through the 6-inch thick concrete walls was quite perceptible: the eastern wall was warmer in the morning, and cooler in the afternoon. So a light metal shield was built *to protect the coudé room walls from direct sunshine, with a gap of about a foot between. The inner walls were painted with a low-emissivity paint, to hold down the radiation transfer.*

After image intensifiers had become the detector of choice (these were called Varo tubes, made by a company in Texas I suppose for night-vision use in the military), it was discovered that there was a faint luminosity in the coudé room that contributed a background on long exposures. It turned out that the green paint on the room walls was glowing in the deep red-near infrared spectral region, and that the near-IR-sensitive intensifiers were responding to it. I showed this dramatically when the room was completely dark by holding a flashlight against the wall for a few seconds, and then scanning the area with a hand-held intensifier. That spot was seen as a bright splotch by the intensifier. It turned out that the culprit was some impurity in TiO_2 *crystals in some ingredient of the paint, and that they glowed (as I recall, in the 7500-9000 Å region) for quite a while after the room lights were turned off. The initial excitation was provided by the white (or fluorescent) room lights (or my flashlight). The solution was to replace the white light bulbs by 'bug lamps': these are yellow, about the color of sodium lamps, that are used for evening outdoor illumination because aerial bugs apparently don't see that part of the spectrum. There was some correspondence with paint companies about this phenomenon; they had never heard of such a thing. Many years later I corresponded with Adolf Witt, who had discovered a similar phenomenon in reflection nebulae and molecular clouds, called ERE (for Extended Red Emission)."*

In contrast to the coudé building, the spectrograph itself was very successful from the beginning. The coudé design used three mirrors (primary, secondary, plus a third mirror to direct the f/36 light beam down along the polar axis to the coudé room), but for objects north of 51° declination (causing too shallow incident angles at the third mirror) a 5-mirror configuration was constructed. The spectrograph included four cameras (20-, 40-, 80-, and 160-inch focal length) and four gratings (400 grooves/mm blazed at 3900 Å, 600 grooves/mm blazed at 7500 Å, 600 grooves/mm blazed at 11400 Å, and 900 grooves/mm blazed at 13000 Å) on a turret, allowing a wide range of spectral resolution and spectral range. Herbig's original spectrograph used photographic plates of different emulsions, and to compensate for their low quantum efficiency, the light from the spectrograph was passed through 'Varo tubes', which were electrostatic image intensifiers. The photographic plates were, however, soon replaced by image dissectors that scanned the output from the image intensifiers, with the digital data stored on magnetic tape. With such a large choice of spectrograph parameters, it was not always easy to determine the optimum integration time, so Herbig devised an exposure meter that was installed right behind the slit with a rotating mirror that cast a small fraction of the light out to a detector. The 120-inch coudé with its fresh aluminum surfaces and properly blazed gratings was quite efficient, especially in the ultraviolet down to the atmospheric cut-off, an ability Herbig took advantage of in some of his studies. To allow observations at the coudé during the majority of the time when the 120-inch telescope was used in either Cassegrain or prime focus, a Coudé Auxiliary Telescope (CAT) was constructed. The CAT is a 0.6 m reflector whose light is focused on the entrance slit of the coudé spectrograph. The mirror is fixed vertically above the coudé room and is fed by an outside siderostat mirror. The CAT is still used today with the coudé to study bright stars.

Later a cross-dispersed echelle spectrograph was developed for use when ultra-high spectral resolution was needed. The optical design was by Herbig and his student David Soderblom, and the latter was in charge of its construction (Soderblom et al. 1978). As a novelty it was computer-driven and used microprocessors to control the grating angle. Around 1980 Reticon detectors were introduced, but shortly afterwards CCDs became the detectors of choice. Herbig's cameras and gratings were used until the Hamilton Echelle Spectrometer was installed at the coudé, where it is still in operation (Vogt 1987).

Herbig was involved with numerous other instrumental projects throughout his career, and in his autobiographical notes he has briefly summarized these activities as follows:

> *"Probably I should at least list here the major and minor instrumental projects in which I was involved at Lick. Some of these were carried through to the point of producing respectable science, others dragged on or turned out to perform below expectation so that nothing came of them. For the record:*
>
> *(1) the 120-inch coudé spectrograph was very successful.*
>
> *(2) the double-pass echelle scanner at the 120-inch coudé was also successful but came on line just when image intensifiers were being replaced by CCDs, and so represents perhaps the last gasp of that technique.*
>
> *(3) the CAT (coudé auxilary telescope) at the 120-inch was started up by George Preston, but finished and commissioned by me when Preston left Lick. It has been quite productive despite all its faults.*
>
> *(4) the Hα slitless spectrograph at the Crossley was highly productive.* [see Section 2.5]
>
> *(5) I also built an image-intensifier camera for direct photography at the*

Crossley. I intended to use it for narrow-band filter imagery of H-H Objects, but somehow never followed through, although a set of expensive interference filters were bought for the project. Gene Harlan did use this camera, and produced a number of 3-color negatives that were combined to make pretty pictures of well-known nebulae and star clusters.

(6) I was responsible for the design and installation of a small grating spectrograph (7-inch camera) and a near-infrared corrector lens (designed for us by Frank Ross) at the 36-inch refractor. Quite a few plates were taken with this spectrograph, but it was hardly competitive with the 120-inch coudé, which became available not long thereafter.

(7) My most ambitious undertaking that did not work out was the unfinished Crossley echelle nebular spectrograph. This I designed to take multi-slit high-dispersion spectrograms of emission line nebulae. It was built around a Bausch and Lomb echelle, and was intended to work either at 3727 Å or at Hα. The very fast air-Schmidt camera had two interchangeable correctors designed for those two wavelengths. The spectrograph structure was a very sophisticated mechanical design. Everything was built, but the whole thing failed because Howard Cowan, the Lick optician, was unable to produce corrector plates of the required accuracy. I remain embarassed and humiliated over this fiasco: so much time and money went into this project, and all I was able to show for it were some poorly-defined spectra of a comparison source. The echelle grating itself was retrieved, however, and went into the coudé scanner (2, above), but the rest of the Crossley echelle structure may still hang, gathering rust and dust, somewhere in the Lick shops."

In 1987, when Herbig turned 67, he retired from Lick Observatory and the University of California at Santa Cruz and moved to Honolulu in a senior position at the Institute for Astronomy at the University of Hawaii, where he worked the next 25 years. At that point, Herbig no longer built any instruments, but instead became an avid user of the telescopes and instruments at Mauna Kea. In particular he focused his attention on HIRES, the high resolution echelle spectrometer on the Keck-I telescope (Vogt et al. 1994), with which he observed regularly until the last year he lived.

12 CLOSING REMARKS

12.1 Administrative Work

While some accomplished scientists take on heavy administrative posts, Herbig did not seek such challenges. He was diligent and very conscientious with the numerous administrative and management tasks that are an integral part of a scientist's life, such as serving on committees and task forces, writing reports, performing reviews and evaluations, etc., but he evaded positions of power. The one major exception to that was when, in 1970, Lick Observatory was in a difficult transition period and the then director left. Herbig, as a senior longtime staff member, was persuaded to take over as director for the observatory until a new director could be installed, and for a year he served in that role, which he relinquished with elation (Figure 113). For Herbig the only thing that mattered was research, to which he devoted himself fully.

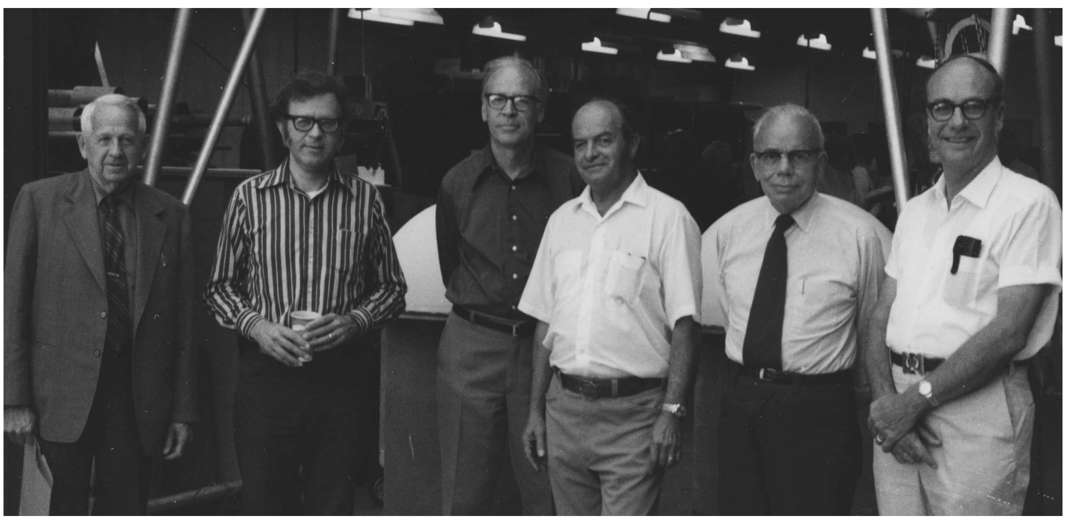


Figure 113: *Five Lick directors and the head of the Lick workshop in the mid-1970s. From left Donald Shane (director 1945-58), Bob Kraft (1968-69, 72, 81-91), George Herbig (1970-71), head of workshop Ray Greeby, Albert Whitford (1958-68), and Don Osterbrock (1973-81). Together these five directors shaped Lick Observatory for 46 years.*

12.2 Awards, Recognitions, Travels

Herbig's major accomplishments in science were already recognized during his lifetime, and he received numerous honors, some of which are listed here:

Warner Prize of the American Astronomical Society (1955); Gold Medal, Université de Liège (1970); Sigma Xi National Lecturer (1971-73); Henry Norris

Russell Lectureship of the American Astronomical Society (1975); Catherine Wolfe Bruce Gold Medal of the Astronomical Society of the Pacific (1980); R.M. Petrie Prize of the Canadian Astronomical Society (1995).

Herbig was elected a member of the National Academy of Science (1964), and of the American Academy of Arts and Sciences (1970). And he was a Foreign Scientific Member of the Max-Planck-Institut für Astronomie, Heidelberg and Member Correspondent of the Société Royale des Sciences de Liège.

Herbig traveled widely, and was Visiting Lecturer/Professor at Chicago (1959), Mexico (1961), Paris (1965), Heidelberg (1969,1973), and Stockholm (1973). He also was an Exchange Lecturer organized between the National Academies of USA and USSR (1965) and an Academy Scholar organized by the same academies (1987). And he served on a committee assembled by the National Science Foundation which visited all the astronomical observatories in China with a view to further collaborations in the aftermath of Mao's death (1977).

Figure 114: *Herbig was member of a committee that went to China in 1977 to visit the astronomical observatories after the death of Mao.*

12.3 Impact

As ferociously focused as Herbig was about his research, about obtaining the best possible data, and about getting the inferences just right, he was remarkably tranquil about the reception of his papers. He would work indefatigably to ensure he got all arguments right, and would worry endlessly about minute details, often to the wonder or exasperation of collaborators, who felt a paper was more than ready for submission while he needed to check just one more completely improbable objection to an argument. But once a paper had appeared he moved his attention to the next exciting idea, and did not worry overly whether people agreed or disagreed with his views. In our conversations he could be blunt about the human frailties that affect scientists as much as anybody else,[52] and sometimes quoted various favorite aphorisms to express certain points. I recall his quote of Edwin Land: *"Once you fall in love with a hypothesis, you lose the ability to test it"*, which he would sometimes gently tell me whenever I had just passionately advocated my latest brilliant insight. If people did not seem to pay attention to an argument he had carefully written and documented, he liked to recall Aldous Huxley's admonition: *"Facts do not cease to exist because they are ignored"*. Sometimes he would re-iterate an argument, noting with André Gide that *"All this has been said before – but since nobody listened, it must be said again"*. As an observer par excellence, he saw it as the ultimate sin to argue on the basis of shoddy data, on occasion quoting Thomas Henry Huxley: *"Pages of formulae will not get a definite result out of loose data"*.

Herbig published papers for seventy years,[53] spanning an incredible evolution of technology, and dating back to a time when in some of his early papers he would include estimates of an object's visual magnitude obtained at the eyepiece of the Lick 36-inch refractor! He worked with all detectors from hypersensitized photographic plates (*"an art more than a science"*) through image intensifiers over the first primitive CCDs to the latest large infrared imagers. He was very well aware that as technology evolves, what was once at the technical forefront would later be seen as almost quaint, and was serene about the fact that all his results would sooner or later be superceded by better data. He also recognized that for each generation science starts with one's PhD, everything before is history, and he lived so long that he witnessed many of his fundamental papers no longer being cited: once an important result becomes part of the bedrock of science, it enters the anonymous realm of 'this is how things are'.

Herbig came from a time and a tradition when scientists often worked alone or at most with a few collaborators. Of Herbig's refereed papers, an astonishing 82% are as first author, and 3/4 of those are as single author. We discussed the growing trend in astronomy towards data mining of massive data sets by increasingly large teams, and while he understood this development, he just said that he personally enjoyed in-depth studies of one object or one region at a time.

At the end of the IAU Symposium No. 75 on 'Star Formation' held in Geneva, Switzerland, Herbig gave the final talk of the conference (Herbig 1977c). Rather than summarizing what everybody had said, he defined a set of critically

Figure 115: *Seventy years separate these two photos of Herbig at the telescope. To the left is a photo that appeared in Los Angeles Times on Nov 30, 1940, when Herbig was 20. To the right, Herbig at 90 is observing at the Keck-I telescope.*

needed observations, a list of interesting new ideas, and some mysteries. But at the end he reminded the audience that

> *"When the historians of science look back on our times with the perspective of the years, all that we do today will certainly be seen to have been either wrong, or irrelevant, or obvious."*

13 REFERENCES

Ábrahám, P., Juhász, A., Dullemond, C.P. et al. 2009, *Episodic formation of cometary material in the outburst of a solar-like young star*, Nature, 459, 224

Abt, H.A. 1979, *The occurrence of abnormal stars in open clusters*, ApJ, 230, 485

Abt, H.A. & Levato, H. 1977, *Spectral types in the Orion OB1 association*, PASP, 89, 797

Adams, F.C., Lada, C.J., Shu, F.H. 1987, *Spectral Evolution of Young Stellar Objects*, ApJ, 312, 788

Alecian, E., Wade, G.A., Catala, C. et al. 2009, *Magnetism and binarity of the Herbig Ae star V380 Ori*, MNRAS, 400, 354

Alencar, S.H.P., Johns-Krull, C.M., Basri, G. 2001, *The Spectral Variability of the Classical T Tauri Star DR Tauri*, AJ, 122, 3335

Alencar, S.H.P., Teixeira, P.S., Guimarães, M.M. et al. 2010, *Accretion dynamics and disk evolution in NGC 2264: a study based on CoRoT photometric observations*, A&A, 519, A88

ALMA Partnership, Brogan, C.L., Pérez, L.M. et al. 2015, *The 2014 ALMA Long Baseline Campaign: First Results from High Angular Resolution Observations toward the HL Tau Region*, ApJ, 808, L3

Alschuler, W.R. 1975, *Observations of lithium dilution and rotational velocity decay in F and G giant stars*, ApJ, 195, 649

Alves, J., Lombardi, M., Lada, C.J. 2008, *The Pipe nebula: A Young Molecular Cloud Complex*, in 'Handbook of Star Forming Regions' Vol. II, ed. Bo Reipurth, ASP, 415

Ambartsumian, V.A. 1947, "Stellar Evolution and Astrophysics", Acad. Sci. Armenian SSR, Yerevan

Ambartsumian, V.A. 1949, *Stellar Associations*, Astron. Zhour., 26, 3

Ambartsumian, V.A. 1950, *Stellar Associations and the Origin of Stars*, Comm. AN SSSR, Physical Series, 14, No. 1, 15

Ambartsumian, V.A. 1954, *The Phenomenon of the Continuous Emission and Sources of Stellar Energy*, Comm. Byurakan Obs. No. 13

Ambartsumian, V.A. 1971, *FUors*, Astrophysics, 7, 331

Andrews, S.M. & Wolk, S.J. 2008, *The LkHα 101 Cluster*, in 'Handbook of Star Forming Regions Vol. I', ed. B. Reipurth, Astron. Soc. Pacific, p. 390

Appenzeller, I., Jankovics, I., Östreicher, R. 1984, *Forbidden-line profiles of T Tauri stars*, A&A, 141, 108

Armitage, P., Livio, M., Pringle, J. 2001, *Episodic accretion in magnetically layered protoplanetary discs*, MNRAS, 324, 705

Aspin, C., Reipurth, B., Herczeg, G.J., Capak, P. 2010, *The 2008 Extreme Outburst of the Young Eruptive Variable Star EX Lupi*, ApJ, 719, L50

Augason, G.C. & Herbig, G.H. 1967, *A Lower Limit on the C^{12}/C^{13} Ratio in the Interstellar Gas*, ApJ, 150, 729

Baade, W. & Minkowski, R. 1937, *The Trapezium Cluster of the Orion Nebula*, ApJ, 86, 119

Bagnuolo, S., Hensberge, H., Landstreet, J.D. et al. 2004, *Discovery of a huge magnetic field in the very young star NGC 2244-334 in the Rosette Nebula cluster*, A&A, 416, 1149

Baines, D., Oudmaijer, R.D., Porter, J.M., Pozzo, M. 2006, *On the binarity of Herbig Ae/Be stars*, MNRAS, 367, 737

Bally, J., Sutherland, R.S., Devine, D., Johnstone, D. 1998, *Externally Illuminated Young Stellar Environments in the Orion Nebula: Hubble Space Telescope Planetary Camera and Ultraviolet Observations*, AJ, 116, 293

Bally, J., Heathcote, S., Reipurth, B. et al. 2002, *Hubble Space Telescope Observations of Proper Motions in Herbig-Haro Objects 1 and 2*, AJ, 123, 2627

Banzatti, A., Meyer, M.R., Bruderer, S. et al. 2012, *EX Lupi from Quiescence to Outburst: Exploring the LTE Approach in Modeling Blended H2O and OH Mid-infrared Emission*, ApJ, 745, A90

Baraffe, I., Vorobyov, E., Chabrier, G. 2012, *Observed Luminosity Spread in Young Clusters and FU Ori Stars: A Unified Picture*, ApJ, 756, A118

Barentine, J.C. & Esquerdo, G.A. 2003, *Near-Infrared Observations of Barnard's Merope Nebula (IC 349)*, BAAS, 204, #64.01

Barnard, E.E. 1891, *On the Nebulosities of the Pleiades and on a New Merope Nebula*, Astron. Nachr., 126, 293

Barnard, E.E. 1919, *On the dark markings of the sky, with a catalogue of 182 such objects*, ApJ, 49, 1

Bateson, F.M. & Jones, A.F. 1957, Circ. R.A.S. New Zealand, Var. Star. Sec., No. 79

Bell, K.R. & Lin, D. 1994, *Using FU Orionis outbursts to constrain self-regulated protostellar disk models*, ApJ, 427, 987

Beristain, G., Edwards, S., Kwan, J. 1998, *Permitted Iron Emission Lines in the Classical T Tauri Star DR Tauri*, ApJ, 499, 828

Bertout, C. 1989, *T Tauri Stars: Wild as Dust*, Ann. Rev. Astron. Astrophys. 27, 351

Bertout, C., Basri, G., Bouvier, J. 1988, *Accretion disks around T Tauri stars*, ApJ, 330, 350

Bertout, C., Siess, L., Cabrit, S. 2007, *The evolution of stars in the Taurus-Auriga T association*, A&A, 473, L21

Bidelman, W.P. & Herbig, G.H. 1958, *A New Emission Line in the Spectra of Long-Period Variables*, PASP, 70, 451

Blaauw, A. 1952, *The age and evolution of the ζ Persei group of O- and B-type stars*, Bull. Astron. Inst. Netherlands, 11, 405

