The History of Infrared Astronomy: the Minnesota-UCSD-Wyoming Axis

By

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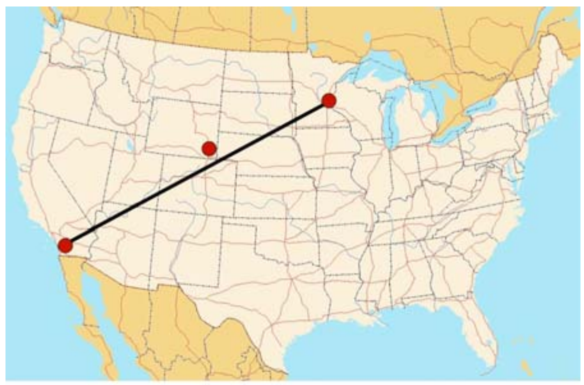

1. Ed Ney, Fred Gillett, Wayne Stein, and Nick Woolf

A complex set of circumstances converged to propel the University of Minnesota (UM), the University of California at San Diego (UCSD), and the University of Wyoming (UW) into a collaboration that played a leading role in the first four decades of infrared (IR) astronomy. The cornerstone was laid in 1962 when Neville J. "Nick" Woolf was a postdoctoral student at Lick Observatory. Martin Schwartzschild of Princeton University, then the boss of Project Stratoscope II (SS2), attended a conference at Lick and met Nick. Their mutual interest in problems in stellar evolution led Schwarzschild to offer Nick a position at Princeton working on SS2. Carl Sagan had suggested to Schwartzschild that a major objective of the project should be to search for water on Mars. Nick realized that the detection of water emission bands in the infrared could be a key to this search. Bob Danielson, an SS2 collaborator and former student of Ed Ney's at UM, had recently read Frank J. Low's paper on the development of the GaGe bolometer (Low 1961) and decided it was the detector of choice. Bob piqued Nick's interest in this prospect, and Nick became the SS2 IR detector guru. Nick visited Frank Low at Texas Instruments, Inc. to learn about his detector and its operation and brought a technology collaboration back to Princeton for SS2.

Ed Ney at UM had a strong belief that being at the scientific forefront meant doing new and difficult things that few others were doing and doing them better. Trained in the style of the "old school", he also believed that to be the best at what you do and the master of your future, you had to be able to learn how to create and advance all of the technology in your own house rather than collaborating too closely with outsiders. As Ed used to say, "If it were easy, everyone would be doing it!" Ed's eclectic interests led him in a natural progression from the nuclear physics of separating Uranium 235 on the Manhattan Project, to measurements of cosmic rays with balloon-borne detectors, to studies of the physics of balloon flight for the US Navy, to studies of atmospheric and solar physics from balloons, to studies of the solar corona from the ground and balloons, to studies of the Zodiacal Light from the ground, balloons and space, and finally into the world of astronomy (see Gehrz, McDonald, and Naugle 1999). Ed's research group was at the very top of the game in the art of flying high altitude balloons. Therefore, Martin Schwartzschild, and Bob Danielson asked Ed to send a couple of graduate students to Palestine, TX to help with the logistics of the SSII launches. These turned out to be Wayne Stein and Fred Gillett, who were in the process of finishing theses based on balloon-born and ground-based observations of the solar corona and the Zodiacal Light (Stein 1964, Gillett 1966). On these expeditions, they met Nick. Even before this, Wayne and Fred had realized that little astronomy was being done in the vast frequency realm of the infrared. Excited about the prospect of pursuing this new field, they soon interested Ed, who had been thinking it was about time for him to switch fields anyway. By 1964, Ed was already first author on an infrared astronomy paper (Ney and Gould 1964) in which he and Bob Gould of UCSD speculated that [Ne II] 12.8μm emission might explain the excess infrared radiation reported to be emitted by several early type stars by Wildey and Murray (1964)[1]. After his PhD graduation in 1964, Wayne went to Princeton to work on SSII as a postdoc. There, he was given half time to pursue his own research interests. As a result of this opportunity, Wayne wrote four seminal theoretical papers predicting the infrared flux expected from various astrophysical objects (Solomon and Stein 1966; Stein 1966a and b, 1968). At that time, postdocs at Princeton were required to have their publications reviewed by senior faculty before submission, and the Director, Lyman Spitzer Jr., became so enthused by Wayne's papers that he submitted a proposal to NASA for funds to do an IR balloon survey for IR emission. He called Wayne into his office, informed him of the proposal submission, and told Wayne he hoped Wayne would not be offended not to have been included as a co-investigator on the proposal motivated by his papers because he was a junior person! How times have changed!

