History of Modern Infrared Astronomy—1960 to 1983

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Abstract: I came to the attention of astronomers through the invention of the low temperature bolometer at Texas Instruments. I was quickly drawn into pioneering infrared astronomy with Carl Sagan and Harold Johnson. Soon afterwards I transferred to NRAO and then to the University of Arizona to make infrared astronomy my focus. Parallel programs were getting under way at the California Institute of Technology, Cornell, the Universities of Minnesota and California at San Diego, and in a few other places on even smaller scales. Although our methods were crude, discoveries were easy and exciting. I was involved in many of them because I could supply good detectors and also invented a number of new techniques that proved quite powerful. Eventually, I supplied detector systems and instruments on a very wide basis through founding of a small company. By the early 1970's, systematic infrared astronomy was under way on many important problems that are still active research topics. The value of the field led to investments in large new telescopes and in the IRAS survey satellite and set the foundation for the major role of the infrared in astronomy today.

Key words: infrared: general; instrumentation: detectors; astronomy: history

1. Introductory Preface

Frank Low and Gerry Neugebauer were invited to describe their roles in early infrared astronomy. Although both accepted, Gerry eventually decided that he could only take a supporting part, not a leading one that he had rightfully earned. Thus, I decided to invite George Rieke and Robert Gehrz to help.

2. Introduction to Infrared Astronomy

Modern historians have reported that in the year 1800 Sir William Herschel discovered infrared light, and then Sir William presumably succeeded in measuring a spectral energy distribution by using a set of thermometers and a glass prism. Now, not surprisingly, we have lost our Knightly capabilities with sensitive thermometers. However, just 80 years later, S. P. Langley improved on them by inventing the bolometer, leaving us with a major advance in IR technology. Then, much later during World War II, the German war machine developed a potentially invaluable weapon that could actually "see in the dark"; it was the very first infrared detector made from lead sulfide, a crystalline material with semiconductive properties. Fortuitously, history intervened and the war came to its end. This key technical information fell happily into the friendly hands of the United Kingdom and their Allies. Then, for at least 20 years or more lead sulfide cells were studied and improved; people even experimented with cooling the detector with solid CO_2 to improve its performance.

Gerard Kuiper saw the potential of the new detectors and had a spectrometer constructed (Kuiper, Wilson, & Cashman 1947) that he used to obtain infrared spectra of the bright planets. He identified strong absorptions due to CO_2 for Venus and Mars and NH_3 and CH_4 for Jupiter (Kuiper 1947; 1949). Eventually, he established the infrared-friendly Lunar and Planetary Laboratory at the University of Arizona, where much of my story takes place. Still very few other astronomers were motivated to research the huge spectral gap that separated optical astronomy from radio astronomy.

In 1960, as very good luck would have it, as a young low-temperature physicist from the State of Texas with a brand new Ph.D. and in my first professional job at Texas Instruments Central Research Lab in Dallas I became interested in developing a modern version of a cryogenically cooled bolometer perfectly suited for exploring the spectral range from 1 μm to 1.2 mm. In early 1961 I published an article that described a novel way to measure infrared radiation by using basic bolometer principles. My paper explains in full detail how the new germanium device functions (Low 1961). When the article finally appeared in print I was greatly surprised by its positive reception among astronomers, and I was intrigued.

The published article was well accepted because theory and experiment were shown to be in agreement. When the article appeared several eager astronomers visited me in Dallas. Among the visitors was Carl Sagan. He was eager to have me build a bolometer system so NASA could fly an infrared spectrometer on a balloon to look for organic molecules in a search for life on Mars. The system needed both the detector and a liquid helium Dewar to hold it just a few degrees above absolute zero. When I graduated from Rice Institute (now Rice University) in 1959 the lab was still using glass liquid helium Dewars, made of Pyrex by skilled glass blowers. I soon changed all that by designing an all-metal Dewar from scratch. With approval from TI, the instrument was built; our flight actually worked very well, but no proof of life on Mars was found. Fortunately, this flight did show that my all-metal liquid helium Dewar was superior to traditional all-glass Dewars because glass breaks easily and their performance does not compete well with all-metal ones.

Sometime afterwards, I learned from a colleague in the Central Research Lab that a professor from the University of Texas had been talking about infrared detectors. Since I was close enough to Austin, I invited myself to visit Professor Harold L. Johnson in his office in mid-1961. Harold and I became immediate friends on that visit, and we arranged to pursue our common interests. I learned about his work with lead-sulfide detectors, and Harold expressed great interest in using my new bolometer to extend the spectral range of his planned IR observations.

2.1 From TI to NRAO

Another visitor to the Central Research Lab in 1962 was the well known Radio Astronomer Frank Drake. He was so enthusiastic about the possibilities for the bolometer that he persuaded me to move my family to the small hamlet of Arbovale, West Virginia, a "suburb" of Green Bank, location of the National Radio Astronomy Observatory. Our move to the isolated valley in eastern West Virginia provided ample opportunities to further develop mm-wave bolometers and to learn astronomy from my new radio colleagues. Clearly, the weather in Green Bank was never suitable for millimeter or sub-millimeter astronomy but the research facilities and the radio astronomers within proved themselves to be perfect for improving the new bolometers and designing a breakthrough 36-foot millimeter wavelength telescope that was later built in Arizona and initiated the field of millimeter wave spectroscopy of interstellar molecules.

Before I left TI, Harold Johnson had decided to extend the wavelength range of his well-established UBVRI stellar photometry with the lead sulfide detectors. By late '61 or early '62 he had built a near-infrared photometer and begun his infrared observations. Therefore, Harold became the first modern infrared astronomer—he had begun to produce the best and only verified infrared data on stars as early as 1962 (Johnson 1962). Lead sulphide detectors responded from 1 to 3.5 μm and Johnson introduced three new near-infrared bands, designated J (1.25 μm), K (2.2 μm) and L (3.2 μm). Eric Becklin, a student of Gerry Neugebauer from Caltech, wisely inserted the H (1.65 μm) wave band. Note that Harold and Eric defined each of these new spectral bands to match the transmission profiles of each terrestrial "window". Ultimately, InSb (indium antimonide), a newly developed binary crystal, was developed by the US Department of Defense to span all of the near-infrared windows from 1 μm to about 5.2 μm. These new and well-behaved InSb detectors soon made PbS detectors obsolete, and Harold replaced his old JKL technology with the more advanced detectors. He then added his new 5 μm M-band nomenclature, bringing the InSb photometer to its long wavelength limit (Johnson & Mitchell 1963).