Blaauw, A. & Morgan, W.W. 1953, *Note on the motion and possible origin of the O-type star HD 34078 = AE Aurigae and the emission nebula IC 405*, Bull. Astron. Netherlands, 12, 76

Blaauw, A. & Morgan, W.W. 1954, *The Space Motions of AE Aurigae and μ Columbae with Respect to the Orion Nebula*, ApJ, 119, 625

Blandford, R.D. & Payne, D.G. 1982, *Hydromagnetic flows from accretion discs and the production of radio jets*, MNRAS, 199, 883

Böhm, K.H. 1956, *A Spectrophotometric Analysis of the Brightest Herbig-Haro Object*, ApJ, 123, 379

Böhm, K.H. & Solf, J. 1994, *A sub-arcecond-scale spectroscopic study of the complex mass outflows in the vicinity of T Tauri*, ApJ, 430, 277

Böhm, K.H., Siegmund, W.A., Schwartz, R.D. 1976, *Emission-line spectra of individual condensations of Herbig-Haro objects*, ApJ, 203, 399

Böhm, K.H., Böhm-Vitense, E., Brugel, E.W. 1981, *The ultraviolet spectrum of Herbig-Haro Object 1*, ApJ, 245, L113

Bok, B.J. 1948, *Dimensions and Masses of Dark Nebulae*, Centennial Symposia, Harvard Observatory Monographs No.7, 53

Bok, B.J. 1966, *Summary. Problems and Outlook*, Vistas in Astronomy, 8, 221

Bok, B.J. 1977, *Dark Nebulae, Globules, and Protostars*, PASP, 89, 597

Bok, B.J. 1978, *Star Formation in or very close to a Southern Globule*, PASP, 90, 489

Bok, B.J. & Reilly, E.F. 1947, *Small Dark Nebulae*, ApJ, 105, 255

Bonnell, I. & Bastien, P. 1992, *A Binary Origin for FU Orionis Stars*, ApJ, 401, L31

Bonsack, W.K. 1961, *The Abundance of Lithium in T Tauri stars: Further Observations*, ApJ, 133, 340

Bonsack, W.K. & Greenstein, J.L. 1960, *The Abundance of Lithium in T Tauri Stars and Related Objects*, ApJ, 131, 83

Bouvier, J., Alencar, S.H.P., Harries, T.J., Johns-Krull, C.M., Romanova, M.M. 2007, *Magnetospheric Accretion in Classical T Tauri Stars*, in 'Protostars and Planets V', eds. B. Reipurth et al., Univ Arizona Press, 479

Bouvier, J., Matt, S.P., Mohanty, S. et al. 2014, *Angular Momentum Evolution of Young Low-Mass Stars and Brown Dwarfs: Observations and Theory*, in 'Protostars and Planets VI', eds. H. Beuther et al., Univ. Arizona Press, 433

Briceño, C., Hartmann, L.W., Stauffer, J.R. et al. 1997, *X-ray Surveys and the Post-T Tauri Problem*, AJ, 113, 740

Brugel, E.W., Böhm, K.H., Mannery, E. 1981, *Emission line spectra of Herbig-Haro objects*, ApJS, 47, 117

Calvet, N., Hartmann, L., Kenyon, S.J. 1993, *Mass loss from pre-main-sequence accretion disks. I - The accelerating wind of FU Orionis* ApJ, 402, 623

Cami, J. & Cox, N.L.J. 2014, IAU Symp. No. 297 *The Diffuse Interstellar Bands*, Cambridge Univ. Press

Casey, B.W., Mathieu, R.D., Vaz, L.P.R. et al. 1998, *The Pre-Main-Sequence Eclipsing Binary TY Coronae Australis: Precise Stellar Dimensions and Tests of Evolutionary Models*, AJ, 115, 1617

Chavarria-K., C. 1985, *Herbig's Ae and Be star LkHα 198, a flare star candidate*, A&A, 148, 317

Chini, R., Kämpgen, K., Reipurth, B. et al. 2003, *SIMBA observations of the R Corona Australis molecular cloud*, A&A, 409, 235

Clarke, C.J., Lodato, G., Melnikov, S., Ibrahimov, M. 2005, *The photometric evolution of FU Orionis objects: disc instability and wind-envelope interaction*, MNRAS, 361, 942

Clayton, D.D. 1983, *Principles of Stellar Evolution and Nucleosynthesis*, The University of Chicago Press, p. 451

Clayton, G.C. 2012, *What are the R Coronae Borealis Stars?*, JAAVSO, 40, 539

Cody, A.M., Stauffer, J., Baglin, A. et al. 2014, *CSI 2264: Simultaneous Optical and Infrared Light Curves of Young Disk-bearing Stars in NGC 2264 with CoRoT and Spitzer–Evidence for Multiple Origins of Variability* AJ, 147, A82

Cohen, M. 1984, *The T Tauri Stars*, Physics Reports, 116, no.4, 173

Cohen, M. & Kuhi, L.V. 1979, *Observational studies of pre-main-sequence evolution*, ApJS, 41, 743

Cohen, M. & Schwartz, R.D. 1979, *The Exciting Star of Herbig-Haro Object 1*, ApJ, 233, L77

Corcoran, D. 1994, *Optical Outflows associated with Herbig Ae/Be Stars*, PhD Thesis

Corcoran, D. & Ray, T.P. 1995, *Herbig-Haro outflows in the V 380 Orionis region* , A&A, 301, 729

Costero, R., Allen, C., Echevarria, J., Georgiev, L., Poveda, A., Richer, M.G. 2008, *The Escaping Spectroscopic Binary θ^1 Ori E*, Rev. Mex. Astron. Astrofis. Ser. Conf., 34, 102

Covey, K.R., Hillenbrand, L.A., Miller, A.A. et al. 2011, *PTF10nvg: An Outbursting Class I Protostar in the Pelican/North American Nebula*, ApJ, 141, A40

Cram, L.E. 1979, *Atmospheres of T Tauri Stars: The Photosphere and Low Chromosphere*, ApJ, 234, 949

Croswell, K., Hartmann, L., Avrett, E.H. 1987, *Mass Loss from FU Orionis Objects* ApJ, 312, 227

Cruz-Gonzalez, I., McBreen, B., Fazio, G.G. 1984, *Far-infrared observations of a star-forming region in the Corona Australis dark cloud*, ApJ, 279, 679

Cudworth, K.M. & Herbig, G.H. 1979, *Two large-proper-motion Herbig-Haro objects*, AJ, 84, 548

Dahm, S.E. 2005, *The Young Cluster NGC 2362*, AJ, 130, 1805

Dahm, S.E., Herbig, G.H., Bowler, B.P. 2012, *The Young Cluster in IC 1274*, AJ, 143, 3

D'Antona, F. & Mazzitelli, I. 1994, *New pre-main-sequence tracks for $M \lesssim 2.5\ M_\odot$ as tests of opacities and convection model*, ApJS, 90, 467

DeWarf, L.E., Sepinsky, J.F. Guinan, E.F., Ribas, I., Nadalin, I. 2003, *Intrinsic Properties of the Young Stellar Object SU Aurigae* , ApJ, 590, 357

de Wit, W.-J., Oudmaijer, R.D., van den Ancker, M.E., Calvet, N. 2014, *Report on the Workshop Herbig Ae/Be Stars: The Missing Link in Star Formation*, The ESO Messenger, 157, 50

Dodin, A.V., Emelyanov, N.V., Zharova, A.V. et al. 2016, *Orbital motions and light curves of young binaries XZ Tau and VY Tau*, Astronomy Letters, 42, 29

Dopita, M.A. 1978, *Optical emission from shocks. IV - The Herbig-Haro objects*, ApJS, 37, 117

Dopita, M.A., Schwartz, R.D., Evans, I. 1982, *Herbig-Haro Objects 46 and 47: Evidence for Bipolar Ejection from a Young Star*, ApJ, 263, L73

Douglas, A.E. 1977, *Origin of diffuse interstellar lines*, Nature, 269, 130

Duncan, D.K. 1981, *Lithium abundances, K line emission and ages of nearby solar type stars*, ApJ, 248, 651

Duncan, D.K., Harlan, E.A., Herbig, G.H. 1981, *Photometry of the Reflection Nebulosity at V1057 Cygni*, AJ, 86, 1520

Edwards, S. 1997, *Magnetospherically Mediated Accretion in Classical T Tauri Stars. Paradigm for Low Mass Stars Undergoing Disk Accretion?* in 'Herbig-Haro Flows and the Birth of Low-Mass Stars', eds. B. Reipurth & C. Bertout (Kluwer), 433

Elmegreen, B.G. 2000, *Star Formation in a Crossing Time*, ApJ, 530, 277

Elmegreen, B.G. 2009, *The Early Years: Lyman Spitzer, Jr. and the Physics of Star Formation* , in Reviews in Modern Astronomy, 'Formation and Evolution of Cosmic Structures', Vol. 21, Wiley-VCH, p. 157-181

Evans, N.R., Welch, D.L., Slovak, M.H. et al. 1993, *The Orbit and Companion of the Cepheid S Sge: A Probable Triple System*, AJ, 106, 1599

Favata, F., Flaccomo, E., Reale, F. et al. 2005, *Bright X-Ray Flares in Orion Young Stars from COUP: Evidence for Star-Disk Magnetic Fields?*, ApJ Suppl., 160, 469

Feigelson, E.D. 1996, *Dispersed T Tauri Stars and Galactic Star Formation*, ApJ, 468, 306

Feigelson, E.D., Townsley, L., Güdel, M., Stassun, K. 2007, *X-Ray Properties of Young Stars and Stellar Clusters*, in 'Protostars and Planets V', ed. B. Reipurth et al., Univ. Arizona Press, 313

Feigelson, E.D. & Kriss, G.A. 1981, *Discovery of three X-ray luminous pre-main sequence stars*, ApJ, 248, L35

Finkenzeller, U. 1983, *Eigenschaften von Herbig-Ae/Be-Sternen*, PhD Thesis

Flannery, B.P. & Herbig, G.H. 1973, *Expansion of the Planetary Nebula surrounding FG Sagittae*, ApJ, 183, 491

Foing, B.H. & Ehrenfreund, P. 1994, *Detection of two interstellar absorption bands coincident with spectral features of* C_{60}^{+}, Nature, 369, 296

Fűrész, G., Hartmann, L.W., Megeath, S.T. et al. 2008, *Kinematic Structure of the Orion Nebula Cluster and Its Surroundings*, ApJ, 676, 1109

Gahm, G. 1970, *The Spectrum of RW Aurigae, 3250 to 4900 Å*, ApJ, 160, 1117

Gahm, G. 1990, *Flares on T Tauri Stars*, in IAU Symp. No. 137 'Flares Stars in Star Clusters, Associations and the Solar Vicinity', eds. L.V. Mirzoyan et al., Kluwer, p. 193

Galli, P., Bertout, C., Teixeira, R., Ducourant, C. 2015, *Evolution of the T Tauri star population in the Lupus association*, A&A, 580, A26

Garrison, R.F. 1967, *Some Characteristics of the B and A Stars in the Upper Scorpius Complex*, ApJ, 147, 1003

Garrison, L.M. 1976, *An observational study of the pre-main sequence Herbig Ae/Be stars*, PhD Thesis

Getman, K.V., Feigelson, E.D., Grosso, N., et al. 2005, *Membership of the Orion Nebula Population from the Chandra Orion Ultradeep Project* , ApJS 160, 353

Ghez, A., Neugebauer, G., Matthews, L. 1993, *The multiplicity of T Tauri stars in the star forming regions Taurus-Auriga and Ophiuchus-Scorpius: A 2.2 micron speckle imaging survey*, AJ, 106, 2005

Ghosh, P. & Lamb, F.K. 1978, *Disk accretion by magnetic neutron stars*, ApJ, 223, L83

Goto, M., Regály, Zs., Dullemond, C.P. et al. 2011, *Fundamental Vibrational Transition of CO During the Outburst of EX Lupi in 2008*, ApJ, 728, A5

Graham, J.A. & Elias, J.H. 1983, *Herbig-Haro objects in the dust globule ESO 210-6A*, ApJ, 272, 615

Graham, J.A. & Phillips, A.C. 1987, *Rapid variability of the R Coronae Australis reflection nebula NGC 6729*, PASP, 99, 91

Greenstein, J.L. 1948, *Stars in Diffuse Nebulae*, ApJ, 107, 375

Greenstein, J.L. 1950, *A Possible Energy Source for T Tauri Stars*, PASP, 62, 156

Grossman, L. 1974, *Chemical fractionation in the solar nebula*, Moon, 11, 385

Gutermuth, R.A., Myers, P.C., Megeath, S.T. et al. 2008, *A Survey of the Cep OB3, S140, and Mon R2 Molecular Clouds with Spitzer and NEWFIRM* , ApJ, 674, 336

Güdel, M., Briggs, K.R., Arzner, K. et al. 2007, *The XMM-Newton extended survey of the Taurus molecular cloud (XEST)* , A&A, 468, 353

Hamann, F. & Persson, S.E. 1992a, *Emission-Line Studies of Young Stars. I. The T Tauri Stars*, ApJS, 82, 247

Hamann, F. & Persson, S.E. 1992b, *Emission-Line Studies of Young Stars. II. The Herbig Ae/Be Stars*, ApJS, 82, 285

Haro, G. 1949, *Faint spectra showing Halpha in emission in the obscuring clouds of Ophiuchus and Scorpius and in a region in Sagittarius*, AJ, 54, 188

Haro, G. 1952, *Herbig's Nebulous Objects Near NGC 1999* , ApJ 115, 572

Haro, G. 1953, *Hα Emission Stars and Peculiar Objects in the Orion Nebula* , ApJ, 117, 73

Haro, G. 1957, *The possible connexion between T Tauri stars and UV Ceti stars*, in IAU Symp. No. 3 on 'Non-Stable Stars', ed. G.H. Herbig, Cambridge Univ. Press, 26

Haro, G. 1968, *Flare Stars*, in 'Nebulae and Interstellar Matter', (Stars and Stellar Systems Vol. VII), eds. B.M. Middlehurst & L.H. Aller, Univ. Chicago Press, p.141

Haro, G. 1976, *An observational approach to stellar evolution - I. (Flare stars and related objects)*, Bol. Inst. Tonantzintla, 2, 2

Haro, G. & Herbig, G.H. 1955, *The Unusual Brightness in the Ultraviolet of Certain T Tauri-Type Stars*, Bol. Obs. Tonantzintla y Tacubaya, 2, 33

Haro, G. & Minkowski, R. 1960, *The Herbig-Haro Objects Near NGC 1999*, AJ, 65, 490

Hartigan, P. 1987, Raymond, J., Hartmann, L. 1987, *Radiative bow shock models of Herbig-Haro objects*, ApJ, 316, 323

Hartmann, L. 2001, *On Age Spreads in Star-Forming Regions*, AJ, 121, 1030

Hartmann, L. 2002, *On Disk Braking of T Tauri Rotation*, 566, L29

Hartmann, L. & Calvet, N. 1995, *Observational constraints on FU Ori winds* AJ, 109, 1846

Hartmann, L. & Kenyon, S.J. 1985, *On the nature of FU Orionis objects*, ApJ, 299, 462

Hartmann, L.W. & Kenyon, S.J. 1996, *The FU Orionis Phenomenon*, Ann. Rev. Astron. Astrophys. 34, 207

Hartmann, L. & Raymond, J.C. 1984, *A high-resolution study of Herbig-Haro objects 1 and 2*, ApJ, 276, 560

Hartmann, L., Hewett, R., Stahler, S., Mathieu, R.D. 1986, *Rotational and Radial Velocities of T Tauri Stars*, ApJ, 309, 275

Hartmann, L. & Raymond, J.C. 1984, *A high-resolution study of Herbig-Haro objects 1 and 2*, ApJ, 276, 560

Hartmann, L., Jones, B.F., Stauffer, J.R., Kenyon, S.J. 1991, *A Proper Motion Survey for Pre-Main-Sequence Stars in Taurus-Auriga*, AJ, 101, 1050

Hartmann, L., Calvet, N., Gullbring, E., D'Alessio, P. 1998, *Accretion and the Evolution of T Tauri Disks*, ApJ, 495, 385

Hayashi, C. 1961, *Stellar Evolution in Early Phases of Gravitational Contraction*, PAS Japan, 13, 450

Henning, Th. & Semenov, D. 2013, *Chemistry in Protoplanetary Disks*, Chemical Reviews, 113, 9016

Henyey, L.G., Lelevier, R., Levée, R.D. 1955, *The Early Phases of Stellar Evolution*, PASP, 67, 154

Herbig, G.H. 1945a, *Emission Lines of Fe I in RW Aurigae*, PASP, 57, 166

Herbig, G.H. 1945b, *Observations of Comets and Asteroids*, Lick Obs. Bull., 19, No. 517, 171

Herbig, G.H. 1946, *A Possible T Tauri Variable in the Diffuse Nebula NGC 1999*, PASP, 58, 163

Herbig, G.H. 1948, *A Search for Isotopes of Titanium in Late-Type Stars*, PASP, 60, 378

Herbig, G.H. 1949a, *Identification of a Molecular Band at λ 3682 in the Spectra of Late-Type Stars*, ApJ, 109, 109

Herbig, G.H. 1949b, *The Spectrum of R Coronae Borealis at the 1948-1949 Minimum*, ApJ, 110, 143

Herbig, G.H. 1950a, *The Spectrum of the Nebulosity Surrounding T Tauri*, ApJ, 111, 11

Herbig, G.H. 1950b, *Spectra of Variable Stars in the Orion Nebula*, ApJ, 111, 15

Herbig, G.H. 1950c, *The Spectra of Five Irregular Variable Stars*, PASP, 62, 211

Herbig, G.H. 1951, *The Spectra of Two Nebulous Objects Near NGC 1999*, ApJ, 113, 697

Herbig, G.H. 1952a, *Emission-line Stars in Galactic Nebulosities*, J. Roy. Astron. Soc. Canada, 46, 222

Herbig, G.H. 1952b, *The Cepheid Variable S Sagittae. II. The Emission Lines*, ApJ, 116, 369

Herbig, G.H. 1952c, *Emission lines of Ca II in Classical Cepheid Variables*, PASP, 64, 302

Herbig, G.H. 1953, *T Tauri and Hind's Nebula*, Leaflet of the Astronomical Society of the Pacific, 6, No. 293, 338

Herbig, G.H. 1954a, *Bright-Hα Stars in IC 348*, PASP, 66, 19

Herbig, G.H. 1954b, *Emission-Line Stars Associated with the Nebulous Cluster NGC 2264*, ApJ, 119, 483

Herbig, G.H. 1956a, *The Source of Illumination of NGC 1579*, PASP, 68, 35

Herbig, G.H. 1956b, *Identification of Aluminum Hydride as the Emitter of Bright Lines Observed in χ Cygni Near Minimum Light*, PASP, 68, 204

Herbig, G.H. 1957a, *On the nature and origin of the T Tauri stars*, in IAU Symp. No. 3 on 'Non-Stable Stars', ed. G.H. Herbig, Cambridge Univ. Press, 3

Herbig, G.H. 1957b, *Emission-Line Stars in the Vicinity of Messier 8, Messier 20, and Simeis 188*, ApJ, 125, 654

Herbig, G.H. 1957c, *The Widths of Absorption Lines in T Tauri-Like Stars*, ApJ, 125, 612

Herbig, G.H. 1958a, *NGC 7000, IC 5070, and the Associated Emission-Line Stars*, ApJ, 128, 25

Herbig, G.H. 1958b, *The Spectrum of the Nebulosity at AE Aurigae*, PASP, 70, 468

Herbig, G.H. 1958c, *Occurrence of Aluminum Hydride Emission in the Spectra of Long-Period Variables*, Science, 128, 1145 (Abstract of paper presented at Autumn meeting of National Academy of Sciences, Berkeley, Nov. 1958)