Larry Peterson, who had done a PhD Thesis observing solar X-rays using balloons at the University of Minnesota under Jack Winckler, was now at UCSD doing X-Ray astronomy from balloons. By the time Fred Gillett finished his PhD in 1966, Larry had become interested in extending the balloon-born astronomy program at UCSD into the infrared because of several exciting papers written by his colleague Bob Gould predicting

[1] The Wildey and Murray (1964) result was later discovered to have resulted from a false signal due to a variable telescope infrared background radiation created by the observing technique being used at the bent Cassegraine focus of the Palomar Mountain 200-inch telescope where the measurement was conducted.

that infrared line emission would be ubiquitous in the universe (e.g. Gould 1963, 1964; Ney and Gould 1964). He convinced Fred, who was already regarded as a top notch experimental physicist, to join the staff there to develop an IR capability. At the same time, the SS2 Project sent Wayne Stein to UCSD to consult with Peterson about how to deal with large noise spikes that cosmic rays were causing in the SS2 photomultiplier tubes. The visit reunited Fred and Wayne, who had grown up together in Minneapolis, MN from boyhood as neighbors and classmates all the way through graduate school. They decided that there was a great opportunity for them to work together to develop the IR program at UCSD and convinced Larry to hire Wayne as well. Shortly thereafter, they entered into a collaboration with Frank Low, by then at the University of Arizona in Tucson, to collaborate on the construction of infrared astronomy's first 2.8-14 μm circular variable filter wheel (CVFW) spectrometer. The collaboration resulted in several seminal publications reporting the mid-infrared spectral energy distributions (SEDs) of stars and planets (Gillett, Low, and Stein 1967, 1968) before the spectrometer was destroyed in a freak accident. Fred, who had been observing at Mount Bigelow, put the spectrometer on a table in the house-trailer that served as the observer's quarters when he left for Tucson to avoid an impending blizzard. When the weather cleared and Fred returned, the trailer was nowhere to be found. The weight of the show had flexed the trailer roof enough to break the heater gas line, and the resulting fire had reduced the trailer and spectrometer to ashes! Despite the loss, Fred and Wayne knew that the future of infrared astronomy was bright. But they also knew that if they were to compete, UCSD would have to have regular access to a high altitude infrared observatory of its own.

Meanwhile, Ed Ney took two sabbatical leaves that shaped the foundations of the IR program at Minnesota. In 1963 he went to Narrabri, Australia to learn astronomy by working with Hanbury Brown and Richard Twiss on their intensity interferometer. While there, he met and formed a strong bond with Sir Fred Hoyle, a friendship that would figure prominently in the UM/UCSD infrared astronomy collaboration a few years later. He also came to an understanding that measurements of the angular diameters of stars, as determined by the intensity interferometer, could be tested by blackbody angular diameters calculated from infrared SEDs. This intensified Ed's interest in pursuing infrared astronomy. At the time Ed became convinced that IR Astronomy was the next frontier, he had been measuring the surface brightness of the Zodiacal Light at visible wavelengths using cameras flown on balloons and hand-held by NASA's Mercury and Gemini astronauts. Extending these measurements into the near and thermal infrared seemed to Ed to be a natural extension of this work. Upon his return from Australia, Ed and his master technicians Ray Maas and Jim Stoddart took a sabbatical to Tucson to learn the techniques of infrared astronomy from the master, Frank Low, upon whom Ed promptly bestowed the moniker "Pope of Infrared Astronomy". During this visit, Ed and his group learned how to build dewars, operate detectors at liquid helium temperatures, and the technique of spatial chopping with synchronous detection to remove background. But more importantly, after learning from Arnold Davidson that a sapphire "jewel" was involved in the mounting, Jim Stoddart was able to figure out how to construct low noise GaGe bolometers. When Ed returned to Minnesota, he had all of the knowledge to do infrared astronomy, but knew that he needed to have access to a telescope where he could pursue this passion full time. He also had an obsession with bettering the Pope at all aspects of the game.