One of our mutual goals was to conquer the "mountain", the enormous peak of blackbody radiation that dominates the mid-IR background. Harold had already faced the thermal background problem at 3.5 μm; he knew the minute signal relative to the natural background could best be detected by switching the beam from a small diameter source to a nearby reference field. The signal from the reference field was subtracted from that from the field that contained the source. When chopping the small pickoff mirror near the focal-plane the rate of motion was limited to 10 repeats per second. However, even the slightest deviation of the pickoff mirror caused a number of problems. Finally, after much trial and error we found a partial solution and we were then able to suppress much of the excess fluctuation and electronic noise. Note that our atmosphere generates the unwelcome 300 K background and all of the attendant problems; consequently platforms much higher than sea level are more than welcome.

Fortunately for me, Harold recognized my urgent need for hands-on experience with a large optical telescope. He solved that problem with the 82-inch McDonald telescope and a lot of luck. A car trip was arranged for me and my family to see the McDonald Observatory, especially the telescope itself and the facilities that were available. On a second trip, Harold and I both came to McDonald bringing a full set of instrumentation, including a supply of liquid helium. After much testing, the technical hurdles were finally overcome. Then, the old but worthy 82-inch telescope, which still sits on top of Mount Locke in the Davis Mountains in West Texas, was scheduled for two weeks of observing in mid-July, 1963. However, with my career hanging in the balance, I first traveled to Mt. Bigelow near Tucson Arizona in April for a dress rehearsal. Harold had just moved there to join Gerard Kuiper's new laboratory. With his encouragement I set up my instruments on a 21-inch telescope to confirm that all of my new equipment would function OK. I was barely able to detect Arcturus, a very bright star, but I felt confident I had succeeded.

In mid-July, the time of the long awaited 10 μm run at McDonald, we had already relocated to Arbovale. Arnold Davidson from NRAO, master bolometer maker and master telescope operator, was introduced to Harold Johnson. Fully prepared, the telescope and the liquid helium cooled instrument were checked out and ready. After a few days of cloudy weather and with preparations complete, Harold explained that he needed to go back to Tucson, his new home, while Arnold and I stayed and watched the clouds.

As I recall, the dome at McDonald Observatory could be reached only by foot on rather narrow and steep steps. One day, as Arnold and I were leaving the dome, we crossed paths with a distinguished looking optical astronomer who was surprised to find two young persons there. He wanted to know who we were and why we were there. We identified ourselves and told him we were working with Harold Johnson in the infrared. His response was that he could not understand why we were spending our time waiting for clear weather when we were not going to get any results in the infrared.

Mercifully, near the end of the run the clouds finally cleared, and that night was clear enough for alignment and focusing on stars, but the data were noisy and unstable as seen on the strip chart recorder. At sunset on the following night the sky cleared and the humidity dropped, providing the perfect opportunity to observe in the thermal infrared. The following morning the clouds returned.

This single almost perfect night at McDonald produced excellent 10 μm photometry of 24 stars as well as the planetary bodies Mars, Jupiter, Saturn and Titan. Arnold and I alternated in guiding and focusing the telescope and collecting the data. All of Harold's selected stars were easily measured along with the available planetary bodies and extra stars (Low & Johnson 1964). The linearity, repeatability and sensitivity were all much higher than one would expect for an all-new instrument. Texas Instruments, Inc. and the National Radio Astronomy Observatory at Green Bank, West Virginia, had generously supported this work. Harold was surprised and pleased with the quality of the data, and he proceeded to construct and publish a table of Ten-Color Photometry, UBVRIJKLMN (0.35 μm to 14 μm).

It became quite obvious that the 8 to 14 μm color measurements were numerically consistent over the full range of stars and their magnitudes. Secondly, the total number of stars that were made available from V-band to N-band in a single summer night was a true technical advance worth a major celebration. Without a doubt, Harold had earned his share of glory. All too soon, a very great set of many talents was lost prematurely and sadly when Harold declined his professorship at Arizona and relocated to a new observatory in Baja Mexico, where he suffered an untimely fatal heart attack. Low and Johnson coauthored just three papers, but these articles were historic in the sense that they were among the first quantitative mid-IR astronomy results. All three articles demonstrated unique results: mid-IR photometry of stars, radiometry of planets and even the marginal detection of a bright QSO, 3C273.

The friendship I shared with Harold had evolved into a deep professional relationship. Clearly, Harold was an expert classical astronomer who held strong convictions in all aspects of high precision photometry including his own version of digital data acquisition and data analysis; I have learned much about science from Harold.

When Dave Heeschen became Director of NRAO he gave me scientific responsibility for many aspects of the unique observatory to be located on the grounds of NRAO's site near Kitt Peak Observatory in Arizona. After two and half years living in beautiful pastoral West Virginia, we (now a family of five including two daughters and an infant son) were ready to move to Arizona's high desert surrounded by much taller mountains.

2.2 Tucson and Surroundings

At the University of Arizona, Gerard P. Kuiper directed the Lunar and Planetary Laboratory, a laboratory of his own making, until his untimely death. One of his notable hobbies was searching out superior astronomical sites, such as Mauna Kea and many others. Gerard had already recruited Harold, and I eagerly joined LPL when I had completed my obligations to the NRAO. Conveniently, the University and the NSF preferred that I be appointed to a full Research Professorship which would be supported by the Lunar and Planetary Laboratory. Gerard must have been highly pleased when he effectively acquired the low temperature germanium bolometer and a mid-IR capability to complement Harold's near infrared program, establishing a broad infrared capability at a low price. Gerard and I soon became close friends and confidants. With so much still to learn I felt I should become a good listener and a better observer.

As a side note, I customarily collaborate with a number of colleagues and I share my ideas and critical information. Bill Hoffmann had visited Tucson to discuss building the detector system he used for the first far-infrared observations, leading to the discovery of the emission of the Galactic Center in this regime. He later spent a sabbatical working with me to attempt sub-mm observations from Mt. Bigelow and to watch over the completion of the NASA 60 inch telescope on Mt Lemmon. Other scientists interested in using bolometers in their own work had no commercial source from which to obtain them, nor did they have the material and expertise to build them. As a result, in November 1967, I was persuaded by a highly ranked officer of the University of Arizona to produce bolometer systems for sale. I was advised to incorporate, so we founded Infrared Laboratories, Inc. We have now provided several thousand bolometers and almost 4000 cryostats and have designed and built numerous instruments, large and small. Our largest customers buy and support infrared microscopes used by the world's largest semiconductor companies.