Herbig, G.H. 1958d, *The Irregular Variable Star V348 Sagittarii*, ApJ, 127, 312

Herbig, G.H. 1958e, *T Tauri Stars, Flare Stars, and Related Objects as Members of Stellar Associations*, in 'Stellar Populations', conference at Vatican Observatory, Castel Gandolfo, ed. D.J.K. O'Connell, Interscience, Ricerche Astronomiche, 5, 127

Herbig, G.H. 1960a, *The Spectra of Be- and Ae-Type Stars Associated with Nebulosity*, ApJ Suppl., 4, 337

Herbig, G.H. 1960b, *Emission-Line Stars in IC 5146*, ApJ, 131, 516

Herbig, G.H. 1960c, *Observations and an Interpretation of VV Puppis*, ApJ, 132, 76

Herbig, G.H. 1960d, *Spectral Classifications for 112 Variable Stars*, ApJ, 131, 632

Herbig, G.H. 1962a, *The properties and problems of T Tauri stars and related objects*, Advances in Astronomy and Astrophysics, 1, 47

Herbig, G.H. 1962b, *Spectral Classification of Faint Members of the Hyades and Pleiades and the Dating Problem in Galactic Clusters*, ApJ, 135, 736

Herbig, G.H. 1962c, *Spectroscopic Studies of Early Phases of Stellar Evolution*, in 'Stellar Evolution', La Plata Observatory, Argentina, ed. J. Sahade, 45

Herbig, G.H. 1962d, *On the Evolutionary Interpretation of the M dwarfs*, in 'Stellar Evolution', La Plata Observatory, Argentina, ed. J. Sahade, 45

Herbig, G.H. 1963, *The Diffuse Interstellar Bands. I. a Possible Identification of λ 4430*, ApJ, 137, 200

Herbig, G.H. 1964, *Apparent Lithium Isotope Ratios in F5-G8 Dwarfs*, ApJ, 140, 702

Herbig, G.H. 1965a, *Lithium Abundances in F5-G8 Dwarfs*, ApJ, 141, 588

Herbig, G.H. 1965b, *Physical Companions to Long-Period Variables*, Veröffentlichungen der Remeis-Sternwarte zu Bamberg, 27, 164

Herbig, G.H. 1966a, *On the Interpretation of FU Orionis*, Vistas in Astronomy, 8, 109

Herbig, G.H. 1966b, *The Diffuse Interstellar Bands. II. The Profile of λ 4430 in HD 183143*, Zeitschrift für Astrophysik, 64, 512

Herbig, G.H. 1968a, *The Structure and Spectrum of R Monocerotis*, ApJ, 152, 439

Herbig, G.H. 1968b, *The Interstellar Line Spectrum of Zeta Ophiuchi*, Zeitschrift für Astrophysik, 68, 243

Herbig, G.H. 1968c, *Emission lines of Mn I in long-period variables*, Mem. Soc. R. Sci. Liège, 37, p. 433

Herbig, G.H. 1969a, *The light variations of the nuclei in Herbig-Haro object No. 2, 1946-1968*, Comm. Konkoly Obs. Hungary, 65, 75

Herbig, G.H. 1969b, *Emission-Line Objects Projected upon the Galactic Bulge*, Proceedings of the National Academy of Science, 63, 1045

Herbig, G.H. 1970a, *Introductory Remarks*, Mémoires de la Société Royale des Sciences de Liège, 19, 13

Herbig, G.H. 1970b, *VY Canis Majoris. II. Interpretation of the Energy Distribution*, ApJ, 162, 557

Herbig, G.H. 1970c, *Interstellar Lines other than Hydrogen*, in 'Ultraviolet Stellar Spectra and Related Ground-Based Observations', IAU Symp. 36, 315

Herbig, G.H. 1970d, *Early Stellar Evolution at Intermediate Masses*, in 'Spectroscopic Astrophysics: An Assessment of the Contributions of Otto Struve', ed. G.H. Herbig, Univ. of California Press, 237

Herbig, G.H 1971a, *The Spectrum of LkHα-101 in the Near-Infrared*, ApJ, 169, 537

Herbig, G.H 1971b, *Interstellar Staub als Nebenprodukt der Sternentstehung*, Sterne und Weltraum, 10, 4

Herbig, G.H. 1972, *VY Canis Majoris. III. Polarization and Structure of the Nebulosity*, ApJ, 172, 375

Herbig, G.H. 1973a, *BD -10°4662 interpreted as a post-T Tauri star*, ApJ, 182, 129

Herbig, G.H. 1973b, *Brightening of Herbig-Haro Object No. 1*, IBVS, No. 832

Herbig, G.H. 1974a, *Interstellar Smog*, American Scientist, 62, 200

Herbig, G.H. 1974b, *On the Nature of the Small Dark Globules in the Rosette Nebula*, PASP, 86, 604

Herbig, G.H. 1974c, *Draft Catalog of Herbig-Haro Objects*, Lick Obs. Bull. No. 658

Herbig, G.H. 1974d, *VY Canis Majoris. IV. The emission bands of ScO*, ApJ, 188, 533

Herbig, G.H. 1975a, *The diffuse interstellar bands. IV - The region 4400-6850 Å*, ApJ, 196, 129

Herbig, G.H. 1975b, *The spectrum and structure of 'Minkowski's footprint' - M1-92*, ApJ, 200, 1

Herbig, G.H. 1976, *Review of Cometary Spectra*, in 'The Study of Comets', NASA Special Publication #393, 136

Herbig, G.H. 1977a, *Eruptive Phenomena in Early Stellar Evolution*, ApJ, 217, 693

Herbig, G.H. 1977b, *Radial Velocities and Spectral Types of T Tauri Stars*, ApJ, 214, 747

Herbig, G.H. 1977c, *Summary of the Conference: Observations*, in 'Star Formation', IAU Symp. 75, eds. T. de Jong & A. Maeder, 283

Herbig, G.H. 1978a, *Can Post-T Tauri Stars Be Found?*, in 'Problems of Physics and Evolution of the Universe', Ed. L.V. Mirzoyan. Yerevan, Publishing House of the Armenian Academy of Sciences, p.171

Herbig, G.H. 1978b, *Some aspects of early stellar evolution that may be relevant to the origin of the solar system*, in 'The origin of the solar system', ed. S.F. Dermott, Wiley-Interscience, p. 219

Herbig, G.H. 1981a, *Some recent results in early stellar evolution*, in 'Recent Advances in Observational Astronomy', eds. H.L. Johnson & C. Allen, UNAM, p.19

Herbig, G.H. 1981b, *The Origin and Astronomical History of Terrestrial Oxygen*, in 'Oxygen and Living Processes: An Interdisciplinary Approach', ed. D.L. Gilbert, Springer-Verlag, p. 65

Herbig, G.H. 1982, *Stars of Low to Intermediate Mass in the Orion Nebula*, 'Henry Draper Symposium', Annals of the New York Academy of Sciences, 395, 64

Herbig, G.H. 1983, *The origin and early history of the sun and the planetary system in the context of stellar evolution*, Highlights of Astronomy, 6, 15

Herbig, G.H. 1985, *Chromospheric Hα Emission in F8-G3 Dwarfs, and its Connection with the T Tauri Stars*, ApJ, 289, 269

Herbig, G.H. 1988, *The diffuse interstellar bands. VI - New features near 6800 Å*, ApJ, 331, 999

Herbig, G.H. 1989a, *FU Orionis eruptions*, in ESO Workshop on 'Low Mass Star Formation and Pre-Main Sequence Objects', ed. B. Reipurth, p. 233

Herbig, G.H. 1989b, *Summarizing remarks on the astronomical evidence for circumstellar disks*, in 'The formation and evolution of planetary systems', Cambridge University Press, p. 296

Herbig, G.H. 1990a, *The Diffuse Interstellar Bands. VII. Search for Diffuse Features in the Absorption Spectrum of Comet P/Halley*, ApJ, 358, 293

Herbig, G.H. 1990b, *Doppler shifts in the coma of Comet P/Halley*, AJ, 99, 1262

Herbig, G.H. 1990c, *The unusual pre-main-sequence star VY Tauri*, ApJ, 360, 639

Herbig, G.H. 1993, *The diffuse interstellar bands. IX - Constraints on the identification*, ApJ, 407, 142

Herbig, G.H. 1994, *The Ae/Be Stars*, in 'The nature and evolutionary status of Herbig Ae/Be stars', ASP Conf. Ser., vol. 62, eds. Pik Sin Thé et al., p. 3

Herbig, G.H. 1995a, *The Diffuse Interstellar Bands*, Ann. Rev. Astron. Astrophys., 33, 19

Herbig, G.H. 1995b, *IC 349: Barnard's Merope Nebula*, J. Roy. Astron. Soc. Can., 89, 133

Herbig, G.H. 1996, *IC 349: Barnard's Merope Nebula*, AJ, 111, 1241

Herbig, G.H. 1998, *The Young Cluster IC 348*, ApJ, 497, 736

Herbig, G.H. 1999, *Examination of the Interstellar Spectrum of AE Aur for Long-Term Changes*, PASP, 111, 809

Herbig, G.H. 2000, *The Search for Interstellar C_{60}*, ApJ, 542, 334

Herbig, G.H. 2002, *Historical introduction. Star formation: the early history*, in Saas-Fee Advanced Course 29 'Physics of star formation in galaxies', eds. A. Maeder & G. Meynet, Swiss Society for Astrophysics and Astronomy, p.1

Herbig, G.H. 2005, *IX Ophiuchi: A High-Velocity Star near a Molecular Cloud*, AJ, 130, 815

Herbig, G.H. 2007, *EX Lupi: History and Spectroscopy*, AJ, 133, 2679

Herbig, G.H. 2008, *History and Spectroscopy of EXor Candidates*, AJ, 135, 637

Herbig, G.H. 2009a, *The Outflowing Wind of V1057 Cyg*, AJ, 138, 448

Herbig, G.H. 2009b, *The Carbon Mira UV Aurigae and its Companion*, AJ, 138, 1502

Herbig, G.H. & Bell, K.R. 1988, *Third Catalog of Emission-Line Stars of the Orion Population*, Lick Observatory Bulletin #1111

Herbig, G.H. & Boyarchuk, A.A. 1968, *The Peculiar Variable FG Sagittae*, ApJ, 153, 397

Herbig, G.H. & Dahm, S.E. 2001, *On the Be and Ae Stars in NGC 6611*, PASP, 113, 195

Herbig, G.H. & Dahm, S.E. 2002, *The Young Cluster IC 5146*, AJ, 123, 304

Herbig, G.H. & Dahm, S.E. 2006, *The Pre-Main-Sequence Population of L988*, AJ, 131, 1530

Herbig, G.H. & Goodrich, R.W. 1986, *Near-Simultaneous Ultraviolet and Optical Spectrophotometry of T Tauri Stars*, ApJ, 309, 294

Herbig, G.H. & Griffin, R.F. 2006, *θ^1 Orionis E as a Spectroscopic Binary*, AJ, 132, 1763

Herbig, G.H. & Harlan, E.A. 1971, *V1057 Cyg*, IBVS, #543

Herbig, G.H. & Hansen, J.M.V. 1944, *Observations of Comets and Asteroids*, Lick Obs. Bull., 19, No. 515, 163

Herbig, G.H. & Jones, B.F. 1981, *Large proper motions of the Herbig-Haro objects HH 1 and HH 2*, AJ, 86, 1232

Herbig, G.H. & Jones, B.F. 1983, *Proper motions of Herbig-Haro objects. III - HH-7 through -11, HH-12, and HH-32*, AJ, 88, 1040

Herbig, G.H. & Kuhi, L.V. 1963, *Emission-Line Stars in the Region of NGC 2068*, ApJ, 137, 398

Herbig, G.H. & Leka, K.D. 1991, *The diffuse interstellar bands. VIII - New features between 6000 and 8650 Å*, ApJ, 382, 193

Herbig, G.H. & McMullin, D.F. 1943, *Comet Oterma 1943a: A Minor Planet?*, PASP, 55, 233

Herbig, G.H. & McNally, D. 1999, *A search for the presence of diffuse interstellar bands in the coma of Comet Hale-Bopp*, MNRAS, 304, 951

Herbig, G.H. & Moore, J.H. 1952, *The Cepheid Variable S Sagittae. I. The Radial-Velocity Variation*, ApJ, 116, 348

Herbig, G.H. & Neubauer, F.J. 1946, *The Spectrum of T Coronae Borealis at the 1946 Maximum*, PASP, 58, 196

Herbig, G.H. & Kameswara Rao, N. 1972, *Second Catalog of Emission-Line Stars of the Orion Population*, ApJ, 174, 401

Herbig, G.H. & Reipurth, B. 2008, *Young Stars and Molecular Clouds in the IC 5146 Region*, in 'Handbook of Star Forming Regions' Vol. I, ed. Bo Reipurth, ASP, 108

Herbig, G.H. & Simon, T. 2001 *Barnard's Merope Nebula Revisited: New Observational Results*, AJ, 121, 3138

Herbig, G.H. & Soderblom, D.R. 1980, *Observations and Interpretation of the Near-Infrared Line Spectra of T Tauri Stars*, ApJ, 242, 628

Herbig, G.H. & Soderblom, D.R. 1982, *The diffuse interstellar bands. V - High-resolution observations*, ApJ, 252, 610

Herbig, G.H. & Spalding, J.F. 1953, *Line Widths in Stars of Spectral Types F0-K5*, PASP, 65, 192

Herbig, G.H. & Spalding, J.F. 1955, *Axial Rotation and Line Broadening in Stars of Spectral Types F0-K5*, ApJ, 121, 118

Herbig, G.H. & Terndrup, D.M. 1986, *The Trapezium Cluster of the Orion Nebula*, ApJ, 307, 609

Herbig, G.H. & Turner, B.A. 1953, *The Spectroscopic Binary 12 Comae Berenices*, ApJ, 118, 477

Herbig, G.H. & Vacca, W.D. 2008, *The Unusual Object IC 2144/MWC 778*, AJ, 136, 1995

Herbig, G.H. & Zappala, R.R. 1968, *Aluminium Hydride Emission Lines in χ Cygni Near Minimum Light*, Zeitschrift für Astrophysik, 68, 423

Herbig, G.H., Preston, G.W., Smak, J., Paczynski, B. 1965, *The Nova-Like Variable V Sagittae as a Short-Period Eclipsing Binary*, ApJ, 141, 617

Herbig, G.H., Vrba, F.J., Rydgren, A.E. 1986, *A spectroscopic survey of the Taurus-Auriga dark clouds for pre-main-sequence stars having CA II H, K emission*, AJ, 91, 575

Herbig, G.H., Aspin, C., Gilmore, A.C. et al. 2001, *The 1993-1994 Activity of EX Lupi*, PASP, 113, 1547

Herbig, G.H., Petrov, P.P., Duemmler, R. 2003, *High-Resolution Spectroscopy of FU Orionis Stars*, ApJ, 595, 384

Herbig, G.H., Andrews, S.M., Dahm, S.E. 2004, *LkHα 101 and the Young Cluster in NGC 1579*, AJ, 128, 1233

Herbst, W. & Shevchenko, V.S. 1999, *A Photometric Catalog of Herbig Ae/Be Stars and Discussion of the Nature and Cause of the Variations of UX Orionis Stars*, AJ, 118, 1043

Herbst, W., Rhode, K.L., Hillenbrand, L.A., Curran, G. 2000, *Rotation in the Orion Nebula Cluster*, AJ, 119, 261

Herczeg, G.J. & Hillenbrand, L.A. 2014, *An Optical Spectroscopic Study of T Tauri Stars. I. Photospheric Properties*, ApJ, 786, A97

Hillenbrand, L. 1995, *Herbig Ae/Be Stars: An Investigation of Molecular Environments and Associated Stellar Populations*, PhD Thesis

Hillenbrand, L., Strom, S.E., Vrba, F.J., Keene, J. 1992, *Herbig Ae/Be stars - Intermediate-mass stars surrounded by massive circumstellar accretion disks*, ApJ, 397, 613

Hillenbrand, L., Miller, A.A., Covey, K.R. et al. 2013, *Highly Variable Extinction and Accretion in the Jet-driving Class I-type Young Star PTF 10nvg (V2492 Cyg, IRAS 20496+4354)*, AJ, 145, A59

Hodapp, K.-W., Hora, J.L., Rayner, J.T. et al. 1996, *An Outburst of a Deeply Embedded Star in Serpens*, ApJ, 468, 861

Hoffmeister, C. 1957, *On RW Aurigae Type Stars and Related Types*, in IAU Symp. No. 3 'Unstable Stars', ed. G.H. Herbig, 22

Hosokawa, T., Offner, S.R., Krumholz, M.R. 2011, *On the Reliability of Stellar Ages and Age Spreads Inferred from Pre-main-sequence Evolutionary Models*, ApJ, 738, A140

Hoyle, F. 1953, *On the Fragmentation of Gas Clouds Into Galaxies and Stars.* , ApJ, 118, 513

Hoyle, F. & Lyttleton, R.A. 1939, *The effect of interstellar matter on climatic variation* , Proc. Cambridge Phil. Soc, 35, issue 3, p.405

Humphreys, R.M., Helton, L.A., Jones, T.J. 2007, *The Three-Dimensional Morphology of VY Canis Majoris. I. The Kinematics of the Ejecta*, AJ, 133, 2716

Iben, I. 1965, *Stellar Evolution. I. The Approach to the Main Sequence*, ApJ, 141, 993

Jeffery, C.S. & Schönberner, D. 2006, *Stellar archaeology: the evolving spectrum of FG Sagittae*, A&A, 459, 885

Jeffries, R.D., Jackson, R.J., James, D.J., Cargile, P.A. 2009, *Low-mass members of the young cluster IC 4665 and pre-main sequence lithium depletion*, MNRAS, 400, 317

Jeffries, R.D., Littlefair, S.P., Naylor, T., Mayne, N.J. 2011, *No wide spread of stellar ages in the Orion Nebula Cluster*, MNRAS, 418, 1948

Johns-Krull, C.M., Valenti, J.A., Koresko, C. 1999, *Measuring the Magnetic Field on the Classical T Tauri Star BP Tauri*, ApJ, 516, 900

Jones, B.F. & Herbig, G.H. 1979, *Proper motions of T Tauri variables and other stars associated with the Taurus-Auriga dark clouds*, AJ, 84, 1872

Jones, B.F. & Herbig, G.H. 1982, *Proper motions of Herbig-Haro objects. II - The relationship of HH-39 to R Monocerotis and NGC 2261*, AJ, 87, 1223

Joy, A.H. 1945, *T Tauri Variable Stars*, ApJ, 102, 168

Joy, A.H. 1949, *Bright-Line Stars among the Taurus Dark Clouds*, ApJ, 110, 424

Joy, A.H. 1960, *Spectra of Dwarf Variable Stars*, in 'Stellar Atmospheres' (Stars and Stellar Systems vol. VI), ed. J.L. Greenstein, Univ. Chicago Press, p. 653

Joy, A.H. & van Biesbroeck, G. 1944, *Five New Double Stars among Variables of the T Tauri Class*, PASP, 56, 123

Keene, J., Davidson, J.A., Harper, D.A. et al. 1983, *Far-infrared detection of low-luminosity star formation in the Bok globule B335*, ApJ, 274, L43

Kenyon, S.J. & Hartmann, L. 1987, *Spectral energy distributions of T Tauri stars - Disk flaring and limits on accretion*, ApJ, 323, 714

Knox Shaw, H. 1916, *Note on the variable nebula in Corona Australis*, MNRAS, 76, 646

Kóspál, Á., Ábrahám, P., Goto, M. et al. 2011, *Near-infrared Spectroscopy of EX Lupi in Outburst*, ApJ, 736, A72