Upon his return to Minnesota, Ed made serious plans to form an infrared astronomy group. The white dwarf star hunter, Wilhem Luyten, retired in the Spring of 1967, and the UM Department of Physics and Astronomy had been searching for a suitable replacement for more than a year. Nick Woolf, who had by then become an Associate Professor of Astronomy at the University of Texas, agreed to come to Minnesota to replace Luyten; the foundation of the UM/UCSD axis in infrared astronomy was thus cemented by the spring of 1968 - Ney and Woolf at UM, Stein and Gillett at UCSD, with both groups collaborating closely together.

2. The O'Brien Observatory (OBO)

Ed Ney realized that UM could actually compete with Frank Low and Gerry Neugebauer in infrared astronomy because of a freak of nature. Infrared radiation is absorbed, primarily, by water vapor in the atmosphere. The competition had big telescopes on high mountains above the atmposheric water. How could Minnesota play in this game? During the Minnesota winter, when the dew point could fall tens of degrees below zero C or F), the air was as free of water as a 10,000 foot high mountain top! Thus, Ed reasoned, one could compete with the "Big Boys" by observing under the right conditions with superior detectors using a rather small (30-inch) telescope. In addition, a telescope in Minnesota would provide a base site close to home during the key experimental development period. His proposal to build an IR observatory in Minnesota was reviewed favorably at NASA, and Ed's Contract Officer, Nancy Boggess, gave him the funding and the go ahead to begin construction. Bids were opened in April of 1966 before a construction site had even been specified. Upon approval of the contract, Ed set about to find an observatory site with superior seeing and sky darkness qualities not too far from the UM campus. The high hills of the St. Croix River valley seemed an ideal place to search. With the aid of his Jaguar XKE and a home-made sky brightness meter that was derived from equipment he had developed for Zodiacal Light measurements, Ed soon located a high hill in Marine on the St. Croix, about an hour from his home. The site seemed ideal for his observatory. Learning that the land was owned by a local named Thomond "Thomy" O'Brien, a descendant of lumber baron William O'Brien whose daughter had donated the land for nearby O'Brien State Park in 1947, Ed soon had Thomy enthralled with the prospect of being involved in the project. Over Martini's on Thomy's front porch in July of 1966, the two cemented a deal whereby O'Brien Observatory (OBO) would be constructed on a parcel of land donated by Thomy to the University of Minnesota. The North-South line was laid on June 27, 1967. Construction was completed and first light achieved during the August of 1967.

3. The O'Brien Observatory (OBO): Early Scientific Contributions

Scientific observations at OBO began in the Spring of 1968 with the participation of the first two members of the second generation of UM infrared astronomers, Don Strecker and Bob Gehrz. Don had been a graduate student of Ney's since 1965, doing a Master's Degree on the analysis of Zodiacal Light images made by Gemini Astronauts using hand-held cameras. Ed assigned him the task of being chief student observer at O'Brien and suggested that he monitor the infrared light curves of Mira variable stars for his PhD thesis. Bob, who entered graduate school in Fall of 1967, became Nick's first graduate student in spring of 1968 and was assigned to learn the ropes of infrared astronomy as Don's assistant. Bob's first experience with observing at the telescope came in April, 1968 when Ed invited him to participate in an infrared measurement of the flux from Mercury. This session ended prematurely when the telescope failed to track properly - Ed said a bad word and threw the control paddle against the wall!

The telescope was soon working well, however, and Ed and his colleagues began turning out a host of new discoveries with OBO. The very first paper from OBO was published by Ney and Stein (1968), who used a 4 arcminute beam to measure the integrated synchrotron flux from the Crab Nebula at λ= 5800 Å 2.2 μm, and 3.5 μm. It was a continuation of their studies of low surface brightness sources like the Zodiacal Light, but marked a new extension of their interests to more traditional stellar astrophysical topics. Certainly, Nick's interests influenced them strongly in this direction. Nick's involvement led to the classic paper reporting the discovery of thermal infrared emission from circumstellar silicate grains in M stars and carbon grains in C stars (Woolf and Ney 1969). After learning that Wayne had detected 3.5 μm emission from the Orion nebula using a 4 arcminute beam, Ney and Allen (1969) discovered the optically thin Trapezium Nebula in Orion, and Wayne and Fred used a new UCSD CVFW on the KPNO 36-inch telescope to show that the Trapezium dust had the same 10 μm emission feature seen in the M-supergiant μ Cephei spectrometer (Gillett and Stein 1969). Shortly there after, Maas, Ney, and Woolf (1970) discovered that a similar 10 μm feature appeared in the spectrum of of Comet Bennett 1969i[2]. Thus, within two years of completing OBO, the UM/UCSD group had established that small carbon and silicate grains, the building blocks of the planets, were ubiquitous in circumstellar winds, regions of star formation, and the debris left over from planet building in the primitive Solar System. In the meantime, by spring of 1969, Bob Gehrz had made a 3σ detection at 10μm on the RV Tauri star AC Her, suggesting that it had the largest infrared excess with respect to the continuum yet detected in a star to that time. Bob and Nick followed up this tantalizing result using a UM bolometer on the 50-inch telescope at Kitt Peak National Observatory, and showed that RV Tauri stars, as a class, had very large excess infrared radiation due to circumstellar dust emission (Gehrz and Woolf 1970). This discovery provided a PhD thesis for Bob (Gehrz 1971). It is now known that the RV Tauri stars occupy an important spot in the HR Diagram and probably are objects in transition between the Post AGB Phase and planetary nebulae.