Early on, Gerard and even Harold agreed that my planetary observations would provide new and interesting science. Certainly the Apollo Project needed more definition of the lunar surface prior to landing on the moon. So, I measured enough temperatures and areas to satisfy Gerard and myself. Much later on Wendell Mendell, a lunar geologist at Rice University, and I used an IR Scanning Radiometer attached to the Apollo 17 Orbiter to generate a calibrated thermal map of a very large portion of the lunar surface (Mendell & Low 1975). One of my scientific hobbies was to urge my small group of IR observers to produce as many multi-spectral observations of as many planetary bodies as possible.

In regard to our ground based observations, I first observed on the 28-inch telescope at "site-two" near the summit of Mt. Bigelow and soon afterwards I moved to a Johnson designed all-aluminum-mirror 60-inch telescope located adjacent to the 28-inch. NASA had funded the LPL 61-inch, but it was a long time before Gerard agreed to a configuration fully optimized for IR performance.

Interestingly, perhaps my most exciting observation came soon after I added a 20 μm filter to our cooled filter wheel in our IR photometer. Doug Kleinmann and I were scanning the inner Orion Nebula where the Caltech observers had recently reported a cool point-source at 2.2 μm, which they had also detected at 10 μm. While searching that area of 20 μm sky through the 28-inch telescope Doug was just missing the reported star-like object. Searching more widely, we were soon rewarded by finding a bright cold nebulous source of 20 μm emission offset from the position of the warmer Caltech object. These two objects have acquired a single name, BNKL, because the two are simply components of a puzzle viewed in different lights. The Caltech discoverers are Eric Becklin and Gerry Neugebauer, BN; the other discoverers are Doug Kleinmann and Frank Low, KL. In reality, a grand puzzle has only been partially solved in the last few decades; we are still working on the task of how star formation actually works.

2.3 How We Removed Most of the Earth's Atmosphere

In the mid 60's, Carl Gillespie retired from the Air Force and joined the staff of the Lunar and Planetary Laboratory to assist with Kuiper's airborne astronomy activities. Carl soon found a lightly used military aircraft that could fly to 45,000 feet, a twin jet Navy bomber that belonged to the China Lake Naval Air Base. The Commander was happy to see his airplane flying on interesting missions. We carried very light equipment in the airplane comprised of a simple vacuum pump and the Dewar along with a pinhole for tracking the target and finally a swiveling ball-joint device that was modified to fit in the standard porthole used for the naval sextant when in the standard configuration. The modified sextant fixture plus super-fluid He Dewar could easily be taken in and out of the plane when on the ground. At high altitudes, Carl and the two pilots flew in their shirtsleeves. Carl could easily attach our smallest liquid helium Dewar to the ball joint and swivel the Dewar to track the motion of the target. Our target for the mission was the Sun. The objective was to measure the brightness temperature of the Sun at a wavelength of 1 mm. On the ground in the Navy's large empty hanger an elaborate calibration procedure was performed. The final result of these flights was a well-measured solar surface temperature of 4500 degrees Kelvin. For two decades, solar models were based on this set of measurements.

Encouraged by the success of this experiment, Carl and I went in search of an aircraft able to fly above the troposphere into the earth's stratosphere. At the Ames Research Center located at Moffett Field in California Carl was able to identify an early model Learjet used to train the novice test pilots. We were fortunate to have the experienced Ames test pilots for the safety qualification flights. Into the emergency door opening we designed, built and tested a 12-inch Cassegrain telescope that could be articulated plus and minus 20 or more degrees in its range of motion (Figure 1). Although the service altitude was 50,000 feet, the cabin air pressure had to be reduced to 30,000 feet equivalent to allow the telescope to move in its bearing. As a result, the two pilots and the operator of the telescope were all provided full pressure breathing apparatus, and regular training was a firm requirement.

To save both time and money, one of the top test pilots at Ames volunteered to assume total responsibility for the entire series of solo test flights required to certify the new configuration of the Learjet. This action was well beyond normal procedures. Without modification to the open port, acoustic noise maximized at about 30,000 feet and was declared unacceptable. On a subsequent test flight an air dam was installed and a satisfactory climb pattern was then established. At that point Carl and a few others were cleared to fly, but without a fully functional chopping mechanism the flights would not be successful.

One clear evening in Tucson, we set up the 12-inch telescope on a sturdy frame in the parking lot of the Lunar and Planetary building and carefully simulated a simple way to tilt the small secondary mirror manually. This basic tilting motion was easily performed, and the results were fantastic; we could move the star signal on and off the

Figure 1. Frank Low in the Learjet airborne observatory.

detector with almost no change in the overall background level. We quickly built a two stroke magnetic drive that satisfied our optical and mechanical requirements. The test results on the next series of Learjet flights were a great success.

Note that many ground based telescopes have adopted the articulated secondary as a better way of subtracting the IR background. Other simple modifications to the telescope can dramatically improve infrared performance. Also note that articulating the secondary mirror in different patterns can be used to facilitate scanning as demonstrated by the 2MASS survey project.

The scientific results from the Learjet ushered in the first systematic flow of measurements from altitudes high enough to provide easy access to far-infrared wavelengths starting around 34 μm and extending to millimeter wavelengths. George Aumann was my first graduate student to fly with Carl Gillespie in the Learjet, and we measured the internal heat of Jupiter and Saturn, the first of the giant planets to reveal this property (Aumann, Gillespie, & Low 1969). Far-infrared studies of the Galactic Center followed (Aumann and Low 1970). Far-infrared galactic and extragalactic sources were observed by Low and Aumann (1970). The Learjet pioneered open port airborne observations, and its successor, the Kuiper Airborne Observatory (KAO), served IR and optical observers well for more than 10 years.

Figure 2. The 28-Inch Telescope. The first experiments toward infrared optimization of groundbased telescopes were conducted here.

2.4 Infrared Optimized Telescopes

With a few exceptions, early infrared astronomy was conducted on telescopes “borrowed” for the purpose from optical users. They tolerated the new field since it could be pursued in otherwise nearly useless bright time, but they were resistant to any changes to their telescopes. Thus, the infrared instruments had to be bolted on in a way that permitted their complete removal when the observations were complete. Although such instruments worked well in the near infrared, at 10 and 20μm the devices used to chop the field of the detector on and off the source also chopped the much larger signals from the telescope and the warm and turbulent air in the dome. The result was excess "sky noise" that severely limited the overall performance. As a result of the success on the Learjet, a chopping secondary mirror was soon implemented on the 28-inch telescope on Mt. Bigelow (Figure 2), and then on Harold Johnson's 60-Inch photometric telescope. These devices proved very effective at combating sky noise because they did not modulate the emission from the telescope or within the dome.