Königl, A. 1991, *Disk Accretion onto Magnetic T Tauri Stars*, ApJ, 370, L39

Kraft, R.P. 1957, *Ca II Emission in Classical Cepheid Variables*, ApJ, 125, 336

Kraft, R.P. 2009, *An Astronomical Life Salted by Pure Chance*, Annual Reviews Astron. Astrophys., 47, 1

Kraus, A. & Ireland, M.J. 2012, *LkCa 15: A Young Exoplanet Caught at Formation?*, ApJ, 745, A5

Kuhi, L.V. 1964, *Mass Loss from T Tauri Stars*, ApJ, 140, 1409

Kurosawa, R. & Romanova, M.M. 2013, *Spectral variability of classical T Tauri stars accreting in an unstable regime*, MNRAS, 431, 2673

Lada, C.J. & Reid, M. 1978, *CO Observations of a Molecular Cloud Complex Associated with the Bright Rim Near VY Canis Majoris*, ApJ, 219, 95

Lagage, P.O., Olofsson, G., Cabrit, S. et al. 1993, *A Deeply Embedded Companion to LkHα 198*, ApJ, 417, L79

Langer, G.E., Kraft, R.P., Anderson, K.S. 1974, *FG Sagittae: The s-process Episode*, ApJ, 189, 509

Larson, R.B. 1980, *The FU Orionis Mechanism*, MNRAS, 190, 321

Larson, R.B. 2011, *Historical Perspective on Computational Star Formation*, in IAU Symp. No. 270 'Computational Star Formation', eds. J. Alves et al., p.1

Laques, P. & Vidal, J.L. 1979, *Detection of a new type of condensations in the center of the Orion Nebula by means of S20 photocathode cells associated with a Lallemand electronic camera*, A&A, 73, 97

Lehmann, T., Reipurth, B., Brandner, W. 1995, *The outburst of the T Tauri star EX Lupi in 1994*, A&A, 300, L9

Leinert, Ch., Zinnecker, H., Weitzel, N. et al. 1993, *A systematic approach for young binaries in Taurus*, A&A, 278, 129

Leinert, Ch., Richichi, A., Haas, M. 1997, *Binaries among Herbig Ae/Be stars*, A&A, 318, 472

Lindroos, K.P. *A study of visual double stars with early-type primaries. V - Post-T Tauri secondaries*, A&A, 156, 223

Loren, R.B, 1975, *Millimeter wavelength molecular emission associated with the young Herbig Be and Ae stars*, PhD Thesis

Lorenzetti, D., Larionov, V.M., Giannini, T. et al. 2009, *Near-Infrared Spectroscopic Monitoring of EXor Variables: First Results*, ApJ, 693, 1056

Luyten, W.J. 1963, Harvard Annu. Card No. 1589

Luyten, W.J. 1971, *The Hyades* (Univ. Minnesota P., Minneapolis)

Lynden-Bell, D. & Pringle, J.E. 1974, *The evolution of viscous discs and the origin of the nebular variables*, MNRAS, 168, 603

Lynds, B.T. 1957, *The Spectra of White Dwarfs*, ApJ, 125, 719

O'Dell, C.R. & Wen, Z. 1994, *Postrefurbishment mission Hubble Space Telescope images of the core of the Orion Nebula: Proplyds, Herbig-Haro objects, and measurements of a circumstellar disk*, ApJ, 436, 194

O'Dell, C.R., Wen, Z., Hu, X. 1993, *Discovery of new objects in the Orion nebula on HST images - Shocks, compact sources, and protoplanetary disks*, ApJ, 410, 696

Osterbrock, D.E. 1958, *Two Dense Nebulae*, PASP, 70, 399

Mamajek, E.E., Meyer, M.R., Liebert, J. 2002, *Post-T Tauri Stars in the Nearest OB Association*, AJ, 124, 1670

Marcy, G.W. 1981, *The magnetic field on the late-type dwarf XI Bootis A*, ApJ, 245, 624

Marcy, G.W. 1984, *Observations of magnetic fields on solar-type stars*, ApJ, 276, 286

Mason, E., Howell, S.B., Barman, T. et al. 2008, *VV Puppis in a low state: secondary-star irradiation or stellar activity?*, A&A, 490, 279

Mathieu, R.D., Ghez, A.M., Jensen, E.L.N., Simon, M. 2000, *Young Binary Stars and Associated Disks* , in 'Protostars and Planets IV', ed. V. Mannings, A.P. Boss, S.S. Russell (Tucson: Univ. Arizona Press), 703

Matthews, B.C., Graham, J.R., Perrin, M.D., Kalas, P. 2007, *The Molecular Gas Environments around Two Herbig Ae/Be Stars: Resolving the Outflows of LkHα 198 and LkHα 225*, ApJ, 671, 483

McGroarty, F., Ray, T.P., Bally, J. 2004, *Parsec-scale Herbig-Haro outflows from intermediate mass stars*, A&A, 415, 189

Mendoza, E.E., Jaschek, M., Jaschek, C. 1969, *The Spectrum of R Coronae Australis*, Bol. Obs. Tonantzintla y Tacubaya, 5, 107

Merchant, A.E. 1966, *Abundance of Lithium in Early M-type Stars*, AJ, 71, 170

Merrill, P.W. & Burwell, C.G. 1949, *Second Supplement to the Mount Wilson Catalogue and Bibliography of Stars of Classes B whose Spectra have Bright Hydrogen Lines*, ApJ, 110, 387

Millan-Gabet, R., Schloerb, F.P., Traub, W.A. 2001, *Spatially Resolved Circumstellar Structure of Herbig Ae/Be Stars in the Near-Infrared*, ApJ, 546, 358

Minkowski, R. 1949, *The Diffuse Nebula in Monoceros*, PASP, 61, 151

Montmerle, T., Koch-Miramond, L., Falgarone, E., Grindlay, J.E. 1983, *Einstein observations of the Rho Ophiuchi dark cloud - an X-ray Christmas tree*, ApJ, 269, 182

Morgan, W.W. & Sharpless, S. 1946, *An Interesting Emission-Line Star Near the Orion Nebula*, ApJ, 103, 249

Muench, A.A., Getman, K., Hillenbrand, L., Preibisch, T. 2008, *Star Formation in the Orion Nebula Cluster I: Stellar Content*, in 'Handbook of Star Forming Regions', Vol. I, ed. Bo Reipurth, Astron. Soc. Pacific Monographs, 483

Mundt, R. & Fried, J. 1983, *Jets from young stars*, ApJ, 274, L83

Muzerolle, J., Hartmann, L., Calvet, N. 1998, *Emission-Line Diagnostics of T Tauri Magnetospheric Accretion. I. Line Profile Observations*, AJ, 116, 455

Najita, J.R., Edwards, S., Basri, G., Carr, J. 2000, *Spectroscopy of Inner Protoplanetary Disks and the Star-Disk Interface*, in 'Protostars and Planets IV', eds. A.P. Boss & S.S. Russell, Univ. Arizona Press, p. 457

Neubauer, F.J. & Herbig, G.H. 1945, *The Spectrum of Nova Aquilae 1945*, PASP, 57, 264

Nikoghosyan, E.H., Magakian, T. Yu., Movsessian, T.A. 2012, *Searches for HH-objects and emission stars in star-formation regions. VIII. Stars with Hα emission in the vicinity of the nebula GM 2-41* , Astrophysics, 55, 70

Ortolani, S. & D'Odorico, S. 1980, *A discussion on the nature of the Herbig-Haro object no. 1 from its far UV spectrum*, A&A, 83, L8

Palla, F. & Galli, D. 1997, *Post-T Tauri Stars: A False Problem*, ApJ, 476, L35

Parenago, P.P. 1954, *Untersuchung der Sterne im Gebiet des Orion-Nebels*, Publ. Astr. Inst. Sternberg, Band 25, p. 393 - 437, Moscow

Parsamian, E.S. & Chavira, E. 1982, *Catalog of H-alpha emission stars in the region of the Orion Nebula*, Bol. Inst. Tonantzintla, 3, 69

Paunzen, E., Pintado, O.I., Maitzen, H.M. 2002, *CCD photometric search for peculiar stars in open clusters. IV* , A&A, 395, 823

Petrov, P.P. 2003, *T Tauri Stars*, Astrophysics, 46, 506

Petrov, P.P. & Herbig, G.H. 1992, *On the interpretation of the spectrum of FU Orionis*, ApJ, 392, 209

Petrov, P.P. & Herbig, G.H. 2008, *Line Structure in the Spectrum of FU Orionis*, AJ, 136, 676

Pettersson, B., Armond, T., Reipurth, B. 2014, *Hα emission-line stars in molecular clouds. II. The M 42 region* , A&A, 570, A30

Pfalzner, S. 2008, *Encounter-driven accretion in young stellar clusters - A connection to FUors?*, A&A, 492, 735

Powell, S.L. et al. 2012, *The periodic spectroscopic variability of FU Orionis*, MNRAS, 426, 3315

Pravdo, S.H., Rodrí guez, L.F. Curiel, S. et al. 1985, *Detection of radio continuum emission from Herbig-Haro objects 1 and 2 and from their central exciting source*, ApJ, 293, L35

Preston, G.W. 1959, *A Spectroscopic Study of the RR Lyrae Stars*, ApJ, 130, 507

Quanz, S.P. 2015, *High-contrast imaging constraints on gas giant planet formation – The Herbig Ae/Be star opportunity*, Astrophys. Spa. Sci., 357, 148

Raga, A.C. & Böhm, K.H. 1985, *Predicted long-slit, high-resolution emission-like profiles from interstellar bow shocks*, ApJS, 58, 201

Raga, A.C., Noriega-Crespo, A., Rodriguez-Gonzales, A et al. 2012, *The Kinematics of HH 34 from HST Images with a Nine-year Time Baseline*, ApJ, 748, 103

Raga, A.C., Reipurth, B., Castellanos-Ramirez, A. et al. 2015, *High Angular Resolution Multi-line Study of HH 1 and 2*, AJ, 150, 105

Raghavan, D., McAlister, H.A., Henry, T.J. et al. 2010, *A Survey of Stellar Families: Multiplicity of Solar-type Stars*, ApJS, 190, 1

Rao, N.K., Giridhar, S., Ashoka, B.N. 1990, *Spectroscopic studies of R CrB during light minima - Absorption spectrum*, MNRAS, 244, 29

Raymond, J.C. 1979, *Shock waves in the interstellar medium*, ApJS, 39, 1

Reipurth, B. 1983, *Star Formation in Bok Globules and Low-mass Clouds. I. The Cometary Globules in the Gum Nebula*, A&A, 117, 183

Reipurth, B. & Aspin, C. 2004a, *The FU Orionis Binary System and the Formation of Close Binaries*, ApJ, 608, L65

Reipurth, B. & Aspin, C. 2004b, *IRAS 05436-0007 and the Emergence of McNeil's Nebula*, ApJ, 606, L119

Reipurth, B. & Bally, J. 2001, *Herbig-Haro Flows: Probes of Early Stellar Evolution*, Ann. Rev. Astron. Astrophys., 39, 403

Reipurth, B. & Bertout, C. 1997, *Herbig-Haro Flows and the Birth of Low Mass Stars*, IAU Symp. No. 182, Kluwer Academic Publishers

Reipurth, B. & Heathcote, S. 1991, *The jet and energy source of HH 46/47*, A&A, 246, 511

Reipurth, B. & Heathcote, S. 1997, *50 Years of Herbig-Haro Research. From discovery to HST*, in IAU Symp. No. 182 'Herbig-Haro Flows and the Birth of Low Mass Stars', Kluwer Academic Publishers, p. 3

Reipurth, B. & Mikkola, S. 2015, *Brown Dwarf Binaries from Disintegrating Triple Systems*, AJ, 149, 145

Reipurth, B. & Zinnecker, H. 1993, *Visual binaries among pre-main sequence stars*, A&A, 278, 81

Reipurth, B., Bally, J., Graham, J.A. et al. 1986, *The jet and energy source of HH 34*, A&A, 164, 51

Reipurth, B., Bally, J., Devine, D. 1997, *Giant Herbig-Haro Flows*, AJ, 114, 2708

Reipurth, B., Heathcote, S., Morse, J. et al. 2002, *Hubble Space Telescope Images of the HH 34 Jet and Bow Shock: Structure and Proper Motions*, AJ, 123, 362

Reipurth, B., Herbig, G.H., Aspin, C. 2010, *The Multiple Pre-main-sequence System HBC 515 in L1622*, AJ, 139, 1668

Reipurth, B., Bally, J., Aspin, C. et al. 2013, *HH 222: A Giant Herbig-Haro Flow from the Quadruple System V380 Ori*, AJ, 146, A118

Reipurth, B., Clarke, C.J., Boss, A.P. et al. 2014, *Multiplicity in Early Stellar Evolution*, in Protostars and Planets VI, (eds. H. Beuther et al.), Univ. of Arizona Press, Tucson, 267

Robberto, M., Soderblom, D.R., Bergeron, E. et al. 2013, *The Hubble Space Telescope Treasury Program on the Orion Nebula Cluster*, ApJS, 207, A10

Roemer, E. 1965, *Orbital Motion of Alpha Ursae Minoris from Radial Velocities*, ApJ, 141, 1415

Rosino, L. 1956, *Nuove ricerche sulle stelle variabili della nebulosa di Orione*, Memorie della Società Astronomia Italiana, 27, p.335

Rydgren, A.E., Strom, S.E., Strom, K.M. 1976, *The Objects of Joy: A Study of the T Tauri Phenomenon*, ApJS, 30, 307

Sallum, S., Follette, K.B., Eisner, J.A. et al. 2015, *Accreting Protoplanets in the LkCa 15 Transition Disc*, Nature, 527, 342

Salpeter, E.E. 1954, *Reactions of Light Nuclei and Young Contracting Stars*, 5^{me} Colloque International d'Astrophysique, Liège, 'Les Processus Nucléaires dans les Astres', p.116

Sanford, R.F. 1947, *High-Dispersion Spectrogram of T Tauri*, PASP, 59, 134

Schmidt, G.D. & Vrba, F.J. 1975, *The nature of Herbig-Haro objects 1 and 2: compact emission nebulae*, ApJ, 201, L33

Schmidt, G.D. & Miller, J.S. 1979, *The emission/reflection nature of Herbig-Haro object 24*, ApJ, 234, L191

Schönberner, D. 2008, *FG Sge, V605 Aql, Sakurai – Facts and Fictions*, in Hydrogen-Deficient Stars, ASP Conf. Ser., Vol. 391, Eds. K. Werner & T. Rauch, p. 139

Schwartz, R.D. 1975, *T Tauri Nebulae and Herbig-Haro Nebulae - Evidence for excitation by a strong stellar wind*, ApJ, 195, 631

Schwartz, R.D. 1977a, *Evidence of star formation triggered by expansion of the Gum Nebula*, ApJ, 212, L25

Schwartz, R.D. 1977b, *A survey of southern dark clouds for Herbig-Haro objects and Hα emission stars*, ApJS, 35, 161

Schwartz, R.D. 1978, *A shocked cloudlet model for Herbig-Haro objects*, ApJ, 223, 884

Sestito, P. & Randich, S. 2005, *Time scales of Li evolution: a homogeneous analysis of clusters from ZAMS to late-MS*, A&A, 442, 615

Shu, F., Najita, J., Ostriker, E. et al. 1994, *Magnetocentrifugally driven flows from young stars and disks. 1: A generalized model*, ApJ, 429, 781

Sicilia-Aguilar, A., Kóspal, A., Setiawan, J. et al. 2012, *Optical spectroscopy of EX Lupi during quiescence and outburst*, A&A, 544, A93

Smak, J.I., Belczynski, K., Zola, S. 2001, *V Sge: a Hot, Peculiar Binary System*, Acta Astron., 51, 117

Smith, B.A. & Terrile, R.J. 1984, *A Circumstellar Disk around β Pictoris*, Science, 226, 1421

Smith, K.W., Balega, Y.Y., Dischl, W.J. et al. 2005, *Close binary companions of the HAeBe stars LkHα198, Elias 1, HK Ori and V380 Ori*, A&A, 431, 307

Smyth, W.H. 1844, *A Cycle of Celestial Objects, Vol. 2* (London:Parker)

Soderblom, D.R. 1982, *Rotational studies of late-type stars. I - Rotational velocities of solar-type stars*, ApJ, 263, 239

Soderblom, D.R. 1983, *Rotational studies of late-type stars. II - Ages of solar-type stars and the rotational history of the sun*, ApJS, 53, 1

Soderblom, D.R., Hartoog, M.R., Herbig, G.H., Mueller, F.S., Robinson, L.B., and Wampler, E.J. 1978, *The Lick Observatory High Resolution Echelle Spectrograph*, High resolution spectrometry, 4th Internat. Coll. on Astrophysics, Trieste, 449

Soderblom, D.R., King, J.R., Siess, L. et al. 1999, *Evolution Of The Lithium Abundances Of Solar-Type Stars. IX. High-Resolution Spectroscopy of Low-Mass Stars in NGC 2264*, AJ, 118, 1301

Solf, J., Böhm, K.H., Raga, A. 1988, *Spatially resolved spectra of HH1 and Burnham's nebula in the range lambda of between about 3700 Å and 10830 Å*, ApJ, 334, 229

Spitzer, L. 1941, *The Dynamics of the Interstellar Medium. II. Radiation Pressure* , ApJ, 94, 232

Stanke, T., Stutz, A.M., Tobin, J.J. et al. 2010, *Hier ist wahrhaftig ein Loch im Himmel. The NGC 1999 dark globule is not a globule*, A&A, 518, L94

Strom, S.E. 1972, *Optical and Infrared Observations of Young Stellar Objects - an Informal Review*, PASP, 84, 745

Strom, S.E., Strom, K.M., Yost, J., Carrasco, L., Grasdalen, G. 1972, *The Nature of the Herbig Ae- and Be-type Stars Associated with Nebulosity*, ApJ, 173, 353

Strom, K.M., Strom, S.E., Grasdalen, G.L. 1974a, *An infrared source associated with a Herbig-Haro object*, ApJ, 187, 83

Strom, S.E., Grasdalen, G.L., Strom, K.M. 1974b, *Infrared and optical observations of Herbig-Haro objects*, ApJ, 191, 111

Strom, K.M., Strom, S.E., Vrba, F.J. 1976, *Infrared surveys of dark-cloud complexes. IV. The Lynds 1517 and Lynds 1551 clouds*, AJ, 81, 320

Strom, S.E., Strom, K.M., Grasdalen, G.L. et al. 1985, *An Optical and Infrared Study of the Region surrounding Herbig-Haro Objects 1 and 2*, AJ, 90, 2281

Strömgren, B. 1939, *The Physical State of Interstellar Hydrogen*, ApJ, 89, 526

Strömgren, B. 1948, *On the Density Distribution and Chemical Composition of the Interstellar Gas*, ApJ, 108, 242

Struve, O. & Rudkjøbing, M. 1949, *Stellar Spectra with Emission Lines in the Obscuring Clouds of Ophiuchus and Scorpius* , ApJ, 109, 92

Struve, O., McNamara, D.H., Kraft, R.P., Kung, S.M., Williams, A.D. 1952, *The Radial Velocity of 16 Lacertae*, ApJ, 116, 81

Symington, N. H., Harries, T. J., & Kurosawa, R. 2005, *Emission-line profile modelling of structured T Tauri magnetospheres*, MNRAS, 356, 1489

Szegedi-Elek, E., Kun, M., Reipurth, B., Pál, A., Balázs, L.G., Willman, M. 2013, *A New Hα Emission-line Survey in the Orion Nebula Cluster*, ApJS 208, A28

Taylor, K.N.R. & Storey, J.W.V. 1984, *The Coronet, an obscured cluster adjacent to R Corona Austrina*, MNRAS, 209, 5P

Teets, W.K., Weintraub, D.A., Kastner, J.H. et al. 2012, *Detection of a Cool, Accretion-shock-generated X-Ray Plasma in EX Lupi during the 2008 Optical Eruption*, ApJ, 760, A89