There were several other important novel results from the early days of O'Brien. David Allen's pioneering imaging studies of the lunar surface showed that there were thermal anomalies during eclipses and phasing that could be explained by the fact that large rocks connected deeply to the subsurface layers cooled more slowly than the loosely packed

[2] Sadly, Ray Maas died of a heart attack within 24 hours of helping to make the Comet Bennett observation.

overlying regolith (Allen 1971a and b). Murdock and Ney (1970), comparing Allen's lunar data with photometry of Mercury during its phase cycle, predicted that Mercury's surface would look like the moon's long before NASA sent back the first images of the Mercurian surface. Gehrz, Ney, and Strecker (1970) discovered that luminous red supergiants as a class (the IC Variable stars) had extensive circumstellar dust envelopes rich in silicates. Gehrz and Woolf (1971) subsequently used extensive OBO 4-color 3.6 - 11.4 μm infrared photometry on many classes of stars to show that it is plausible that mass loss winds can be driven by radiation pressure on circumstellar grains that carry away the gas as well by momentum coupling.

4. The Mount Lemmon Observing Facility (MLOF) and the British Connection

Despite the early success of OBO, the UM/UCSD group realized that they needed regular access to a larger aperture, infrared-optimized telescope that was located at a dry, high altitude site with clear sky . Wayne, Fred, Nick, and Ed proposed to construct a 60-inch infrared telescope, similar to one that the University of Arizona's Harold Johnson had designed for Mt. Lemmon. Two problems presented themselves: How to fund the project and where to locate the observatory.

The funding problem was solved by gaining support from four parties. The National Science Foundation (NSF) agree to put in $100,000 in return for $50,000 matches from UM and UCSD. Ed's connection with Fred Hoyle at Narrabri, Australia had cemented a bond with the British, who wished to develop an expertise in infrared astronomy. Hoyle offered to contribute an unrestricted $100,000 to the group through the National Research Council of Great Britain on the agreement that the training of aspiring British infrared astronomers be conducted at Minnesota. The three eventually trained under this agreement were David Allen, John Hackwell, and Martin Cohen.

The location problem was tackled by conducting an extensive survey of mountain sites in the southwestern United States and Hawaii, with data on weather, thermal infrared emission, water vapor content, and logistical support being collected primarily by Bob Gehrz with help from Don Strecker and other members of the UM/UCSD infrared group. The sites evaluated included Mauna Kea, HI, Mt. Laguna, CA, Palomar Mountain, CA, White Mountain, CA, Mt. Charleston, NV, Angel Peak, NV, the Snowy Range, WY, Hualapi Peak, AZ, Kitt Peak, AZ, Mt. Graham, AZ, Mt. Hopkins, AZ, and Mt. Lemmon, AZ. One memorable experience during this odyssey occurred during a June, 1969 expedition to Mauna Kea when all of Gehrz's equipment, packed in large military-style crates, was accidently sent to Saigon during the height of the Vietnam War. To while away the time in Honolulu while waiting for the equipment to be located and returned, he bought a surf board. Not having had previous experience with the tropical sun, he was soon burned to a terrible crisp that left him in misery throughout the subsequent experiments at the 13,800 ft. altitude of Mauna Kea