However, we still had to fight the thermal background emitted by the telescope. The most direct attack was to observe through tiny apertures that would reject most of the background except that within a few arcsec of the source. Harold Johnson's aluminum mirror photometric telescope had mediocre image quality, inadequate for really tiny apertures. However, just around the corner on Mt. Bigelow was Kuiper's gem, a 61-Inch with superb optics to allow diffraction-limited planetary photography. The telescope had been built with interchangeable top ends carrying f/13.5 and f/45 secondary mirrors (the latter because it fit Jupiter or Saturn neatly on a frame of 35mm film). By good fortune, the top end for f/45 allowed the mirror to be protected by removing it to be stored in a cabinet. As a result, it was possible to replace it with an alternative f/45 mirror equipped with solenoid drivers that chopped it. Together with George Rieke, who joined my group as a postdoc in 1970, we completed the infrared optimization of the telescope by modifying the overall top end and secondary mirror mount design. When we were done, everything except the very thin spiders (Kuiper wanted to minimize diffraction effects) hid behind the secondary mirror, which itself was matched to the footprint of the primary mirror image. From the position of the detector one could see only sky reflected off the mirrors, not emissive telescope structure. The 61-Inch, carefully designed to be ideal for planetary photography, became the first fully optimized groundbased infrared telescope (Low & Rieke 1974).

3. Parallel Programs

3.1 The Two Micron Survey

Infrared astronomy had started to grow in other places also. In the Caltech Geology Department, Bob Wildey, Bruce Murray, and Jim Westphal applied liquid-hydrogen-cooled germanium photoconductors to measuring stars for the first time in the 10μm atmosphere window (Wildey & Murray 1964). They used the new capability to map Venus and Jupiter (Murray, Wildey, & Westphal 1963; Wildey 1965) and to observe the Galilean satellites and their cooling during eclipses (Murray, Wildey, & Westphal 1964; Murray, Wildey, & Westphal 1965).

A major advance was the first all-sky survey conducted at Caltech. Two concepts of Bob Leighton, a Caltech Physics Professor, led to the Two Micron Sky Survey (Neugebauer & Leighton 1969): (1) Do something unique that no one else is doing. (2) You will find something new and interesting by looking at the sky in an unbiased way at a new wavelength.

Bob was a brilliant experimentalist and physicist who had opened new fields in solar and planetary physics. He had literally built his own house and small telescope and he thought he could build a major telescope cheaply. When Westphal reported his first measurements of α Ori at 10μm, Bob was impressed because of the huge thermal background that had been overcome and praised the work: "young man, you have done something really important." Gerry Neugebauer had been a graduate student with Leighton, and the two kept in contact while Neugebauer was in the US Army at JPL where he worked on a space infrared radiometer that observed Venus. The association led to Leighton's involvement with the TV on the Mariner probe to Mars and continued when Neugebauer joined the Caltech physics faculty.

Around 1963, NASA gave Caltech a broad based grant in "space related" physics with Leighton as the principal investigator. The desire to build a world class telescope, the background in infrared physics, plus the advent of PbS detectors sensitive to 2.2μm radiation made an unbiased, all-sky survey in the near-infrared a natural component. The grant supported the survey for its duration with only annual written progress reports until the publication of the final catalog.

The mirror was made in Leighton's office by pouring epoxy into a 62-inch diameter pan that rotated on an air bearing while the epoxy hardened to form a f/1 parabolic surface. The telescope, an equatorial mount, was manufactured in the physics machine shop. An array of eight PbS cells was made by Santa Barbara Research Co. It was put at the prime focus of the telescope, where it projected to about 40 x 6 arcminutes. The detectors were cooled by liquid nitrogen and a filter limited their response to 2.2μm (K band) radiation. To minimize the effects of terrestrial radiation, the mirror was chopped at 20 Hz to oscillate the image between columns in the array. The I magnitude (0.84 μm) was measured by a single silicon detector centered on the PbS array to complement the K magnitude.

The telescope was first assembled and tested in an alley in back of Leighton's office. Luckily, β Pegasus, one of the very few stars visible in the narrow confines of the alleyway and one of the brightest stars in the sky at 2.2μm, was available. The telescope was then moved to Mt. Wilson Observatory and a garage-like building with a roll-off roof built by the students and faculty in the group.

The telescope automatically scanned a raster pattern to survey a strip four hours in right ascension by 3.5 degrees in declination each night. The synchronously detected signals were recorded on separate tracks of a six channel strip chart recorder that were later digitized by hand and the observations fed into a computer to be sorted into separate stars. Although the blur circle of the telescope was about 3' and the detector dimensions exceeded 3', the coordinates could be determined to better than 1' by combining the several sightings of any star.

Harold Johnson (Johnson, et al. 1966) had obtained PbS measurements of some 430 bright stars so it was known that stars emitted radiation outside of the visible wavelengths. He kindly sent his photometry to Caltech on punched cards so that consistency with his photometric system was maintained.

Astronomers in general did not consider the infrared wavelengths important. They predicted the survey would net less than 100 sources. On the first night of operation, a very red, previously unknown source with an I-K of 8.2 mag was observed. This source, which became known as NML Cygnus (Neugebauer, Martz & Leighton, 1965), was the reddest source found in the survey.

In all, the survey detected about 20,000 sources at declinations ranging from -33 to +81 degrees. About 5,500 of these were brighter than K = 3.0 mag and a complete and reliable catalog was constructed of this sub-set. Only one source in the catalog, M31, is extragalactic. Most of the sources are late type stars with expected, typical colors 0.0 < I-K < 3.0 mag. Some 18 sources, more than half previously unknown, are heavily embedded in dust with colors I-K > 6 mag (Neugebauer, Martz & Leighton 1965; Ulrich et al. 1966). This mixture thus reinforced the fact that the infrared wavelength emission was ubiquitous and confirmed the belief that "you will find something new and interesting by looking at the sky in an unbiased way at a new wavelength".

3.2 The Galactic Center

Shapley demonstrated that the Sun lies toward the edge of the vast system of the Milky Way, but his methods could locate the center of the system to no better than two degrees (Shapley 1930). Since its location was so poorly determined, until 1958 astronomers used a Galactic coordinate system with a zero point independent of the center of the system and, in fact, displaced by more than 30 degrees from it. The discovery of the bright radio source Sgr A and use of the 21cm HI line to probe the dynamics of the interstellar gas in the 1950s allowed the direction to be localized well (Oort & Rougoor 1960), allowing the IAU to re-center the Galactic coordinates in 1958.