Tenn, J.S. 2012, *Long-Publishing Astronomers, or the Problem of Classification*, Jour. Astronomical History and Heritage, 15, 47

Thé, P.-S., Perez, M.R., Van den Heuvel, P.J. 1994, *The nature and evolutionary status of Herbig Ae/Be stars*, ASP, San Francisco

Thackeray, A.D., Wesselink, A.J., Oosterhoff, P.Th. 1950, *Additional Observations and I proved Ephemeris of VV Puppis*, Bull. Astron. Inst. Netherlands, XI, 193

Tielens, A.G.G.M. 2014, *Diffuse Interstellar Bands: The Way Forward*, in IAU Symp. No. 297 'The Diffuse Interstellar Bands', eds. J. Cami & N.L.J. Cox, Cambridge Univ. Press, p. 399

Tuthill, P.G., Monnier, J.D., Danchi, W.C., Hale, D., Townes, C.H. 2002, *The Disk around the Luminous Young Star LkHα 101 with Infrared Interferometry*, ApJ, 577, 826

Uchida, Y. & Shibata, K. 1985, *Magnetodynamical acceleration of CO and optical bipolar flows from the region of star formation*, PASJ, 37, 515

Vincke, K., Breslau, A., Pfalzner, S. 2015, *Strong effect of the cluster environment on the size of protoplanetary discs?*, A&A, 577, A115

Vogel, S.N. & Kuhi, L.V. 1981, *Rotational Velocities of Pre-Main Sequence Stars*, ApJ, 245, 960

Vogt, S.S. 1987, *The Lick Observatory Hamilton Echelle Spectrometer*, PASP, 99, 1214

Vogt, S.S. et al. 1994, *HIRES: the high resolution echelle spectrometer on the Keck 10-m telescope*, Proc. SPIE, 2198, 362

Vorobyov, E.I. & Basu, S. 2015, *Variable Protostellar Accretion with Episodic Bursts*, ApJ, 805, A115

Wachmann, A.A. 1939, Beob. Zirk. Astron. Nachr., 21, 12

Wachmann, A.A. 1954, *Das bisherige Verhalten von FU Orionis*, Zeitschrift für Astrophysik, 35, 74

Wagner, K., Apai, D., Kasper, M., Robberto, M. 2015, *Discovery of a Two-Armed Spiral Structure in the Gapped Disk in HD 100453*, ApJ, 813, L2

Walawender, J., Reipurth, B., Bally, J. 2013, *Optical and Near-Infrared Shocks in the L988 Cloud Complex*, AJ, 146, A66

Walker, M.F. 1956, *Studies of Extremely Young Clusters. I. NGC 2264* ApJS, 2, 365

Walter, F.M. 1986, *X-ray sources in regions of star formation. I - The naked T Tauri stars*, ApJ, 306, 573

Walter, F.M. and Kuhi, L.V. 1981, *The smothered coronae of T Tauri stars*, ApJ, 250, 254

Wehinger, P.A., Wyckoff, S., Herbig, G.H., Herzberg, G., and Lew, H. 1974, *Identification of H_2O in the Tail of Comet Kohoutek (1973f)*, ApJ, 190, L43

Welin, G. 1971, *Rapid Evolution of LkHa 190*, A&A, 12, 312

Wellmann, P. 1951, *Veränderungen im Spektrum von FU Orionis*, Zeitschrift für Astrophysik, 29, 154

Whipple, F.L. 1946, *Concentrations of the Interstellar Medium*, ApJ, 104, 1

White, R.E. & Bally, J. 1993, *Interstellar matter near the Pleiades. IV - The wake of the Pleiades through the interstellar medium in Taurus* , ApJ, 409, 234

Wiramihardja, S. D., Kogure, T., Yoshida, S. et al. 1989, *Survey observations of emission-line stars in the Orion region. I - The KISO area A-0904* , PASJ, 41, 155

Woolf, V.M. & Lambert, D.L. 1999, *Three Very Young Hg-Mn Stars in the Orion OB1 Association*, ApJ, 520, L55

Yee, J.C. & Jensen, E.L.N. 2010, *A test of pre-main sequence lithium depletion models*, ApJ, 711, 303

Zappala, R.R. 1972, *Lithium Abundances of Stars in Open Clusters*, ApJ, 172, 57

Zhu, Z., Hartmann, L., Calvet, N. et al. 2008, *Long-Wavelength Excesses of FU Orionis Objects: Flared Outer Disks or Infalling Envelopes?*, ApJ, 684, 1281

Zhu, Z., Hartmann, L., Gammie, C., McKinney, J. 2009, *Two-dimensional Simulations of FU Orionis Disk Outbursts*, ApJ, 701, 620

14 BIBLIOGRAPHY

Refereed papers and catalogs
Review articles
Conference proceedings
Editor of books
Notes, book reviews, and minor items
Popular articles

Herbig, G. 1938, **Amateur Astronomical Society of Los Angeles**, Popular Astronomy, 46, 293 [pdf]

Herbig, G.H. 1940, **Revised Values of the Linear Diameters of Seven Bright Stars**, Publ. Astron. Soc. Pacific, 52, 327-329 [pdf]

Herbig, G.H. and Bunton, G.W. 1941, **Photograph of Cunningham's Comet, 1940 December 29**, Publ. Astron. Soc. Pacific, 53, 37 [pdf]

Herbig, G.H. 1943, **Advances in Astronomical Photography**, Griffith Observer, 7, 18-22 [pdf]

Herbig, G.H. 1943, **A study of the multiple meteoritic falls of the world**, Popular Astronomy, 51, 455-458 [pdf]

Herbig, G.H. and Mcmullin, D.F. 1943, **Comet Oterma 1943 a: A Minor Planet?**, Publ. Astron. Soc. Pacific, 55, 233-238 [pdf]

Herbig, G.H. 1943, **Peculiar Stars**, Griffith Observer 7, 114-122 [pdf]

Herbig, G.H. 1944, **Peculiar Stars**, Leaflet of the Astronomical Society of the Pacific, vol. 4, No. 182, 246-253 [pdf]

Herbig, G.H. 1944, **Review of "Introductory Astronomy" (Sidgwick)**, PASP, 56, 133-134 [pdf]

Herbig, G.H. 1944, **Review of "Twentieth Century Physics" (Jordan)**, Publ. Astron. Soc. Pacific, 56, 209-210 [pdf]

Herbig, G.H. 1944, **Light from Comets**, Griffith Observer, 8, 128-131 [pdf]

Herbig, G.H. 1944, **Direction of Rotation of Galaxies**, Griffith Observer, 8, 134-135 [pdf]

Herbig, G.H. and Hansen, J.M.V. 1944, **Observations of comets and asteroids**, Lick Observatory Bulletin, 19, No. 515, 163-166 [pdf]

Herbig, G.H. 1944, **A photograph of a meteor trail made with the Crossley Reflector**, Popular Astronomy, 52, 459-463 [pdf]

Herbig, G.H. 1944, **The Variable Star UZ Serpentis**, Publ. Astron. Soc. Pacific, 56, 230-234 [pdf]

Herbig, G.H. 1945, **Stellar Magnitudes**, Leaflet of the Astronomical Society of the Pacific, vol. 4, No. 198, 386-393 [pdf]

Herbig, G.H. 1945, **Observations of comets and asteroids**, Lick Observatory Bulletin, 19, No. 517, 171-173 [pdf]

Herbig, G.H. 1945, **The Rotation of the Stars**, Griffith Observer, 9, 66-69 [pdf]

Herbig, G.H. 1945, **Review of "A Meteoric Theory of the Origin of the Earth and Planets" (Schmidt)**, Popular Astronomy, 53, 358-359 [pdf]

Herbig, G.H. 1945, **A Photovisual Comparison Sequence for AE Aquarii**, Publ. Astron. Soc. Pacific, 57, 48-49 [pdf]

Herbig, G.H. 1945, **Comet Notes**, Publ. Astron. Soc. Pacific, 57, 99-100 [pdf]

Herbig, G.H. 1945, **Emission Lines of Fe I in RW Aurigae**, Publ. Astron. Soc. Pacific, 57, 166-168 [pdf]

Herbig, G.H. 1945, **The Spectrum of T Pyxidis**, Publ. Astron. Soc. Pacific, 57, 168-171 [pdf]

Herbig, G.H. 1945, **Soviet Astronomy and World War II.**, Publ. Astron. Soc. Pacific, 57, 196-201 [pdf]

Neubauer, F.J. and Herbig, G.H. 1945, **The Spectrum of Nova Aquilae 1945**, Publ. Astron. Soc. Pacific, 57, 264-266 [pdf]

Herbig, G.H. 1946, **Review of "Experimental Spectroscopy" (Sawyer)**, Publ. Astron. Soc. Pacific, 58, 67 [pdf]

Herbig, G.H. 1946, **A Possible T Tauri Variable in the Diffuse Nebula NGC 1999**, Publ. Astron. Soc. Pacific, 58, 163-164 [pdf]

Herbig, G.H. and Neubauer, F.J. 1946, **The Spectrum of T Coronae Borealis at the 1946 Maximum**, Publ. Astron. Soc. Pacific, 58, 196-208 [pdf]

Herbig, G.H. 1947, **The Eclipsing Binaries ZZ Cephei and UY Virginis**, Astrophys. J., 106, 112-120 [pdf]

Herbig, G.H. 1948, **The Rotation of the Stars**, Leaflet of the Astronomical Society of the Pacific, vol. 5, No. 229, 241-248 [pdf]

Herbig, G.H. 1948, **A Study of Variable Stars in Nebulosity.**, Ph.D. Thesis, 106 pages [pdf]

Herbig, G.H. 1948, **Astronomical Meeting in Pasadena, June 28-July 1, 1948**, Publ. Astron. Soc. Pacific, 60, 219-220 [pdf]

Herbig, G.H. 1948, **The Irregular Variable RW Aurigae and Related Objects**, Publ. Astron. Soc. Pacific, 60, 256-257 [pdf]

Herbig, G.H. 1948, **A Search for Isotopes of Titanium in Late-Type Stars**, Publ. Astron. Soc. Pacific, 60, 378-380 [pdf]

Herbig, G.H. 1948, **Review of "Atlas Stellarum Variabilium, Series IX" (J. Stein)**, Publ. Astron. Soc. Pacific, 60, 135 [pdf]

Herbig, G.H. 1949, **Identification of a Molecular Band at λ 3682 in the Spectra of Late-Type Stars**, Astrophys. J., 109, 109-115 [pdf]

Herbig, G.H. 1949, **The Spectrum of R Coronae Borealis at the 1948-1949 Minimum**, Astrophys. J., 110, 143-155 [pdf]

Herbig, G.H. 1949, **Spectroscopic Observations of the Short-Period Variable AI Velorum**, Astrophys. J., 110, 156-159 [pdf]

Herbig, G.H. 1950, **The Spectrum of the Nebulosity Surrounding T Tauri**, Astrophys. J., 111, 11-14 [pdf]

Herbig, G.H. 1950, **Spectra of Variable Stars in the Orion Nebula**, Astrophys. J., 111, 15-19 [pdf]

Herbig, G.H. 1950, **Some Advances in Observational Astronomy in the Pacific Area During 1949**, Leaflet of the Astronomical Society of the Pacific, vol. 5, No. 250, 407-414 [pdf]

Struve, O., Herbig, G., and Horak, H. 1950, **The Spectrum of YY Geminorum (Castor C).**, Astrophys. J., 112, 216-219 [pdf]

Herbig, G.H. 1950, **The Spectra of Five Irregular Variable Stars**, Publ. Astron. Soc. Pacific, 62, 211-215 [pdf]

Herbig, G.H. 1950, **Variable Stars in Diffuse Nebulae**, Publ. Astron. Soc. Pacific, 62, 142-143 [pdf]

Herbig, G.H. 1951, **The Spectra of Two Nebulous Objects Near NGC 1999**, Astrophys. J., 113, 697-699 [pdf]

Herbig, G.H. 1951, **Stellar Radial-Velocity Programs of the Lick Observatory**, Publ. Astron. Soc. Pacific, 63, 191-199 [pdf]

Grasberger, W.H. and Herbig, G.H. 1952, **Radial Velocity Observations of DT Cygni**, Publ. Astron. Soc. Pacific, 64, 28-30 [pdf]

Herbig, G.H. 1952, **The Spectra of Variable Stars of the RW Aurigae Type**, Trans. IAU, 8, 805-808 [pdf]

Herbig, G.H. and Moore, J.H. 1952, **The Cepheid Variable S Sagittae. I. The Radial-Velocity Variation**, Astrophys. J., 116, 348-368 [pdf]

Herbig, G.H. 1952, **The Cepheid Variable S Sagittae. II. The Emission Lines**, Astrophys. J., 116, 369-381 [pdf]

Herbig, G.H. 1952, **Emission-line Stars in Galactic Nebulosities**, J. Roy. Astron. Soc. Canada, 46, 222-233 [pdf]

Herbig, G.H. 1952, **Emission lines of Ca II in Classical Cepheid Variables**, Publ. Astron. Soc. Pacific, 64, 302-304 [pdf]

Herbig, G.H. 1953, **T Tauri and Hind's Nebula**, Leaflet of the Astronomical Society of the Pacific, 6, No. 293, 338-345 [pdf] (translated to Danish in Nordisk Astronomisk Tidsskrift, 142-147, 1953)

Herbig, G.H. and Spalding, J.F., Jr. 1953, **Line Widths in Stars of Spectral Types F0-K5**, Publ. Astron. Soc. Pacific, 65, 192 [pdf]

Herbig, G.H. and Turner, B.A. 1953, **The Spectroscopic Binary 12 Comae Berenices**, Astrophys. J., 118, 477-480 [pdf]

Herbig, G.H. 1954, **Bright-Hα Stars in IC 348**, Publ. Astron. Soc. Pacific, 66, 19-22 [pdf]

Herbig, G.H. 1954, **Emission-Line Stars Associated with the Nebulous Cluster NGC 2264**, Astrophys. J., 119, 483-495 [pdf]

Walker, M.F. and Herbig, G.H. 1954, **Photoelectric and Spectroscopic Observations**

of UX Ursae Majoris, Astrophys. J., 120, 278-304 [pdf]

Herbig, G.H. and Spalding, J.F., Jr. 1955, **Axial Rotation and Line Broadening in Stars of Spectral Types F0-K5**, Astrophys. J., 121, 118-143 [pdf]

Haro, G. and Herbig, G.H. 1955, **The unusual brightness in the ultraviolet of certain T Tauri-type Stars**, Boletin de los Observatorios Tonantzintla y Tacubaya, 2, num. 12, 33-44 [pdf]

Herbig, G.H. 1955, **HD 224869: an Optical Companion to WZ Cassiopeiae**, Publ. Astron. Soc. Pacific, 67, 181-183 [pdf]

Herbig, G.H. and Worley, C.E. 1956, **Some Basic Astronomical Data**, Leaflet of the Astronomical Society of the Pacific, 7, No. 325, 193-207 [pdf]

Herbig, G.H. 1956, **Identification of Aluminum Hydride as the Emitter of Bright Lines Observed in χ Cygni Near Minimum Light**, Publ. Astron. Soc. Pacific, 68, 204-210 [pdf]

Herbig, G.H. 1956, **The Source of Illumination of NGC 1579**, Publ. Astron. Soc. Pacific, 68, 353-356 [pdf]

Herbig, G.H. 1956, **Observations of the Spectrum of the Companion to BD + 4°4048**, Publ. Astron. Soc. Pacific, 68, 531-533 [pdf]

Herbig, G.H. 1956, **Review of "Gaseous Nebulae" (Aller)**, Publ. Astron. Soc. Pacific, 68, 557-558 [pdf]

Herbig, G.H. 1957, **The Identification of the Emission Lines Observed in the Long-Period Variable χ Cygni near Minimum Light**, in *Les Molecules dans les Astres*, Mem. Soc. Roy. Sci. Liège, 4th Ser., 18, 288-291 [pdf]

Herbig, G.H. 1957, **The Stars of the Orion Nebula**, Leaflet of the Astronomical Society of the Pacific, 7, 273-281 [pdf]

Herbig, G.H. 1957, **Non-stable stars**, Proceedings of IAU Symposium No. 3 held in Dublin, Sept. 1, 1955, Editor G.H. Herbig, Cambridge University Press [contents]

Herbig, G.H. 1957, **On the nature and origin of the T Tauri stars**, *Non-stable stars*, IAU Symp. No. 3, Ed. G.H. Herbig, Cambridge University Press, 3-10 [pdf]

Herbig, G.H. 1957, **The Widths of Absorption Lines in T Tauri-Like Stars**, Astrophys. J., 125, 612-613 [pdf]

Herbig, G.H. 1957, **Emission-Line Stars in the Vicinity of Messier 8, Messier 20, and Simeis 188**, Astrophys. J., 125, 654-660 [pdf]

Gould, N.L., Herbig, G.H., and Morgan, W.W. 1957, **BD +75°325: A Subluminous O-Type Star**, Publ. Astron. Soc. Pacific, 69, 242-244 [pdf]

Herbig, G.H. and Mayall, N.U. 1957, **An Emission-Line Object of High Radial Velocity**, Publ. Astron. Soc. Pacific, 69, 563-565 [pdf]

Herbig, G.H. 1957, **Review of "The Nature of Light and Colour in the Open Air" (Minnaert)**, Publ. Astron. Soc. Pacific, 69, 280 [pdf]

Herbig, G.H. 1958, **T Tauri Stars, Flare Stars, and Related Objects as Members of Stellar Associations**, Ricerche Astronomiche, 5, 127-147 , Proceedings of conference on 'Stellar Populations' at Vatican Observatory, Castel Gandolfo, May 20-28, 1957, edited by D.J.K. O'Connell, Amsterdam: North-Holland, and New York: Interscience, 1958 [pdf]

Herbig, G.H. 1958, **Review of "The Galactic Novae" (Payne-Gaposchkin)**, Sky and Telescope, 17, 245 [pdf]

Herbig, G.H. 1958, **Review of "Vistas in Astronomy" (Beer)**, Publ. Astron. Soc. Pacific, 70, 225-226 [pdf]

Herbig, G.H. 1958, **The Irregular Variable Star V348 Sagittarii**, Astrophys. J., 127, 312-318 [pdf]

Herbig, G.H. 1958, **NGC 7000, IC 5070, and the Associated Emission-Line Stars**, Astrophys. J., 128, 259-266 [pdf]

Bidelman, W.P. and Herbig, G.H. 1958, **A New Emission Line in the Spectra of Long-Period Variables**, Publ. Astron. Soc. Pacific, 70, 451-452 [pdf]

Herbig, G.H. 1958, **The Spectrum of the Nebulosity at AE Aurigae**, Publ. Astron. Soc. Pacific, 70, 468-472 [pdf]

Herbig, G.H. 1958, **Identification Charts for Twelve Variable Stars**, Publ. Astron. Soc. Pacific, 70, 605-606 [pdf]

Herbig, G.H. 1958, **Occurrence of Aluminum Hydride Emission in the Spectra of Long-Period Variables**, Science, 128, 1145 (Abstract of paper presented at Autumn meeting of National Academy of Sciences, Berkeley, Nov. 1958) [pdf]

Herbig, G.H. 1958, **Stars of Types F, G and K with Emission Lines. Introductory Report**, *Mém. Soc. roy. Sci. Liège* [4] 18, 251 [pdf]

Herbig, G.H. 1959, **Observations and an interpretation of VV Puppis**, Astron. J., 64, 128-129 [pdf]

Herbig, G.H. 1959, **Review of "Astrophysics II. Stellar Structure (Handb. Der Physik)"**, Publ. Astron. Soc. Pacific, 71, 551-552 [pdf]

Herbig, G.H. 1960, **Observations of Interstellar Lines**, Astron. J., 65, 491 [pdf]

Herbig, G.H. and Worley, C.E. 1960, **Some basic Astronomical Data**, Leaflet of the Astronomical Society of the Pacific (Supplement), 1, 1-16 [pdf]