Two of the best sites meteorologically, Mauna Kea and the Snowy Range, were ruled out on logistical grounds given the realities of the project budget. Mt. Lemmon was chosen after much soul searching, primarily because it came with an existing dormitory/laboratory building and easy access to liquid helium at the nearby University of Arizona. The observatory, named the Mt. Lemmon Observing Facility (MLOF) was constructed during 1970 and first light was achieved in December, 1970. It has had a long and productive life. Major early science results associated with MLOF over the years included the first large-scale census of the infrared radiation from RV Tauri stars and other evolved Post Main Sequence (PMS) stars (Gehrz 1971, 1972), the first comprehensive survey of the SEDs of pre-Main Sequence stars (Cohen 1973 a, b, c, and d), the first attempts to obtain systematic 7-14 μm CVFW spectroscopy of stellar sequences (Merrill and Stein 1973a, b, and c), and the first attempt to detect the 10 μm radiation from globular cluster cores (Cohen and Fawley 1974) . Originally manually slewed and pointed because of the low construction budget, the MLOF telescope was modified by Gehrz and Terry J. Jones in 1989 to be completely automated under computer control with the capability of being remotely operated by observers anywhere in the world using a phone modem.

5. Early Thermal Infrared Observations in the Southern Hemisphere

Ed Ney's passion for mounting scientific expeditions dated back to the late 1950's and early 1960's when he had traveled as far away as the North African desert and Tahiti to observe the Solar corona and the Zodiacal Light during total Solar eclipses. He learned to operate highly sophisticated scientific equipment at remote locations with a minimum of interaction with the outside world. These skills were a prerequisite for doing infrared astronomy in Chile at the time. In those days, the southern celestial hemisphere was virgin territory for infrared astronomers. The nearest helium liquefier was in Los Angeles, and the technical support at CTIO was basically limited to people who understood film cameras and photomultipliers. Ed and Don Strecker mounted an expedition to CTIO during the Austral summer of 1971, and Ed and Bob Gehrz, who had gained a wealth of experience in mounting remote expeditions during a six year career as a wilderness canoe tripping guide, made a follow-up trip during the Austral summer of 1972. They spent their observing nights trying to find the most extreme examples of excess circumstellar radiation among the exotic stars of the as yet virtually unexplored southern sky. During the 1971 run, Roberta Humphreys, a guest observer doing optical observations of luminous G supergiants, provided Ed and Don with a list of her personal favorites. When HR 4337 and HR 5171A turned out to have two of the largest 10 μm infrared excess known at the time, Ed named them "Gee" and "Gee Whiz" respectively. The successes of this small survey (Humphreys, Strecker and Ney 1971) and another documenting IR excesses due to silicate emission in 30 M supergiants in Carinae (Humphreys, Strecker, and Ney 1972) impressed Ed, and he soon hired Roberta at Minnesota. The next year, Bob and Ed were able to establish that southern RV Tauri stars, like their northern counterparts, had enormous infrared excesses (Gehrz and Ney 1972). They used the small beams allowed by the excellent seeing at CTIO to establish that the strong silicate emission coming from the trapezium nebula was actually centered upon the brightest of the OB stars, θ1C (Ney, Strecker, and Gehrz 1973) and to make the first measurement of the angular diameter of the infrared dust shell ejected in the eruption of η Carinae (Gehrz et al. 1973). These infrared observations were the first of a long series of ever more detailed infrared imaging studies of η Car by the Minnesota IR group, the most recent being conducted within the last few years with the Magellan Telescope of the Carnagie Southern Observatory (see Gehrz 2004).

It was on these expeditions that Ed invented "Caltech Roulette", where he would scour the CIT catalog for the reddest sources and measure their 1-25 μm SEDs. This game led to the classification of the carbon-rich "NML Cygnids" and the oxygen-rich "NML Taurids" (Strecker, Ney, and Murdock 1973; Strecker and Ney 1974).