Still, the great star clouds that marked the centers of other galaxies had never been detected; they remained hidden behind very dense clouds of interstellar dust in the plane of the Milky Way. Without finding them, it would never be certain where the true center lay. Previous efforts in the very near infrared had failed (even at 1 micron and with modern detectors, the detection of the region is difficult; Rosa et al. 1992, Liu et al. 1993). However, the interstellar extinction toward the Center was expected to fall so rapidly (from a factor of 10^{12} to a factor of ~ 15 from the visible to 2 microns) that the chances for success by looking farther into the infrared were good. In 1960, Moroz (1961) used a germanium diode and a lead sulphide cell operating together from 1 to 2.5 microns to scan a region about 10 arcmin in diameter centered on the radio emission. Although Moroz's sensitivity estimates may have been optimistic, each channel probably was still capable of detecting the Galactic Center. He failed. There was too much sky to cover with a single detector (or even two).

Finding the center of the Milky Way seemed a plausible goal for Neugebauer's expanding program (see Figure 3). He set out on the search using the 62-inch 2.2 μm survey telescope on Mount Wilson. The question was where to look. Radio astronomy was advancing rapidly, and by 1966 the radio emission had been isolated to a field about 3.5 arcmin diameter (Downes and Maxwell 1966). As Neugebauer describes what came next: "We had actually detected it with our 62-Inch telescope several years earlier, but did not know it. I went to an optical astronomer, who is very famous, and asked him for the coordinates. He thought 'these guys don't know anything about it;' he gave them to me but did not tell me that they weren't precessed, so we missed it." Eric Becklin, Gerry's graduate student, had been working with Gerry and others to develop a system more sensitive than the survey. He had a night to test it on the 24-inch telescope and Gerry asked him "what he was going to do with it. 'Look for the Galactic Center' Becklin said. Don't bother, it isn't there". However, it was. Radiation at 2.2 μm was detected on the first scan. Becklin recalls: "I thought maybe the Galactic Center was just below the survey limit or there was confusion of multiple sources. It never occurred to me that the position looked at on the survey was wrong."

It took several nights of mapping and scanning to determine the peak position of maximum flux. The peak lay about 1.5 arcmin away from the peak of the low frequency radio emission that had provided the beacon to locate it (see, e.g., Pedlar et al. 1989). The radio source that had guided the searches is now known to lie behind the Galactic Center and is probably not associated closely with it. At high radio frequencies, the Galactic Center has since been shown to host a fascinating complex of radio sources including Sgr A*, associated with a supermassive black hole; that, however, is another story.

When the discovery and detailed observations that demonstrated the close resemblance to the center of M31 were published (Becklin & Neugebauer 1968), the instrumentation was so new that the paper starts with a detailed description of how it worked. Although contour maps are presented, a careful comparison of the contours with the single-pixel scans on which they are based indicates that Neugebauer and Becklin had not received sufficient time on the 200-Inch to map the region thoroughly (Guido Muench had let them have a little time out of his allocation). Instead, they published strip chart tracings to illustrate the structure of the very core of the Milky Way. In this era of megapixel high performance infrared arrays, the strip chart figures from this paper have become part of the lore of the field.

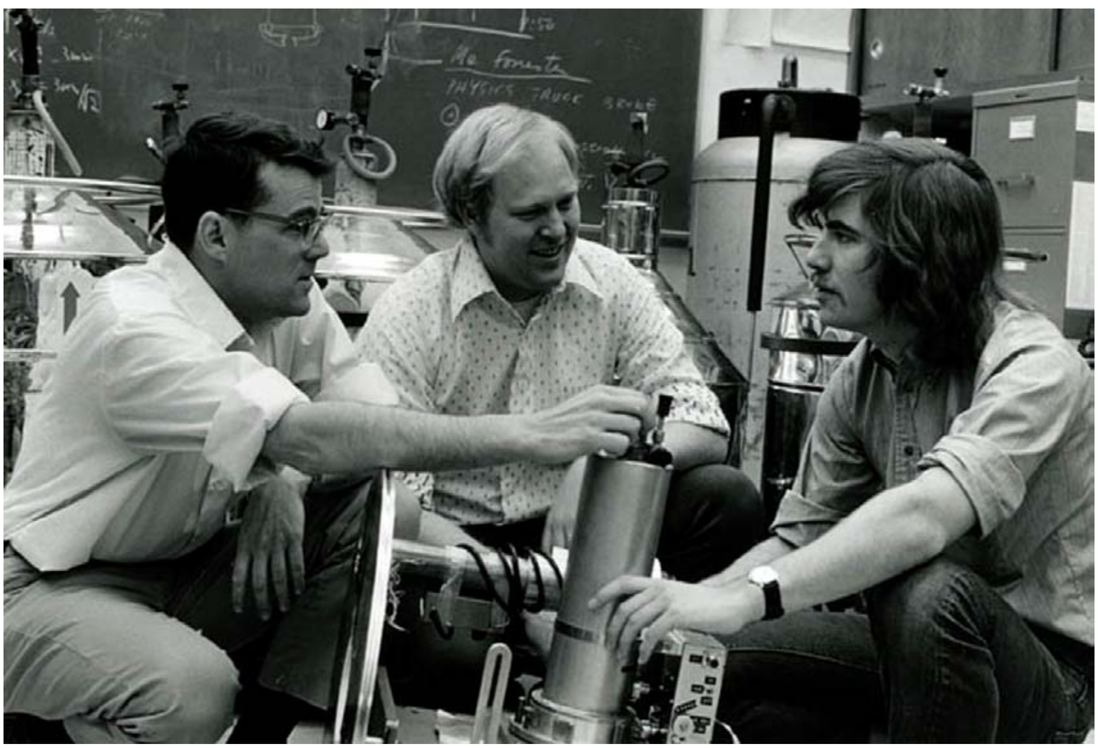

Figure 3. Gerry Neugebauer (left) discusses observing strategy with Eric Becklin (center) and Gareth Wynn-Williams (right).

In parallel, Bill Hoffmann of the Goddard Institute for Space Studies had become interested in the predictions by Franz Kahn (1958, unpublished), Wayne Stein (Stein 1966) and Nick Woolf (Hoffmann et al. 1967) that starlight could heat the interstellar dust in the Milky Way. To look for it required observations above the atmosphere, so Hoffmann led the development of a simple balloon gondola as suggested by Nick Woolf, carrying a 1 inch telescope (with a field of view of 2 degrees) placed within a helium Dewar that housed and cooled a germanium bolometer detector. To upgrade his equipment, he visited me in Tucson; the resulting Dewar/detector was in essence serial number 1 of the thousands of Dewars that have been produced since by my company "Infrared Laboratories."