Herbig, G.H. and Mendoza v., E.E. 1960, **Wolf-Rayet Stars in the vicinity of the association VI Cygni**, Boletin de los Observatorios Tonantzintla y Tacubaya, 2, 21-23 [pdf]

Herbig, G.H. 1960, **Emission-Line Stars in IC 5146**, Astrophys. J., 131, 516-517 [pdf]

Herbig, G.H. 1960, **The Spectra of Be- and Ae-Type Stars Associated with Nebulosity**, Astrophys. J. Suppl., 4, 337-368 [pdf]

Herbig, G.H. 1960, **Spectral Classifications for 112 Variable Stars**, Astrophys. J., 131, 632-637 [pdf]

Herbig, G.H. 1960, **Observations and an Interpretation of VV Puppis**, Astrophys. J., 132, 76-86 [pdf]

Rach, R.A. and Herbig, G.H. 1961, **The Orbit of the Spectroscopic Binary Phi Cygni**, Astrophys. J., 133, 143-147 [pdf]

Herbig, G.H. 1961, **Observations of RY Tauri**, Astrophys. J., 133, 337-340 [pdf]

Herbig, G.H. 1961, **Report on Irregular Variable Stars in Very Young Clusters and Associations**, Trans. IAU, 118, 275-278 [pdf]

Herbig, G.H. 1962, **Review of "Tools of the Astronomer" (G.R. Miczaika and W. Sinton)**, Applied Optics, 1, 168 [pdf]

Herbig, G.H. 1962, **The properties and problems of T Tauri stars and related objects**, Advances in Astronomy and Astrophysics, 1, 47-103 [pdf]

Herbig, G.H. 1962, **Spectroscopic Studies of Early Phases of Stellar Evolution**, in *Stellar Evolution*, ed. J. Sahade, La Plata Observatory, Argentina, 23-32 [pdf]

Herbig, G.H. 1962, **On the Evolutionary Interpretation of the M Dwarfs**, *Stellar Evolution*, ed. J. Sahade, 45-59 [pdf]

Herbig, G.H. and Haro, G. 1962, **A Wide Pair of Me Dwarfs**, Boletin de los Observatorios Tonantzintla y Tacubaya, 3, 118 [pdf]

Herbig, G.H. 1962, **Spectral Classification of Faint Members of the Hyades and Pleiades and the Dating Problem in Galactic Clusters**, Astrophys. J., 135, 736-747 [pdf]

Herbig, G.H. 1962, **Displaced Lines of Ni II in P Cygni**, Astrophys. J., 135, 965-968 [pdf]

Herbig, G.H. 1963, **The Diffuse Interstellar Bands. I. A Possible Identification of λ 4430**, Astrophys. J., 137, 200-212 [pdf]

Herbig, G.H. 1963, **Some Spectroscopic Problems of the Interstellar Medium**, J. Quant. Spectrosc. Radiat. Transfer, vol. 3, 529-536 [pdf]

Herbig, G.H. and Kuhi, L.V. 1963, **Emission-Line Stars in the Region of NGC 2068**, Astrophys. J., 137, 398-400 [pdf]

Herbig, G.H. 1963, **Search for Residual Traces of the T Tauri Phenomenon in Normal Stars: Lithium in G-Type Dwarfs**, Astron. J., 68, 280 [pdf]

Wallerstein, G., Herbig, G.H., and Conti, P. 1963, **Observations of Lithium in Main Sequences Stars in the Hyades and Other F Stars**, Astron. J., 68, 298 [pdf]

Herbig, G.H. 1963, **Dwarf Variable Stars**, article for *Dictionary of Physics* [pdf]

Herbig, G.H. 1964, **Apparent Lithium Isotope Ratios in F5-G8 Main Sequence Stars**, Astron. J., 69, 141 [pdf]

Herbig, G.H. and Wilde, K. 1964, **Spectrum of Nova Puppis 1963**, Information Bulletin on Variable Stars, #53 [pdf]

Herbig, G.H. 1964, **Apparent Lithium Isotope Ratios in F5-G8 Dwarfs**, Astrophys. J., 140, 702-706 [pdf]

Herbig, G.H., Preston, G.W., Smak, J., and Paczynski, B. 1964, **V Sagittae**, Information Bulletin on Variable Stars, #68, 1-3 [pdf]

Herbig, G.H. 1964, **MV Sagittarii: a Helium-Rich Variable Star**, Astrophys. J., 140, 1317-1319 [pdf]

Herbig, G.H. 1964, **Las Estrellas T Tauri**, Aster, 16, No. 128, 2-5 [pdf]

Herbig, G.H. 1965, **Physical Companions to Long-Period Variables**, Veröffentlichungen der Remeis-Sternwarte zu Bamberg, 27, 164-168 [pdf]

Herbig, G.H. 1965, **Lithium Abundances in F5-G8 Dwarfs**, Astrophys. J., 141, 588-609 [pdf]

Herbig, G.H. 1965, **Measured Equivalent Widths for F5-G8 Dwarfs**, Lick Obs. Bull. No. 595a [pdf]

Herbig, G.H. 1965, **Junge Sterne, Lithium and frühe Sternentwicklung**, Umschau in Wissenschaft und Technik, 65, Heft 2, 40-43 [pdf]

Wallerstein, G., Herbig, G.H., and Conti, P.S. 1965, **Observations of the Lithium Content of Main-Sequence Stars in the Hyades**, Astrophys. J., 141, 610-616 [pdf]

Herbig, G.H., Preston, G.W., Smak, J., and Paczynski, B. 1965, **The Nova-Like Variable V Sagittae as a Short-Period Eclipsing Binary**, Astrophys. J., 141, 617-648 [pdf]

Herbig, G.H. and Moorhead, J.M. 1965, **BD-21°6267A: a New dMe Double-Line Spectroscopic Binary**, Astrophys. J., 141, 649-651 [pdf]

Herbig, G.H. 1965, **Report of the Committee on the Spectra of Variable Stars**, Trans. IAU, 12A, 372-390 [pdf]

Herbig, G.H. 1966, **On the interpretation of FU Orionis**, Vistas in Astronomy, 8, 109-125 [pdf]

Herbig, G.H. 1966, **The Occurrence of Lithium in F5-G8 Main-Sequence Stars**, in *Spectral Classification and Multicolour Photometry*, IAU Symp. 24, ed. K. Lodén, 13-14 [pdf]

Herbig, G.H. and Peimbert, M. 1966, **The distribution of Emission-line Stars in the Taurus Dark Clouds**, Trans. IAU, Series 12B, 412-415 [pdf]

Herbig, G.H. 1966, **The Orion Nebula: Introduction**, Transactions of the International Astronomical Union, Series B, 12, 443-443 [pdf]

Herbig, G.H. 1966, **Lithium in Main-Sequence Stars**, in *Stellar Evolution*, eds. R.F. Stein & A.G.W. Cameron, Plenum Press, 411-415 [pdf]

Herbig, G.H. 1966, **The Diffuse Interstellar Bands. II. The Profile of λ 4430 in HD 183143**, Zeitschrift für Astrophysik, 64, 512-517 [pdf]

Field, G.B., Herbig, G.H., and Hitchcock, J. 1966, **Radiation Temperature of Space at λ2.6 mm**, Astron. J., 71, 161 [pdf]

Herbig, G.H. and R.J. Wolff 1966, **Lithium abundances in F, G and K-type subgiants**, Annales d'Astrophysique, 29, 593-600 [pdf]

Herbig, G.H. and R.J. Wolff 1966, **Measured Equivalent Widths for F, G and K-type subgiants**, Lick Obs. Bull. No. 595b [pdf]

Herbig, G.H. 1966, **FU Orionis – Star in Process of Formation**, in *Earth and the Universe*, 3, 19-27 [in Russian] [pdf]

Herbig, G.H. 1967, **The Youngest Stars**, Scientific American, 217, no. 2, 30-36 [french translation in Orion, vol. 13, 31-37, 1968] [pdf]

Herbig, G.H. 1967, **The diffuse interstellar bands, III: The situation in 1966**, in *Radio Astronomy and the Galactic System*, IAU Symp. 31, 85-89 [pdf]

Herbig, G.H. 1967, **Experience with large Telescopes**, Mitteilungen der Astronomischen Gesellschaft Hamburg, 23, 28-30 [pdf]

Eggen, O.J. and Herbig, G.H. 1967 (eds.), **Clusters and stellar evolution**, Mon. Not. Roy. Astron. Soc., 137, 111 [pdf]

Herbig, G.H. 1967, **On the Duplicity of VI Cygni Nos. 5 and 8A**, Publ. Astron. Soc. Pacific, 79, 502 [pdf]

Augason, G.C. and Herbig, G.H. 1967, **A Lower Limit on the C^{12}/C^{13} Ratio in the Interstellar Gas**, Astrophys. J., 150, 729-730 [pdf]

Herbig, G.H. 1968, **Emission lines of Mn I in long-period variables**, Mémoires de la Société Royale des Sciences de Liège, 37, 433-436 [pdf]

Herbig, G.H. 1968, **The Absorption Spectrum of Interstellar Material**, Proceedings of *International Conference on Spectroscopy*, Bombay, Jan 1967, 15-29 [pdf]

Herbig, G.H. 1968, **The Occurrence of Lithium in Stars**, Highlights of Astronomy, 1, 230 [pdf]

Herbig, G.H. and Boyarchuk, A.A. 1968, **On the Variability of the Central Star of the Planetary Nebula HZ 1-5**, Planetary Nebulae, IAU Symp. 34, 383-385 [pdf]

Herbig, G.H. 1968, **Etoiles Variables (Variable Stars)**, Transactions of the International Astronomical Union, Series B, 13, 148-153 [pdf]

Herbig, G.H. 1968, **The Interstellar Line Spectrum of Zeta Ophiuchi**, Zeitschrift für Astrophysik, 68, 243-277 [pdf]

Herbig, G.H. and Zappala, R.R. 1968, **Aluminium Hydride Emission Lines in χ Cygni Near Minimum Light**, Zeitschrift für Astrophysik, 68, 423-430 [pdf]

Herbig, G.H. 1968, **Announcement of IAU Colloquium on Variable Stars**, Information Bulletin on Variable Stars, #243, 1-2 [pdf]

Herbig, G.H. 1968, **Nova Vul 1968**, Information Bulletin on Variable Stars, #272, 1 [pdf]

Herbig, G.H. 1968, **The Structure and Spectrum of R Monocerotis**, Astrophys. J., 152, 439-441 [pdf]

Herbig, G.H. and Boyarchuk, A.A. 1968, **The Peculiar Variable FG Sagittae**, Astrophys. J., 153, 397-420 [pdf]

Herbig, G.H. 1968, **Review of "Interstellar Grains" (Wickramasinghe)**, Publ. Astron. Soc. Pacific, 80, 109 [pdf]

Herbig, G.H. 1969, **Forbidden emission transitions in cool stars**, Mémoires de la Société Royale des Sciences de Liège, *Les Transitions Interdites dans les Spectres des Astres*, 25, 353-361 [pdf]

Herbig, G.H. 1969, **Emission-Line Objects Projected upon the Galactic Bulge**, Proceedings of the National Academy of Science, 63, 1045-1050 [pdf]

Herbig, G.H. 1969, **The light variations of the nuclei in Herbig-Haro object No. 2, 1946-1968**, Communications of the Konkoly Observatory Hungary, 65, 75-84 [pdf]

Herbig, G.H. 1970, **Introductory Remarks**, in *Evolution Stellaire avant La Séquence Principale*, Mémoires de la Société Royale des Sciences de Liège, 5. série, vol. 19, 13-26

[pdf]

Herbig, G.H. 1970, **VY Canis Majoris. II. Interpretation of the Energy Distribution**, Astrophys. J., 162, 557-570 [pdf]

Herbig, G.H. 1970, **Interstellar Lines Other than Hydrogen**, *Ultraviolet Stellar Spectra and Related Ground-Based Observations*, IAU Symp. 36, 315-319 [pdf]

Herbig, G.H. 1970, **Spectroscopic astrophysics. An assessment of the contributions of Otto Struve**, University of California Press [pdf]

Herbig, G.H. 1970, **Introduction: A Personal and Scientific Appreciation of Otto Struve**, in *Spectroscopic Astrophysics. An Assessment of the Contributions of Otto Struve*, Ed. G.H. Herbig, University of California Press, 1-3 [pdf]

Herbig, G.H. 1970, **Early Stellar Evolution at Intermediate Masses**, in *Spectroscopic Astrophysics. An Assessment of the Contributions of Otto Struve*, Ed. G.H. Herbig, University of California Press, 237-248 [pdf]

Herbig, G.H. and Zappala, R.R. 1970, **Near-Infrared Spectra of NML Cygni and IRC+10216**, Astrophys. J., 162, L15-L18 [pdf]

Herbig, G.H. 1970, **Variable Star Colloquium in Bamberg 31 August - 3 September 1971**, Information Bulletin on Variable Stars, #491 [pdf]

McNally, D. and Herbig, G.H. 1971, (Eds.) **Interstellar molecules**, in *Joint discussion during the XIVth general assembly of the IAU, Brighton 1970*, Highlights of Astronomy, 2, 333-462 [pdf]

Herbig, G.H. 1971, **Introductory Remarks**, Highlights of Astronomy, 2, 335 [pdf]

Herbig, G.H. 1971, **Basic Note**, in IAU Colloq. 15 *New Directions and New Frontiers in Variable Star Research*, 8 [pdf]

Herbig, G.H. 1971, **Interstellar Staub als Nebenprodukt der Sternentstehung.**, Sterne und Weltraum, 10, 4-8 [pdf]

Faulkner, J. and Herbig, G.H. 1971, **Research Units and Academic Departments, University of California: IV. Santa Cruz Campus: A.) Board of Studies in Astronomy and Astrophysics; B.) Lick Observatory. Report 1969-1970**, Bull. Amer. Astron. Soc., 3, 51-58 [pdf]

Herbig, G.H. and Harlan, E.A. 1971, **V1057 Cyg**, Information Bulletin on Variable Stars, #543, 1-2 [pdf]

Herbig, G.H. 1971, **Daytime and Other Unanticipated Uses of Telescopes**, *Conference on Large Telescope Design*, Ed. R.M. West, ESO, 477-480 [pdf]

Herbig, G.H. 1971, **The Spectrum of LkHα-101 in the Near-Infrared**, Astrophys. J., 169, 537-541 [pdf]

Herbig, G.H., Stephenson, C.B., Wisniewski, W., Lee, T., Wdowiak, T., Michlovic, J., Matchett, V.L., and Mayer, E.H. 1972, **Supernova in NGC 5253**, IAU Circular#2407 [pdf]

Herbig, G.H. 1972, **MWC 349**, IAU Circular#2457 [pdf]

Herbig, G.H. 1972, **VY Canis Majoris. III. Polarization and Structure of the Nebulosity**, Astrophys. J., 172, 375-381 [pdf]

Herbig, G.H. and Kameswara Rao, N. 1972, **Second Catalog of Emission-Line Stars of the Orion Population**, Astrophys. J., 174, 401-423 [pdf]

Herbig, G.H. 1972, **A Highly Reddened Star Near NGC 6231**, Astrophys. J., 174, L89-L91 [pdf]

Herbig, G.H., Sherrod, C., Scovil, C.E., Kojima, N., and Seki, T. 1973, **Comet Kohoutek (1973f)**, IAU Circular#2596 [pdf]

Feast, M.W., Sawyer Hogg, H.B., Zwicky, F., Herbig, G.H., and Chugajnov, P.F. 1973, **Variable stars (Étoiles variables)**, Transactions of the International Astronomical Union, Series A, 15, 313-356 [pdf]

Herbig, G.H. 1973, **BD -10°4662 interpreted as a post-T Tauri star**, Astrophys. J., 182, 129-138 [pdf]

Flannery, B.P. and Herbig, G.H. 1973, **Expansion of the planetary nebula surrounding FG Sagittae**, Astrophys. J., 183, 491-498 [pdf]

Herbig, G.H. 1973, **Emission Bands of Scandium Oxide in the Spectrum of VY CMa**, Bull. Amer. Astron. Soc., 5, 442 [pdf]

Tsuchiya, K., Urata, T., Seki, T., Lorenzi, L., Giclas, H.L., Herbig, G.H., Duncan, D., and Marsden, B.G. 1973, **Comet Kohoutek (1973f)**, IAU Circular#2588 [pdf]

Herbig, G.H. 1973, **Brightening of Herbig-Haro Object No. 1**, Information Bulletin on Variable Stars, #832, 1-2 [pdf]

Milet, B., Schoenmaker, A.A., Giclas, H.L., Kantz, M.L., Soulié, G., Harrington, R.S., Morrison, B.A., Herbig, G.H., Baratta, G.B., Buonanno, R., Smriglio, F., Nesci, R., and Viotti, R. 1974, **Comet Kohoutek (1973f)**, IAU Circular#2629 [pdf]

Herbig, G.H. 1974, **Draft Catalog of Herbig-Haro Objects**, Lick Observatory Bulletin, 658, 1-21 [pdf]

Herbig, G.H. 1974, **LST-A Window on Stellar Nurseries**, *Large Space Telescope - A New Tool for Science*, 39 [pdf]

Herbig, G.H. 1974, **Interstellar Smog**, American Scientist, 62, 200-207 [pdf]

Herbig, G.H. 1974, **VY Canis Majoris. IV. The emission bands of ScO**, Astrophys. J., 188, 533-538 [pdf]

Herbig, G.H. and Lorre, J. 1974, **Structure of the OH/infrared object NML Cygnus. I. Analysis of the near-infrared image**, Astrophys. J., 189, 73-74 [pdf]

Herbig, G.H. 1974, **Structure of the OH/infrared object NML Cygnus. II. Analysis of the OH interferometry**, Astrophys. J., 189, 75-79 [pdf]

Wehinger, P.A., Wyckoff, S., Herbig, G.H., Herzberg, G., and Lew, H. 1974, **Identification of H_2O in the Tail of Comet Kohoutek (1973f)**, Astrophys. J., 190, L43-L46 [pdf]

Herbig, G.H. 1974, **On the nature of the small dark globules in the Rosette Nebula**, Publ. Astron. Soc. Pacific, 86, 604-608 [pdf]

Herbig, G. 1974, **A. H. Joy, 1882 September 23 - 1973 April 18**, Quart. J. Roy. Astron. Soc., 15, 526-531 [pdf]

Herbig, G.H. and Hoffleit, D. 1975, **Coronal lines in the spectrum of AS 295**, Mémoires de la Société Royale des Sciences de Liège, 9, 403 [pdf]

Herbig, G. 1975, **Spectroscopy of the coma and tail**, NASA Special Publication #355 *Comet Kohoutek*, 233-235 [pdf]

Herbig, G.H. 1975, **The diffuse interstellar bands. IV - The region 4400-6850 A**, Astrophys. J., 196, 129-160 [pdf]

Cohen, M., Anderson, C.M., Cowley, A., Coyne, G.V., Fawley, W., Gull, T.R., Harlan, E.A., Herbig, G.H., Holden, F., Hudson, H.S., Jakoubek, R.O., Johnson, H.M., Merrill, K.M., Schiffer, F.H., Soifer, B.T., and Zuckerman, B. 1975, **The peculiar object HD 44179 'The red rectangle'**, Astrophys. J., 196, 179-189 [pdf]

Herbig, G.H. 1975, **Emission Lines in the Hydrogen-Deficient Variable MV Sagittarii Near Maximum Light**, Astrophys. J., 199, 702-704 [pdf]

Herbig, G.H. 1975, **The spectrum and structure of 'Minkowski's footprint' - M 1-92**, Astrophys. J., 200, 1-5 [pdf]

Herbig, G.H. and Hoffleit, D. 1975, **The coronal line spectrum of AS 295**, Astrophys. J., 202, L41-L45 [pdf]