6. The Wyoming Infrared Observatory (WIRO)

Derek Prowse, Head of the Department of Physics and Astronomy at the University of Wyoming, was an empire builder. Jim Rosen a former student of Ed Ney's, had invited Bob Gehrz and Don Strecker to evaluate the mountain sites near Laramie, Wyoming durin the UM/UCSD MLOF site survey. When the data showed that the Snowy Range, WY was a first-class infrared site, Prowse determined that the his department could become a leader in the young field by building an infrared telescope near the campus to take advantage of the meteorological advantages of the local environment. Then disaster struck. Prowse, only 48 years old, died in January 1971 of a massive heart attack as he struggled to free his snowmobile from a drift during a winter trip in the Snowy Range. The new department head, Walter T. "Tom" Grandy, Jr., was determined to follow the path charted by his predecessor. In 1971, he hired John Hackwell who was just graduating with his PhD from the Minnesota group. He then set about to lure Fred Gillett from UCSD. Fred opted to turn down the Wyoming offer to take an appointment at KPNO, where he would be a major player in the IRTF, IRAS, and International Gemini Projects. Grandy then made an offer to Bob Gehrz who had received his PhD from Minnesota in December, 1971. When Gehrz joined the Wyoming faculty in June of 1972, he and Hackwell immediately began building a vigorous infrared astronomy program. Bob had learned to construct GaGe bolometers from Jim Stoddart at Minnesota[3], so he and John were able to produce state-of-the-art 1-25 μm multi-filter photometers and spectrometers on a shoe-string budget. As they pressed their new equipment into service at KPNO and MLOF, they developed a plan to construct a new computer-controlled 92-inch infrared telescope at Jelm Mountain, WY. This 9,656 site, discovered by Bob's student Terry Flower (now head of the Physics Department at St. Catherine's College in St. Paul, MN), proved to have exceptional seeing and infrared transmission compared to the Snowy Range sites. Geoff and Margaret Burbidge, Fred Gillett, Ed Ney, Wayne Stein, and Nick Woolf were particularly supportive of all aspects of the development of the Wyoming infrared program. Two months of lobbying by Bob and John at the 1975 Wyoming State Legislature precipitated a $1 Million dollar capitol appropriations bill which was then matched by a $625,000 award from the Division of Astronomical Sciences at NSF. In October of 1977, when the Wyoming Infrared

[3] In 1972, only three people in the world knew how to construct state-of-the art GaGe bolometers. They were Arnold Davidson at Arizona, Jim Stoddart at Minnesota, who learned the technique from Davidison, and Gehrz.

Telescope (Gehrz and Hackwell 1978) received first light, it was the largest operational infrared telescope in the world and produced visual image cores as small as those being achieved by the new CTIO 4-m. Within 2 years, it was exceeded in aperture by NASA's IRTF and UKIRT. An amusing incident occurred during the construction of the Wyoming Infrared Observatory (WIRO). NASA's IR Division Chief, Ishtiaque Rassool , alarmed at the $10 Million price tag of the 120-inch IRTF, convened a review committee to investigate the situation. Bob and John were summoned to explain how the Wyoming telescope, only slightly smaller than IRTF could possibly be expected to meet considerably more stringent operating specifications at a cost of only $1.6 million. The claims of the Wyoming contingent, which were met with considerable skepticism at the meeting, were completely validated by performance tests of the optics and mechanical systems during commissioning of the telescope. One key to keeping costs down was that Bob and John had actually served as the prime contractors, personally directing and coordinating the work of a dozen subcontractors. Two others were the use of an unprecedentedly thin, fast primary mirror and the use of computer modeling of flexures to achieve sub-arcsecond pointing with a lightweight telescope mount. An online movie of the history of the development and construction of the Wyoming Infrared Observatory may be viewed at:

http://webusers.astro.umn.edu/~gehrz/WIRO/Public_Slide_Show/WIRO_with_Music_and_RDG_9.0_08_19_08.wmv

WIRO has made made substantial contributions to several areas of study. The WIRO group, like the group at UM, specialized in building equipment that could record 1-25 μm SEDs in a single observation. They used this capability to good advantage. The first dust formation episode in a Wolf-Rayet star was recorded soon after first light (Hackwell, Gehrz, and Grasdalen 1979). Twenty years of observations of Classical Nova explosions with WIRO led to the discovery of ONeMg white dwarfs in "neon novae" (Gehrz, Grasdalen, and Hackwell 1985) and established the details of the dust formation process in CO novae. For a review of the results of the WIRO nova program, see Gehrz (1999, 2002). The powerful pointing capabilities of the Wyoming telescope were used to record the infrared temporal development of the SEDs of many comets (including P/Encke and P/Halley) at perihelion passage at elongation angles within a few degrees of the sun (Gehrz and Ney 1992). A hazard of this activity was the occasional scorching of paint on the front end ring of the telescope! A large number of SEDs of CIT and AFGL sources and variable stars were recorded at WIRO over the years (Jones et al. 1990). Finally, before the advent of large format infrared array detectors, the control computer at WIRO enabled this telescope to record the first sub-arc-second accuracy images of regions of star formation using single detector photometers and a "software" camera scanning program (Gehrz et al. 1982; Hackwell, Grasdalen, and Gehrz 1982).

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