Ballooning was primitive (Figure 4). Telemetry was a particular problem; the uplink was based on transmitting audio tones that were used to vibrate reeds in the payload. Each reed could activate a relay – the system usually, but not always, got the right one. The mass of a chart recorder would have limited the balloon altitude. To provide a very compact and lightweight way to record the data, Hoffmann used a custom-manufactured camera with no shutter and continuous film advance, looking at the needles of a set of analog meters. To his graduate student, Carl Frederick, went the duty of developing the exposed film and joining hundreds of enlarged prints to form a 'strip chart' for visual interpretation. The first flights were discouraging: "in two initial flights, … approximately half of the celestial sphere was surveyed including most of the northern Milky Way….The thermal radiation of the moon was detected but no other source was observed (Hoffmann et al. 1967)."

Figure 4. Bill Hoffmann about to launch his balloon gondola.

The Galactic Center was targeted for the next flights, in the summer of 1968. Three flights were planned, but the first two failed. Hoffmann says "I wanted to go home for my wife's birthday, but Carl wanted a thesis," so they decided to try again. As it happened, the launch geometry permitted them to scan over the moon, which up to this point was the only celestial object they had ever detected. Once again, it came through early in the flight. The gondola had been fixed at the elevation that would let the telescope point continuously over the region of the sky containing the Galactic Center, with a nutating mirror that caused the detector to scan in an ellipse. The detector output was taken to two phase sensitive amplifiers adjusted to detect gradients along orthogonal directions around the elliptical motion; it happened that one of these directions was parallel and the other perpendicular to the Galactic plane. No signal was recorded in the first case, but there was a good one in the second, leading to the conclusion that a source had been found that was roughly uniformly distributed along the Galactic plane over the 6.5 degrees observed but confined to less than 2 degrees perpendicular to it (Hoffmann & Frederick 1969). The position of the source was reconstructed from the balloon magnetometer readings, the command sequence, the initial setting of the gondola and telescope, and an acetate overlay on a sky chart. Fortunately, the sighting of the moon confirmed the pointing to within about a degree. The detection appeared to be offset by about 3 degrees from the Galactic plane, but given the previous experience on how rarely the equipment could detect anything, it was easy to conclude that the signal in fact came from the Galactic Center region. Hoffmann and Frederick (1969) triumphantly proclaimed: "We believe this to be the first object outside the solar system that has been detected in the region of the spectrum from 25μ to 1000μ (1mm)." Their paper was accepted seven days after submission.

Returning to the ground, Neugebauer and I carried on a friendly but intense rivalry. My group had access only to the 60 and 61-inch telescopes run by the Lunar and Planetary Laboratory (and very occasionally to the Steward Observatory 90-inch). Neugebauer's group using the 200-Inch had an advantage over a 60-inch by an order of magnitude in signal to noise in the 2 micron region. However, in the thermal infrared where the emission of the atmosphere and telescope tended to blind the detector, telescope size was less important. It was just as critical to have a good way to cancel the atmospheric emission without letting it dominate the noise of the overall detection system. Therefore, we had concentrated on these longer wavelengths, using the germanium bolometer that I had invented on our high performance 61-Inch Telescope.

We had scanned the Galactic Center in the mid-infrared early-on and found evidence for complex structure. However, the strip chart recordings of the scan had been mislaid. I would occasionally join my new postdoc, George Rieke, at the telescope to be sure everything was proceeding smoothly. On one such occasion I decided around 11:00 that I could monitor things as well from a bed in the dormitory. When I returned at dawn, George had managed to locate the Galactic Center using the crude dial indicators on the telescope (which had been built for planetary observations where accurate pointing was not required to identify the source). Together, we scanned it thoroughly. The missing strip charts were eventually recovered and together with the new scans allowed construction of the first map of the region in the mid-infrared, demonstrating the existence of at least five individual sources (Rieke & Low 1971).

My group also targeted the Galactic Center in the far infrared with the Learjet telescope. Our observations confirmed the existence of a strong source of mid- and far-infrared radiation centered right where Becklin and Neugebauer had found the peak of the emission by the stellar population (Low et al. 1969). This source appeared to be very compact, which together with the preliminary indication of a very strong far-infrared output caused me to suggest it emitted non-thermally. However, further speculation in this direction was soon squelched by additional observations and skeptical referees. A key observation was the first full far infrared map of the region, made with a 12-inch balloon borne telescope by Bill Hoffman, Carl Frederick, and Roger Emery (1971a).

3.3 Cornell

Martin Harwit at Cornell had done a Ph.D. thesis on thermal fluctuations in infrared radiation. He became intrigued by the possibility to apply his knowledge of infrared methods to astronomy. From the beginning, he was interested in the benefits of observing with cold telescopes to avoid the infrared background radiation, and operating them in space. Therefore, in 1963 he contacted Herbert Friedman, an X-ray and UV astronomer at Naval Research Laboratory whose group had conducted a series of successful observations from rockets. They arranged for Harwit to spend a year at NRL as the first E. O. Hulburt fellow.

The US Air Force was planning to launch a secret payload on an Atlas rocket. There was a little lifting capability left, and the NRL group got permission for a "piggyback" launch of a science package. The focus of Harwit's visit became building a cluster of three liquid nitrogen cooled telescopes to take advantage of this stroke of fortune. They would operate in the near infrared, where excellent sensitivity was possible with nitrogen cooling. The three would look along sight lines separated by about 60 degrees to triple the amount of data to be gleaned from this rare opportunity. Because there was room only for a small package, the telescopes needed to be small and the resolution would be low; but that was fine, because the strength of a cold telescope was measuring extended emission like the zodiacal light or the plane of the Milky Way. However, the tightness of the packaging posed another problem; the nitrogen had to last long enough to allow the launch operations with reasonable contingency for holds on the pad. Finally, a Dewar was developed that was good for four to six hours.

After a frantic but successful effort to complete the package in time, the Air Force delayed their part of the mission, and thus the entire launch, for a year. When the time finally came, Harwit (2003) described the results as follows:

Figure 5. Martin Harwit makes an adjustment on the payload for an Aeobee launch.

"When the Atlas flight eventually did take place, it was a total fiasco. On the night of the flight, the launch kept getting further and further delayed. When the maximum four-hour hold time passed, [I] requested that the payload be removed from the missile, but the Air Force now needed it as ballast and refused. Finally, the launch took place after a six-hour delay on the launch pad. The telemetry signals showed the last of the liquid nitrogen evaporating just as the rocket lifted off. It was heart-breaking.

"The lesson [I] learned from this was to never accept an offer for a free 'piggyback' flight. It was far better to have a more modest launch on a rocket under the sole control of the scientist, than an opulent flight over which the experimenter had little control."