Herbig, G.H. 1976, **The diffuse interstellar lines**, in *Molecular Spectroscopy: Modern Research*, Volume II, 255-259 [pdf]

Herbig, G.H. 1976, **Review of cometary spectra**, NASA Special Publication #393 *The Study of Comets*, 136-158 [pdf]

Bortle, J., O'Meara, S., MacKinnon, P., Somers, D., Welch, D., Dick, R., Lossing, F., Murrell, S., Knuckles, C., Reese, E.J., Neff, J.S., Ketelsen, D.A., Smith, V.V., Herbig, G.H., Duncan, D., Soderblom, D., Pilcher, F., Maley, P., and Ikeya, K. 1976, **Comet West (1975n)**, IAU Circular #2927 [pdf]

Herbig, G.H. 1976, **A Universe Teeming with Planetary Systems - Perhaps**, Mercury, vol.5, no.2, p.2-7 [pdf]

Herbig, G.H. 1977, **Summary of the Conference: Observations**, in IAU Symp. No. 75 *Star Formation*, ed. T. de Jong & A. Maeder, 283-289 [pdf]

Herbig, G.H. 1977, **Radial velocities and spectral types of T Tauri stars**, Astrophys. J., 214, 747-758 [pdf]

Herbig, G.H. 1977, **Duplicity and Spectral Types of HV 10814**, Information Bulletin on Variable Stars, #1323 [pdf]

Herbig, G.H. 1977, **Eruptive phenomena in early stellar evolution**, Astrophys. J., 217, 693-715 [pdf]

Soderblom, D.R., Hartoog, M.R., Herbig, G.H., Mueller, F.S., Robinson, L.B., and Wampler, E.J. 1978, **The Lick Observatory High Resolution Echelle Spectrograph**, in *High resolution spectrometry*, 4th Internat. Coll. on Astrophysics, Trieste, 449-458 [pdf]

Herbig, G.H. 1978, **Some aspects of early stellar evolution that may be relevant to the origin of the solar system**, in *The Origin of the Solar System*, ed. S.F. Dermott, Wiley & Sons, 219-235 [pdf]

Herbig, G.H. 1978, **Can Post-T Tauri Stars Be Found?**, in *Problems of Physics and Evolution of the Universe*, Academy of Sciences of Armenian SSR, Yerevan, 171-179 [pdf]

Bouchet, P., Adam, G., Maley, P., Herbig, G.H., and Harlan, E. 1978, **Nova Serpentis 1978**, IAU Circular #3198 [pdf]

Seki, T., Herbig, G.H., Harlan, E.A., Maley, P., Mayo, M.J., and Truxton, J. 1978, **Comet Bradfield (1978c)**, IAU Circular #3199 [pdf]

Cudworth, K.M. and Herbig, G. 1979, **Two large-proper-motion Herbig-Haro objects**, Astron. J., 84, 548-551 [pdf]

Herbig, G.H. and Landolt, A.U. 1979, **SU Tauri**, IAU Circular #3418 [pdf]

Jones, B.F. and Herbig, G.H. 1979, **Proper motions of T Tauri variables and other stars associated with the Taurus-Auriga dark clouds**, Astron. J., 84, 1872-1889 [pdf]

Henize, K., Herbig, G.H., Boyarchuk, A.A., Whitney, C.A., Wenzel, W., Furtig, W., Jurcsik, J., and Szabados, L. 1980, **A Very Rapidly Evolving Star = FG-Sagittae = 20H09.7M+20DEG11**, Sky & Telescope, 59, 462 [pdf]

Jones, B.F. and Herbig, G.H. 1980, **Motion of HH-1 and HH-2**, Bull. Amer. Astron. Soc., 12, 843 [pdf]

Herbig, G.H. 1980, **R Aquarii**, IAU Circular #3535 [pdf]

Herbig, G.H. and Soderblom, D.R. 1980, **Observations and interpretation of the near-infrared line spectra of T Tauri stars**, Astrophys. J., 242, 628-637 [pdf]

Herbig, G.H. 1981, **Life-Supporting Environments**, in *Life in the Universe*, NASA, 75 [pdf]

Herbig, G.H. 1981, **Some recent results in early stellar evolution**, in *Recent Advances in Observational Astronomy*, eds. Harold L. Johnson & Christine Allen, 19-23 [pdf]

Griffin, R.F. and Herbig, G.H. 1981, **Spectroscopic Orbits of ξ Piscium, 60 Andromedae and ξ^1 Ceti**, Mon. Not. Roy. Astron. Soc., 196, 33-43 [pdf]

Herbig, G.H. and Jones, B.F. 1981, **Large proper motions of the Herbig-Haro objects HH 1 and HH 2**, Astron. J., 86, 1232-1244 [pdf]

Duncan, D.K., Harlan, E.A., and Herbig, G.H. 1981, **Photometry of the Reflection Nebulosity at V1057 Cygni**, Astron. J., 86, 1520-1525 [pdf]

Herbig, G.H. 1981, **The Origin and Astronomical History of Terrestrial Oxygen**, Chapter 4 in *Oxygen and Living Processes: An Interdisciplinary Approach*, ed. D.L. Gilbert, Springer-verlag, p. 65-72 [pdf]

Herbig, G.H. and Soderblom, D.R. 1982, **The diffuse interstellar bands. V - High-resolution observations**, Astrophys. J., 252, 610-615 [pdf]

Herbig, G.H. 1982, **Summary of the Workshop - Observations**, in *Cool Stars, Stellar Systems, and the Sun II*, eds. M.S. Giampapa & L. Golub, SAO Special Report, 392, vol. 2, 205-208 [pdf]

Duncan, D., Harlan, E., and Herbig, G. 1982, **A Short-Lived Nebula Near V1057-Cygni**, Sky & Telescope, 63, 364 [pdf]

Sopka, R.J., Herbig, G., Kafatos, M., and Michalitsianos, A.G. 1982, **Radio and optical observations of the R Aquarii jet**, Astrophys. J., 258, L35-L39 [pdf]

Jones, B.F. and Herbig, G.H. 1982, **Proper motions of Herbig-Haro objects. II - The**

relationship of HH-39 to R Monocerotis and NGC 2261, Astron. J., 87, 1223-1232 [pdf]

Herbig, G.H. 1982, **Stars of low to intermediate mass in the Orion Nebula**, in *Symposium on The Orion Nebula to Honor Henry Draper*, eds. A.E. Glassgold, P.J. Huggins, E.L. Schucking, Annals of the New York Academy of Sciences, 395, 64-77 [pdf]

Herbig, G.H. 1983, **The origin and early history of the sun and the planetary system in the context of stellar evolution**, Invited Discourse at 18th IAU Gen. Assembly, Patras, Greece, Highlights of Astronomy, 6, 15-28 [pdf]

Herbig, G.H., Harlan, E.A., Kraft, R.P., and Locher, K. 1983, **Variable Star in Orion**, IAU Circular #3778 [pdf]

Mundt, R., Walter, F.M., Feigelson, E.D., Finkenzeller, U., Herbig, G.H., and Odell, A.P. 1983, **Observations of suspected low-mass post-T Tauri stars and their evolutionary status**, Astrophys. J., 269, 229-238 [pdf]

Herbig, G.H. and Jones, B.F. 1983, **Proper motions of Herbig-Haro objects. III - HH-7 through -11, HH-12, and HH-32**, Astron. J., 88, 1040-1052 [pdf]

Herbig, G.H. 1984, **Review of "The Orion Complex - a Case Study of Interstellar Matter" (Goudis)**, Astrophys. Lett., 24, 103-104 [pdf]

Herbig, G.H. 1985, **Observable consequences of star formation in molecular clouds**, in Blaauw symposium *Birth and Evolution of Massive Stars and Stellar Groups*, eds. W. Boland & H. van Woerden, Reidel, p. 41-48 [pdf]

Herbig, G.H. 1985, **T Tauri stars: Some observational aspects**, in *Birth and Infancy of Stars*, eds. R. Lucas et al., (North Holland), p. 535-555 [pdf]

Lyons, R., Bolton, C.T., Harlan, E.A., Herbig, G.H., Maley, P., and Medway, K. 1985, **Nova Vulpeculae 1984 No. 2**, IAU Circular #4028 [pdf]

Herbig, G.H. 1985, **Chromospheric H-alpha emission in F8-G3 dwarfs, and its connection with the T Tauri stars**, Astrophys. J., 289, 269-278 [pdf]

Simon, T., Herbig, G., and Boesgaard, A.M. 1985, **The evolution of chromospheric activity and the spin-down of solar-type stars**, Astrophys. J., 293, 551-570 [pdf]

Goodrich, R.W. and Herbig, G.H. 1986, **Simultaneous Ultraviolet and Optical Spectrophotometry of T Tauri Stars**, in *Cool Stars, Stellar Systems and the Sun IV*, eds. M. Zeilik & D.M. Gibson, p. 109-111 [pdf]

Herbig, G.H., Vrba, F.J., and Rydgren, A.E. 1986, **A spectroscopic survey of the Taurus-Auriga dark clouds for pre-main-sequence stars having CA II H, K emission**, Astron. J., 91, 575-582 [pdf]

Herbig, G.H. and Terndrup, D.M. 1986, **The Trapezium cluster of the Orion nebula**, Astrophys. J., 307, 609-618 [pdf]

Herbig, G.H. and Goodrich, R.W. 1986, **Near-simultaneous ultraviolet and optical spectrophotometry of T Tauri stars**, Astrophys. J., 309, 294-305 [pdf]

Irvine, C.E. and Herbig, G.H. 1986, **V1302 Aquilae (IRC +10420)**, IAU Circular #4286 [pdf]

Herbig, G. 1987, **The T Tauri stars**, Journal of the American Association of Variable Star

Observers, 16, 1-3 [h87] [pdf]

Herbig, G.H. and Bell, K.R. 1988, **Third Catalog of Emission-Line Stars of the Orion Population**, Lick Observatory Bulletin #1111, 90 pages [pdf]

Herbig, G.H. 1988, **The diffuse interstellar bands. VI - New features near 6800 A**, Astrophys. J., 331, 999-1003 [pdf]

Herbig, G.H. 1989, **Summarizing remarks on the astronomical evidence for circumstellar disks**, in *The Formation and Evolution of Planetary Systems*, eds. H.A. Weaver & L. Danly, Cambridge Univ. Press, p. 296-303 [pdf]

Herbig, G.H. 1989, **FU Orionis eruptions**, in *Low Mass Star Formation and Pre-Main Sequence Objects*, ed. Bo Reipurth, ESO Conference and Workshop Proceedings 33, p. 233-246 [pdf]

Herbig, G.H. 1990, **The diffuse interstellar bands. VII - Search for diffuse features in the absorption spectrum of Comet P/Halley**, Astrophys. J., 358, 293-297 [pdf]

Herbig, G.H. 1990, **Doppler shifts in the coma of Comet P/Halley**, Astron. J., 99, 1262-1267 [pdf]

Herbig, G.H. 1990, **The unusual pre-main-sequence star VY Tauri**, Astrophys. J., 360, 639-649 [pdf]

Griffin, R.F. and Herbig, G.H. 1991, **Spectroscopic binary orbits from photoelectric radial velocities. Paper 99: Phi Piscium**, The Observatory, 111, 155-162 [pdf]

Herbig, G.H. and Leka, K.D. 1991, **The diffuse interstellar bands. VIII - New features between 6000 and 8650 A**, Astrophys. J., 382, 193-203 [pdf]

Herbig, G.H. 1992, **The Canis Majoris OB1 Association**, in *Low Mass Star Formation in Southern Molecular Clouds*, Ed. Bo Reipurth, ESO Scientific Report No. 11, 59-67 [pdf]

Herbig, G.H. and Smak, J.I. 1992, **Expanding envelope of DQ Herculis**, Acta Astronomica, 42, 17-28 [pdf]

Petrov, P.P. and Herbig, G.H. 1992, **On the interpretation of the spectrum of FU Orionis**, Astrophys. J., 392, 209-217 [pdf]

Herbig, G.H., Suntzeff, N., and Blanco, B. 1992, **The Photometric Range of EX Lupi**, Information Bulletin on Variable Stars, #3755 [pdf]

Herbig, G.H., Gilmore, A.C., and Suntzeff, N. 1992, **The Photometric Range of EX Lupi: a Correction to IBVS 3755**, Information Bulletin on Variable Stars, #3808 [pdf]

Herbig, G.H. 1992, **A high-latitude Be star**, Rev. Mex. Astron. Astrof., 24, 187-191 [pdf]

Herbig, G.H. 1993, **The diffuse interstellar bands. IX - Constraints on the identification**, Astrophys. J., 407, 142-156 [pdf]

Herbig, G.H. 1994, **The Contributions of the Böhms to Stellar and Circumstellar Astrophysics**, in *Stellar and Circumstellar Astrophysics, a 70th birthday celebration for K. H. Böhm and E. Böhm-Vitense*, 57, 3-11 [pdf]

Herbig, G.H. 1994, **The Ae/Be Stars**, in *The Nature and Evolutionary Status of Herbig Ae/Be Stars*, eds. P.-S. Thé, M.R. Pérez, E.P.J van den Heuvel, Astron. Soc. Pacific Conf. Ser. 62, 3-11 [pdf]

Hibbins, R.E., Miles, J.R., Sarre, P.J., and Herbig, G.H. 1994, **Diffuse interstellar bands between 3900 A and 4200 A**, *The Diffuse Interstellar Bands*, Ed. A.G.G.M Tielens, NASA Conf. Pub. 10144, 31 [pdf]

Herbig, G.H. 1994, **Star formation: some issues that need attention**, Rev. Mex. Astron. Astrof., 29, 17-22 [pdf]

Herbig, G.H. 1994, **Highlights and Closing Remarks**, Rev. Mex. Astron. Astrof., 29, 207-208 [pdf]

Herbig, G.H. 1995, **The Diffuse Interstellar Bands**, Ann. Rev. Astron. Astrophys., 33, 19-74 [pdf]

Herbig, G.H. 1995, **IC349 - Barnard's Merope Nebula**, J. Roy. Astron. Soc. Canada, 89, 133-134 [pdf]

Preibisch, T., Zinnecker, H., and Herbig, G.H. 1996, **ROSAT X-ray observations of the young cluster IC 348**, in *Cool Stars, Stellar Systems, and the Sun, IX*, ASP Conf. Ser. vol. 109, 377-378 [pdf]

Herbig, G.H. 1996, **IC 349: Barnard's Merope Nebula**, Astron. J., 111, 1241-1251 [pdf]

Preibisch, T., Zinnecker, H., and Herbig, G.H. 1996, **ROSAT X-ray observations of the young cluster IC 348**, Astron. Astrophys., 310, 456-473 [pdf]

Trimble, V.L. and Herbig, G.H. 1997, **Parallaxes and Proper Motions of Prototypes of Astrophysically Interesting Classes of Stars**, Bulletin of the American Astronomical Society, 29, 811 [pdf]

Trimble, V., Herbig, G.H., and Kundu, A. 1998, **Parallaxes and Proper Motions of Prototypes of Astrophysically Interesting Classes of Stars**, Highlights of Astronomy, vol. 11A, 559 [pdf]

Herbig, G.H. 1998, **The Young Cluster IC 348**, Astrophys. J., 497, 736-758 [pdf]

Herbig, G.H. and McNally, D. 1999, **A search for the presence of diffuse interstellar bands in the coma of Comet Hale-Bopp**, Mon. Not. Roy. Astron. Soc., 304, 951-956 [pdf]

Herbig, G.H. 1999, **Examination of the Interstellar Spectrum of AE Aur for Long-Term Changes**, Publ. Astron. Soc. Pacific, 111, 809-811 [pdf]

Herbig, G.H. 1999, **The Optical Spectrum of the O-Type Subdwarf BD +28°4211**, Publ. Astron. Soc. Pacific, 111, 1144-1148 [pdf]

Herbig, G.H. 2000, **The Search for Interstellar C_{60}**, Astrophys. J., 542, 334-343 [pdf]

Herbig, G.H. and Dahm, S.E. 2001, **On the Be and Ae Stars in NGC 6611**, Publ. Astron. Soc. Pacific, 113, 195-196 [pdf]

Herbig, G.H. and Simon, T. 2001, **Barnard's Merope Nebula Revisited: New Observational Results**, Astron. J., 121, 3138-3148 [pdf]

Urban, A., Meyer, M.R., Herbig, G.H., and Dahm, S. 2001, **The Stellar Population Associated with NGC7023**, Bulletin of the American Astronomical Society, 33, 1449 [pdf]

Herbig, G.H., Aspin, C., Gilmore, A.C., Imhoff, C.L., and Jones, A.F. 2001, **The 1993-1994 Activity of EX Lupi**, Publ. Astron. Soc. Pacific, 113, 1547-1553 [pdf]

Herbig, G. 2002, **Historical introduction. Star formation: the early history**, in *Physics of Star Formation in Galaxies*, Saas-Fee Advanced Course 29. Eds. A. Maeder & G. Meynet, p. 1-8 [pdf]

Herbig, G.H. and Dahm, S.E. 2002, **The Young Cluster IC 5146**, Astron. J., 123, 304-327 [pdf]

Herbig, G.H., Petrov, P.P., and Duemmler, R. 2003, **High-Resolution Spectroscopy of FU Orionis Stars**, Astrophys. J., 595, 384-411 [pdf]

Ruch, G., Humphreys, R.M., and Herbig, G.H. 2003, **The Velocity Structure of the Circumstellar Nebula of the Extreme Red Supergiant VY CMa**, Bulletin of the American Astronomical Society, 35, 1359 [pdf]

Herbig, G.H., Andrews, S.M., and Dahm, S.E. 2004, **LkHα 101 and the Young Cluster in NGC 1579**, Astron. J., 128, 1233-1253 [pdf]

Herbig, G.H. 2005, **IX Ophiuchi: A High-Velocity Star Near a Molecular Cloud**, Astron. J., 130, 815-824 [pdf]

Herbig, G.H. and Dahm, S.E. 2006, **The Pre-Main-Sequence Population of L988**, Astron. J., 131, 1530-1543 [pdf]

Herbig, G.H. and Griffin, R.F. 2006, θ^1**Orionis E as a Spectroscopic Binary**, Astron. J., 132, 1763-1767 [pdf]

Jones, T.J., Humphreys, R.M., Helton, A., Wallerstein, G., and Herbig, G. 2006, **The 3D Morphology of VY CMa**, Bulletin of the American Astronomical Society, 38, #101.08 [pdf]

Reipurth, B., Aspin, C., Beck, T., Brogan, C., Connelley, M.S., and Herbig, G.H. 2007, **V733 Cep (Persson's Star): A New FU Orionis Object in Cepheus**, Astron. J., 133, 1000-1011 [pdf]

Herbig, G.H. 2007, **EX Lupi: History and Spectroscopy**, Astron. J., 133, 2679-2683 [pdf]

Herbig, G.H. 2008, **History and Spectroscopy of EXor Candidates**, Astron. J., 135, 637-648 [pdf]

Petrov, P.P. and Herbig, G.H. 2008, **Line Structure in the Spectrum of FU Orionis**, Astron. J., 136, 676-683 [pdf]

Herbig, G.H. and Vacca, W.D. 2008, **The Unusual Object IC 2144/MWC 778**, Astron. J., 136, 1995-2010 [pdf]

Herbig, G.H. and Reipurth, B. 2008, **Young Stars and Molecular Clouds in the IC 5146 Region**, in *Handbook of Star Forming Regions, Volume I*, ed. Bo Reipurth, Astron. Soc. Pacific Monographs, 108-123 [pdf]

Vacca, W.D., Herbig, G.H., Perrin, M.D., and Graham, J.R. 2009, **A Multiwavelength Study of the Young Stellar Object MWC 778**, Bulletin of the American Astronomical Society, 41, #414.02 [pdf]

Herbig, G.H. 2009, **The Outflowing Wind Of V1057 Cygni**, Astron. J., 138, 448-451 [pdf]

Herbig, G.H. 2009, **The Carbon Mira UV Aurigae and its Companion**, Astron. J., 138, 1502-1507 [pdf]

Dahm, S.E., Bowler, B., and Herbig, G.H. 2010, **Star Formation in IC 1274 and the L227 Molecular Cloud**, Bulletin of the American Astronomical Society, 36, #606.38 [pdf]

Reipurth, B., Herbig, G., and Aspin, C. 2010, **The Multiple Pre-main-sequence System HBC 515 in L1622**, Astron. J., 139, 1668-1680 [pdf]

Thommes, J., Reipurth, B., Aspin, C., and Herbig, G.H. 2011, **V900 Monocerotis**, Central Bureau Electronic Telegrams, #2795 [pdf]

Dahm, S.E., Herbig, G.H., and Bowler, B.P. 2012, **The Young Cluster in IC 1274**, Astron. J., 143, A3 [pdf]

Reipurth, B., Aspin, C., and Herbig, G.H. 2012, **V900 Mon and Thommes' Nebula: A New FUor in Monoceros**, Astrophys. J., 748, L5 [pdf]

15 NOTES

1: Quoted from Herbig's autobiographical notes written in 1993.