The group switched to Aerobee rockets (see Figure 5), which allowed for about 5 minutes of high altitude observations per launch. The payload now had to be made very lightweight and small. Only 5 to 7-inch telescopes could be squeezed into the packages after allowance for the vacuum shell and insulation required for a Dewar. The instrumentation was optimized for very extended emission, with a 3 degree field of view and a total power chopping system. Suppressing stray light was very difficult, given the large field, the low background implicit in the cold telescope operating above the atmosphere, and the blazing sources of infrared emission that included not only the earth but also the aura of gases and particles surrounding the rocket at altitude. These problems negated the ambitious goals (with the NRL group) to measure a cosmic background. In fact, the initial the efforts did not return much useful data but did train students and postdocs who have had a major influence on the field. The instrumental problems were eventually beat down in a series of flights continuing with the nitrogen cooled telescopes.

Jim Houck joined the group as a postdoc right after finishing a Ph.D. at Cornell in solid state physics. Jim, with his skills in device physics, cryogenics, and all manner of laboratory techniques, was a perfect complement to Martin Harwit. The graduate students in the group were set to work manufacturing detectors and filters and inventing a better black paint. Not long afterwards successful flights began with helium cooled telescopes (Harwit, Houck, & Fuhrmann 1968), leading to the first accurate measurements of the infrared emission from the zodiacal dust cloud (Soifer, Houck, & Harwit 1971; Pipher 1971). The zodiacal cloud is of interest in its own right, but it is also the limiting infrared background from space, so the data had implications for planning future space infrared missions. The group also observed the Galactic Center (Houck et al. 1971), providing homogeneous four-color spectral energy distributions over the region that supported consistent physical interpretation. An important and at the time under-appreciated result of the rocket flights was the evidence that the far infrared Galactic sources were often very extended and that the small aperture, chopped groundbased measurements were missing out on a lot of their output (Houck et al. 1971; Soifer, Pipher, & Houck 1972).

Perhaps in part because of the frustrations and delays in the rocket program, the Cornell group published a number of theoretical papers that have turned out to be very prescient as infrared astronomy has developed. One example is an analysis of the expected near infrared emission lines from molecular hydrogen (Gould & Harwit 1963); these lines are now part of the bread and butter of near infrared spectroscopy. Davidson & Harwit (1967) predicted that massive young stars might be embedded in dust cocoons that would hide them in the visible and lead to bright infrared outputs at a nominal temperature of ~ 100K. Such sources are now frequently found in regions of star formation.

3.4 Minnesota/San Diego

3.4.1 A Complex Start

A complex set of circumstances resulted in a collaboration in infrared astronomy between the University of Minnesota (UM) and the University of California at San Diego (UCSD). In 1962, Martin Schwarzschild of Princeton University, then the leader of Project Stratoscope II (SS2), attended a conference at Lick Observatory and met a postdoctoral student, Neville J. (Nick) Woolf. Their mutual interest in stellar evolution led Schwarzschild to offer Nick a position at Princeton working on SS2. Carl Sagan had suggested that Schwarzschild use SS2 to search for water on Mars. Nick offered to handle improved equipment to look for water emission bands in the infrared, the key to this search. Bob Danielson, an SS2 collaborator and former student of Ed Ney's at UM, had recently read my paper on bolometers (Low 1961) and decided it was the detector of choice. Bob piqued Nick's interest, and Nick became the SS2 IR detector guru. Nick visited me at Texas Instruments to learn about my 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. He also felt 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. Ed's eclectic interests led him in a natural progression from the Manhattan Project, to measurements of cosmic rays, to studies of the physics of balloon flight, to atmospheric and solar physics, to research on the solar corona and the zodiacal light, and finally into the world of astronomy (see Gehrz, McDonald, & Naugle 1999). Ed's research group was at the very top of the game in flying high altitude balloons. Schwarzschild asked Ed to help with the logistics of the SS2 launches by contributing a couple of graduate students. The "volunteers" were Wayne Stein and Fred Gillett, who were finishing theses based on balloon-born and ground-based observations of the solar corona and the zodiacal light (Stein 1964, Gillett 1966). Wayne and Fred had realized that little astronomy was being done in the vast frequency realm of the infrared. On the SS2 expedition, they met Nick Woolf, who shared their enthusiasm for this spectral region. They soon interested Ed, who had been thinking it was time to switch fields anyway.

After receiving his PhD in 1964, Wayne went to Princeton to work on SS2 as a postdoc. There, he was given half time to pursue his own research interests. As a result of this opportunity, Wayne wrote a number of theoretical papers predicting the infrared flux expected from various astrophysical objects. For example, in Stein (1966a), he predicted that detectable far infrared signals would be emitted by interstellar grains. In Stein (1966b and 1967), he modeled the infrared emission of circumstellar dust and of HII regions.

Meanwhile, Larry Peterson convinced Fred Gillett to join the staff at UCSD to develop an IR extension to Larry's program of X-ray astronomy from balloons. At the same time, the SS2 Project sent Wayne 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 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. Shortly thereafter, they entered into a collaboration with me on the construction of a 2.8-14 μm circular variable filter wheel (CVFW) spectrometer. The work resulted in several publications on the mid-infrared spectral energy distributions (SEDs) of stars and planets (Gillett, Low, & Stein 1967, 1968) before the spectrometer was destroyed in a freak accident. Fred, who had been observing at Mount Bigelow, left the spectrometer in the house-trailer that served as the observer's quarters when he left for Tucson to escape a blizzard. When the weather cleared, the trailer was nowhere to be found. The weight of the snow had flexed the trailer roof enough to break the heater gas line, and the resulting fire had reduced the trailer and spectrometer to ashes!

Ed Ney took two sabbatical leaves that shaped 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. Upon his return, Ed and his master technician took a sabbatical to Tucson to learn the techniques of infrared astronomy from me, upon whom I am told 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, they learned from Arnold Davidson that a sapphire "jewel" was critical to the mounting of bolometers to provide electrical isolation with good thermal conduction. This clue allowed them to figure out how to construct bolometers themselves. When Ed returned to Minnesota, he had all of the knowledge to do infrared astronomy. He also had an obsession with bettering the "Pope" at all aspects of the game. However, he knew that he needed to have access to a telescope where he could pursue this passion full time.

Ed started by forming 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.