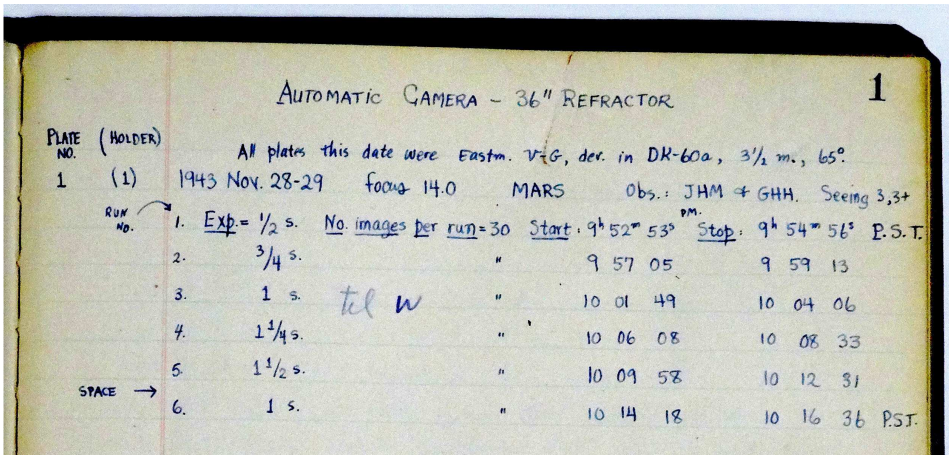
2: In a letter dated Sept 3, 1938, Jack Preston tells his father that he is sending the young George Herbig up to Lake Elsinore to get back on his feet and enjoy the good observing conditions, but warned that "George is worse than you when it comes to 'looking' – don't let him stay up all night all the time – he needs some sunshine as well as lots of food and rest".

3: In a letter dated August 23, 1999, Herbig wrote - in response to an inquiry from Roy S. Clarke of the Smithsonian - as follows about Frederick Leonard (1896-1960): *"The 'Department' then consisted of Leonard (the chairman), the very junior Samuel Herrick (orbit theory, celestial navigation), and fractionally, Joseph Kaplan from the Physics Department (who conducted molecular spectroscopy in a tiny laboratory off the departmental suite). Leonard was short, rather rotund, sported a VanDyke, was fastidious in dress and manner, utterly self-assured. [...] For a year or more I was employed as an assistant in the Department, and among my duties was to assist Leonard in proofreading the Contributions of the Society for Research on Meteorites, edited by him, which appeared regularly in 'Popular Astronomy', a journal that no longer exists. [...] Personally, I found Leonard to be a most kind and generous person, who helped and encouraged this struggling and impoverished student more than once during my undergraduate years. I have always been grateful for his thoughtfulness and support at crucial times in my early career."* Leonard's research focused on meteorites, and the Meteoritical Society's most prestigious award is named the Leonard Medal.

4: In a letter dated February 4, 1944, Lick Director J.H. Moore includes the following statement: "Recently on Dr. Leonard's recommendation we appointed to an Assistantship in the Lick Observatory Mr. George Herbig, an astronomy major at U.C.L.A., who graduated last October. In the short time he has been with us he has proved himself to be one of the most capable assistants we have had in this Observatory, and I predict that he will go far in astronomy."

5: Herbig's first wife, Delia, was a mathematician, and they wrote one paper together, an orbital analysis of the relation between comet Oterma and the Hilda group of asteroids (Herbig & McMullin 1943). They were divorced in 1968.

6: Herbig's first night of observations at Lick Observatory was the night of November 28-29, 1943, when Moore introduced the young Herbig to direct photography at the 36-inch refractor. The target was Mars as part of a program to monitor the planets. Figure 116 shows the entrance in Herbig's observing log book, the first one of innumerable such logs during his 44 years of observations at Lick telescopes.



AUTOMATIC CAMERA – 36" REFRACTOR 1

PLATE NO. (HOLDER) All plates this date were Eastm. V-G, dev. in DK-60a, 3½ m., 65°.

1 (1) 1943 Nov. 28-29 focus 14.0 MARS Obs.: JHM + GHH. Seeing 3,3+

RUN NO.	Exp.	No. images per run	Start	Stop
1.	½ s.	30	9h 52m 53s P.M.	9h 54m 56s P.S.T.
2.	¾ s.	"	9 57 05	9 59 13
3.	1 s. tel W	"	10 01 49	10 04 06
4.	1¼ s.	"	10 06 08	10 08 33
5.	1½ s.	"	10 09 58	10 12 31
SPACE → 6.	1 s.	"	10 14 18	10 16 36 P.S.T.

Figure 116: *The first observation Herbig did at Lick was a direct plate of Mars obtained at the 36-inch refractor on November 28-29, 1943.*

7: In a memorandum, Director C.D. Shane summarized a conversation he had on August 16, 1946 with Herbig: "I told Herbig that we are holding the position of Junior Astronomer for him at the time he receives his degree subject to the continuance of performance on his part approximately equal to what it is at the present time. I asked him if his inclinations were such as to lead us to think he would accept an appointment and he replied that they were. It was agreed that in view of our holding the position for him that he would keep us informed if he has any changes of intentions in this regard. – He expressed himself as being unwilling to take any position in the East. I told him that I was quite sure Struve was interested in him, and I thought we could make a sale to Mt. Wilson, but I was not going to advertize him to them unless they should approach me directly concerning him in which case I would tell them frankly the opinion we held concerning him."

8: The world's largest operating telescope in 1948/49 was still the Mt. Wilson 100-inch, although around 1951 it would be eclipsed when the Palomar 200-inch telescope went into regular operation.

9: Now known as the Henyey method, or the relaxation method (see, e.g., Clayton 1983, p. 451).

10: Further technical information was given in Herbig (1952b): *"The combination of a red filter and the Eastman 103a-E emulsion isolates a short spectral region between $\lambda 6300$ and $\lambda 6700$ for the observation of the $H\alpha$ line at $\lambda 6562$. The grating concentrates a large fraction of the incident energy in the direction of the first-order red on one side; the dispersion in that order is about 450 Å per mm. The field of the spectrograph is 43 by 53 minutes of arc; the images are good and their quality is adequately uniform over this region. The faintest stars in which $H\alpha$ has been detected, on a 60-minute exposure, are near photographic magnitude 18.5."*

11: From Herbig (1962a).

12: The review article was published in an annual book series called 'Advances in Astronomy and Astrophysics', which had started at about the same time that the Annual Reviews series appeared. Eventually the market was too small for two such series and Annual Reviews prevailed and became the dominant institution it is today. Herbig originally wrote the review as a chapter for the then famous book series Stars and Stellar Systems, which was published by the University of Chicago Press in the early 1960s and was meant to provide authoritative review articles on all aspects of astronomy and astrophysics. Harold Weaver from Berkeley (who earlier was head of Herbig's dissertation committee) was to compile and edit a volume on 'Clusters and Associations', but never managed to get the volume finished. Hence Herbig's review ended up in the today little-known 'Advances in Astronomy and Astrophysics' series.

13: Herbig maintained a life-long interest in RW Aur, and he took spectra of it on several occasions with the 120-inch, material that he handed over for detailed analysis to a young visiting student from Sweden, Gösta Gahm, who recalls: "After having completed my licentiate thesis in Stockholm in 1969 I got the opportunity to stay for 1 1/2 years at Lick to work with George Herbig, a stay that turned out to be crucial for my future activities in astronomy. Herbig introduced me to observations at the coudé spectrograph at the 120-inch telescope, and my first task was to analyze the complex emission line spectrum of RW Aur A (Gahm 1970). Herbig was a wonderful mentor and I always left his office with some new idea in my head. He inspired me to later investigate spectral regions of T Tauri stars that had not been explored before (radio, UV, X-rays)."

14: The concept of flash variables was short-lived, and today it is recognized that young stars have flares for the same reason that old UV Ceti-type stars have flares, namely from the interaction of convection, rotation, and magnetic fields.

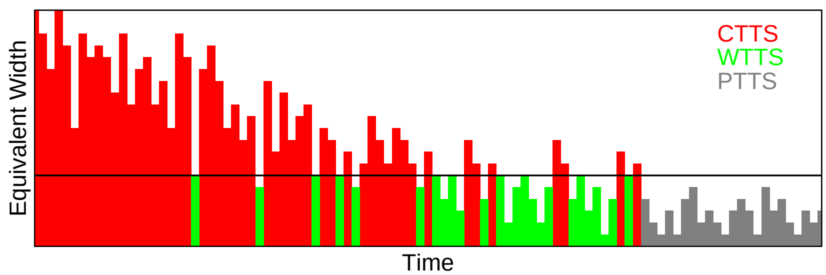


Figure 117: *A schematic presentation illustrating the long-term, erratic evolution of a CTTS to a WTTS and eventually to a PTTS. The horizontal line indicates the 10 Å border that defines and separates the CTTS and the WTTS.*

15: To illustrate the erratic transformation of a star from CTTS to WTTS to PTTS, Figure 117 shows a schematic representation of the evolution of variable Hα emission over time. At early ages when accretion is strong, Hα emission is generally intense, albeit highly variable, but eventually the mean Hα equivalent width declines, and more and more often the Hα emission falls below the 10 Å lower limit of the CTTS and thus the star is more and more frequently in the WTTS stage. Eventually, Hα emission never rises above 10 Å, and hence the star then enters the PTTS stage. Evidently, there is no precise moment of transition from one stage to the other, and the concepts of CTTS, WTTS, and PTTS are merely helpful as shorthand to describe how a given star is interpreted at the moment.

16: The minutes of the First Workshop on Extrasolar Planetary Detection, held March 23-24 1976 at Lick Observatory, can be downloaded from http://ifa.hawaii.edu/SP1/exoplanetworkshop.pdf

17: Steve Strom has provided these recollections: "I need to confess that the Rydgren, Strom and Strom (1976) paper might have been a true landmark had I not insisted on too early publication. Rick Rydgren was aware of the Lynden-Bell and Pringle paper and suggested that we try to understand the ultraviolet veiling phenomenon in terms of a disk accretion model. Instead I continued to think in terms of 'shells' and urged Rick to publish the work in its current form. George was not at all pleased with the paper, despite its assembly of a good deal of new, quantitative data regarding TTS. I had sent him a pre-publication copy, set up a breakfast meeting at an AAS meeting, and was devastated to hear his comments. They basically indicated that he thought the paper went *"well beyond what the data says"* - a comment typical of George, but difficult for me to accept given the respect I had for him."

18: The Stellar Populations conference held at the Vatican in 1957 was attended by many of the leading astronomers at the time, including Baade, Blaauw, Fowler, Herbig, Hoyle, Lindblad, Morgan, O'Connell, Oort, Salpeter, Schwarzschild, Spitzer, Strömgren, and Thackeray.

19: Ambartsumian first mentions in his 1954 paper this new type of objects: "Interestingly, Herbig found and studied near NGC 1999 three nebulous objects on one line, which were subsequently studied by Haro." In Ambartsumian's subsequent papers on young stars he refers to Herbig-Haro objects as a new type of young stellar objects (at that time it was still supposed that HH objects contained stars in the process of formation).

20: Kyle Cudworth, priv. comm.

21: Burton Jones, priv. comm.

22: This is now known as the Orion A or L1641 giant molecular cloud.

23: http://www.eso.org/sci/meetings/2014/haebe2014.html

24: Today most people are familiar with FUors, but Herbig's Russell lecture was then met with astonishment and great enthusiasm. As an example, the esteemed spectroscopist W.W. Morgan from Yerkes wrote to Herbig when he received the preprint: "This paper is the finest of the many fine things you have done, and will be just as vitally important in the year two thousand as it is today. It seems certain to me to become the classical work for a certain stage in the evolutionary process for young stars." Indeed, this prediction has come true, and the highly cited 1977 paper is in fact one of the very few papers which has seen its citations go *up* with time rather than down.

25: From interview in Star Formation Newsletter No. 260, 2014.

26: From interview in Star Formation Newsletter No. 267, 2015.

27: This is the Jain version of the parable as provided on Wikipedia.

28: Listed as 'anon' in Herbig (1950b).

29: Here Herbig uses the term near-infrared in its old meaning of deep red 'near' the infrared region.

30: Herbig lamented that when the proofs of that paper came back from the editor of the Ann. N.Y. Acad. Sci., he found that all the wavelengths had been changed from Angstroms to nanometers. In the resulting confusion, some of the exponents in the fluxes in the main table were printed incorrectly.

31: Herbig noted that in the overlap region between his image and the smaller HST field of O'Dell & Wen (1994) four of his objects were identified as proplyds: object 5 = 159-418, object 6 = 185-519, object 7 = 182-413, object 10 = 177-341.

32: Alexander Tielens, priv. comm.

33: http://www.iau.org/science/meetings/past/symposia/1062/

34: The discussions about the possible move of the Lick astronomers became complex and heated, to the point that Director Whitford feared for losing his staff. In a note dated June 8, 1965, the chancellor of University of California Santa Cruz wrote to Sidney S. Hoos, University Dean of Academic Personnel for all campuses of the University of California, stating that "Director Whitford is much concerned lest Caltech takes from Lick Professor George Herbig. If President Dubridge [of Caltech] does notify President Kerr [of University of California] of intention to negotiate with Herbig, Director Whitford and I would like to know immediately". In the end, the storm passed and no special efforts were required to retain Herbig.

35: A detailed account of the history of Lick Observatory, including the move to Santa Cruz, is given in the book by Donald Osterbrock et al. 'Eye on the Sky', University of California Press 1988.

36: Beverly Lynds, priv. comm.

37: From Herbig's unpublished notes on the history of Lick Observatory.

38: Preston later were to return to Carnegie Observatories, where he was Director from 1980 to 1986.

39: George Preston, priv. comm.

40: Leonard Kuhi, priv. comm.

41: Hans Boesgaard was an engineer at the Lick 120-inch telescope and later married Ann Merchant.

42: Ann Merchant Boesgaard, priv. comm.

43: Robert Zappala, priv. comm.

44: William Alschuler, priv. comm.

45: N. Kameswara Rao, priv. comm.

46: David Soderblom, priv. comm.

47: Douglas Duncan, priv. comm. Duncan has added: "Possibly my favorite Herbig story, though uncharacteristic, took place in the Lick dining hall. We were having dinner before observing, and the server brought out a plate including meat and vegetables. George ate the meat but not the veggies. She said to George, 'Why George, you didn't eat your vegetables'. George paused and suddenly said, 'At home my wife tells me to eat my vegetables, but damn it, no one on Mt. Hamilton is going to tell me that!!' 'Yes George' was the reply. That subject never came up again."

48: Geoff Marcy, priv. comm.

49: Scott Dahm, priv. comm.

50: Interview by David Block Oct 26, 2001.

51: Students who were trained in observing techniques have reported how shocked they were to hear the usually softspoken Herbig unleashing floods of esoteric curses and colorful invective when one of his long-exposure plates snapped.

52: As mild-mannered as Herbig generally appeared, he had no patience for longwinded pathos and could produce very acerbic comments, here is an example about a paper which did not meet with his approval:

"I think people are awed by its length, the complexity of the discussion, and all the esoteric considerations dragged in from all directions, and because of its impenetrability, assume that it must be a work of erudition and sound scholarship."

53: Tenn (2012) noted that among the longest-publishing astronomers, Herbig shared an 8th-place together with Ambartsumian and Whipple. The record-holder is Hans Bethe who published for 80 years.

16 ACKNOWLEDGEMENTS

Numerous people have helped me in various ways while I was preparing this book, and I am thankful to *W.R. Alschuler* for recollections of his student years, *Katherine Robbins Bell* for recollections about the Herbig-Bell catalog, *Claude Bertout* for discussions about weak-line TTS, *Ann Merchant Boesgaard* for recollections and photos, *Lewis Chilton* for information about Herbig's time at the Los Angeles Astronomical Society, *Kyle Cudworth* for recollections about HH proper motions, *Scott Dahm* for recollections of his student years and CCD images of LkHα 324, *Douglas K. Duncan* for recollections of his student years, *Gösta Gahm* for recollections and information on flare stars, *Maria Eugenia Gómez* for library help, *Louise Good* for latex help with the bibliography, *Roger F. Griffin* for information about 1976 exoplanet meeting, *Lee Hartmann* for comments on manuscript and recollections, *Guenther Hasinger* for permission to post the book at IfA, *Hannelore Herbig* for her unending support of this book project, *Burton Jones* for recollections about HH proper motions, *Len V. Kuhi* for recollections of his student years, *Beverly T. Lynds* for recollections of her student years, *Tigran Magakian* for information on Ambartsumian's papers, *Geoff Marcy* for recollections of his student years, *Derek McNally* for recollections about work with Herbig, *Tony Misch* for a guided tour of Lick Observatory and information on spectrographs, *Peter Petrov* for recollections on FUors, *George W. Preston* for recollections about Herbig, *Narayan Raja* for setting up the website hosting this book, *N. Kameswara Rao* for recollections about the Herbig-Rao catalog, *Kathleen Robertson* for library help, *Steve Rodney* for software to prepare an index, *Barbara Schaefer* for a photo of Herbig at Keck telescope, *Dave Soderblom* for recollections and discussions, *Remington Stone* for a guided tour of Lick Observatory and information about instruments, *Steve Strom* for recollections and comments on manuscript, *Alexander Tielens* for recollections and extensive comments on DIBs, and *Robert R. Zappala* for recollections of his student years.

I am grateful for the use of the following figures to the Los Angeles Astronomical Society (Figs. 3 and 4), to the Mary Lea Shane Archives of Lick Observatory at University of California at Santa Cruz (Figs. 8, 17, 82 and 109), to STScI (front-cover, Figs. 36, 55, 97 and 104), to McDonald Observatory (Fig. 12a), to Michael Marfell (Fig. 13), to Capella Observatory (Figs. 14 and 64), to Robert Gendler for preparing the color-composites in Figs. 44 and 49, to ESO (Figs. 48 and 83), to Carole Westphal/Adam Block/NOAO/AURA/NSF (Fig. 51), to Chart32/Johannes Schedler (Fig. 56), to Mercia Reipurth (Fig. 70), to Colin Aspin (Fig. 74), to Jean-Charles Cuillandre (Fig. 90), to NASA/JPL-Caltech/UCLA (Figs. 94 and 96), and to Hannelore Herbig (Fig. 115b). I furthermore acknowledge ApJ, AJ, A&A, MNRAS, PASP, and Chemical Reviews for use of figures published in papers in these journals. I also wish to acknowledge the NASA Astrophysics Data System, which I used extensively in the preparation of this book.

Finally, I want to thank my wife Mercia, who with grace and patience accepted the long hours I spent in front of a computer writing this book.

17 INDEX