3.4.2 The O'Brien Observatory (OBO)

Ney realized that UM could actually compete with Neugebauer and me 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 atmospheric water. How could Minnesota play in this game? During the Minnesota winter, when the dew point could fall tens of degrees below zero, the air was as free of water as a 10,000 foot high mountain top! Thus, Ed's strategy was to observe under superb conditions with superior detectors using a rather small telescope. In addition, a telescope in Minnesota would provide a base site close to home during the key experimental development period. The down side was the necessity to operate the telescope and instrument in the bitter Minnesota winter. It was rumored that Ed would take a number of graduate students observing, so they could be used up serially to get through a long, cold night.

The proposal to build an IR observatory in Minnesota was reviewed favorably at NASA, and Ed's Contract Officer, Nancy Boggess, gave him the go ahead. With the aid of his racy Jaguar XKE sports car and a home-made sky brightness meter that was derived from equipment he had developed for zodiacal light measurements, Ed soon selected a site in the high hills on the St. Croix, about an hour from his home. The land was owned by Thomond "Thomy" O'Brien, a descendent of lumber baron William O'Brien. Over martinis on Thomy's front porch, the two cemented a deal to build O'Brien Observatory (OBO) on a parcel of land to be 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 two months later.

The telescope was soon working well and Ed and his colleagues began turning out new discoveries (Figure 6). The first paper reported measurements of the integrated synchrotron flux from the Crab Nebula at λ= 5800 Å, 2.2 μm, and 3.5 μm (Ney and Stein 1968). Nick Woolf's involvement led to the discovery of 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, Ney and Allen (1969) discovered the optically thin Trapezium Nebula in Orion, and Wayne and Fred used a new UCSD CVFW spectrometer (Gillett and Stein 1969) to show that the Trapezium dust had the same 10 μm emission feature seen in the M-supergiant μ Cephei. Shortly thereafter, Maas, Ney, & Woolf (1970) showed that a similar 10 μm feature appeared in the spectrum of of Comet Bennett 1969i. 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.

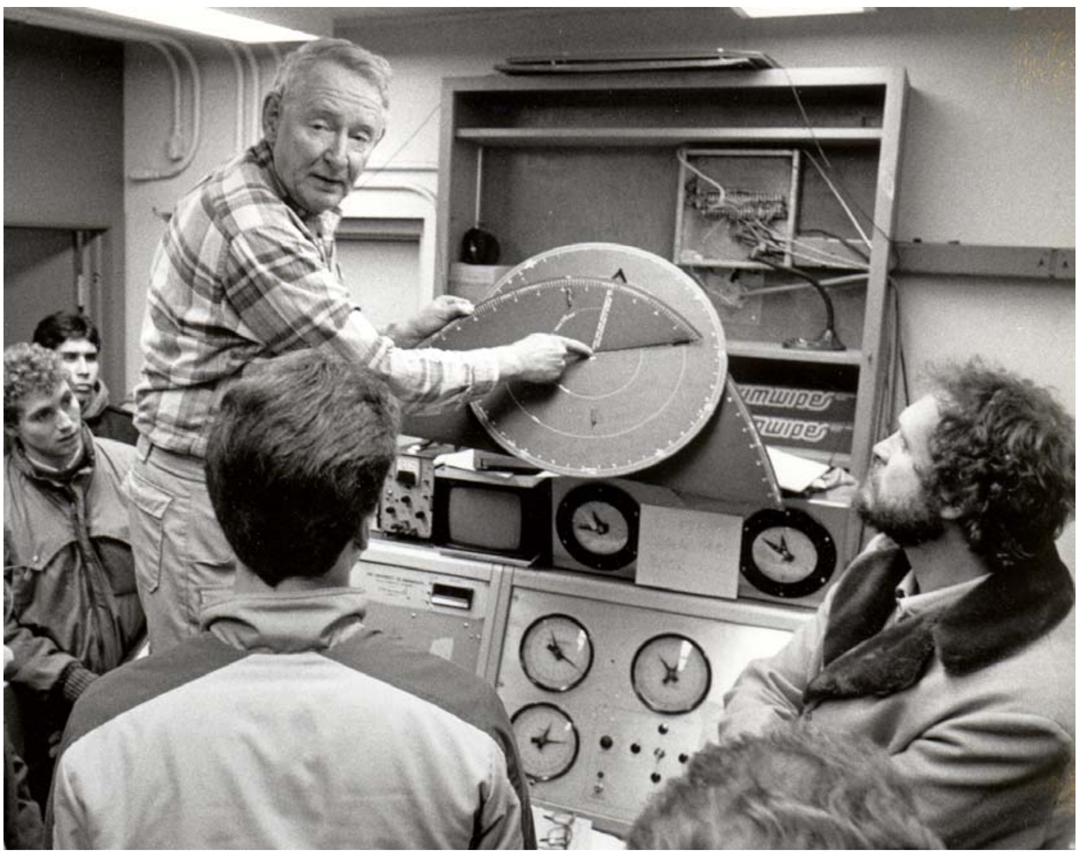

Figure 6. Ed Ney explaining comet orbits in the control room of O'Brien Observatory. Bob Gehrz is to the right.

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 over phases that could be explained by the fact that large rocks connected deeply to the subsurface layers cooled more slowly than the loosely packed 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, & Strecker (1970) discovered that luminous red supergiants as a class (the Ic Variable stars) had extensive circumstellar dust envelopes rich in silicates.

3.4.3 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 Harold Johnson had designed for Mt. Lemmon.

They obtained funding from four parties. The National Science Foundation (NSF) agreed to put in $100,000 in return for $50,000 matches from UM and UCSD. Based on the connection at Narrabri, Fred Hoyle offered to contribute an unrestricted $100,000 to the group on the agreement that aspiring British infrared astronomers be trained at Minnesota.

Bob Gehrz led an extensive survey of mountain sites in the southwestern United States and Hawaii. 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.

3.4.4 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, 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 Cerro Tololo during the Austral winter of 1971, and Ed and Bob Gehrz made a follow-up trip during the Austral winter 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 AX Sgr and HR 5171A turned out to have two of the largest 10 μm infrared excesses known, Ed named them "Gee" and "Gee Whiz" respectively. 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).

4. Graduating from "D-Mode"

When conditions at the telescope were only fair, Doug Kleinmann, one of my graduate students, would announce that he was observing in "D-mode", short for discovery mode. This term meant that he would point at random objects to see if any were bright. By the late 1960's to early 1970's (depending on spectral range and science topic), infrared astronomy was graduating from D-mode and beginning to be applied more systematically to significant astronomical issues. Interestingly, with the very notable exception of

Harold Johnson, virtually everyone involved up to this point was trained in physics (and Harold had learned the same skills in the MIT Radiation Laboratory during World War II). It was now time for a few adventuresome astronomers to get involved. From 1970 to 1975, the collaboration between them and the physicists set infrared astronomy in directions that are still at the forefront of the field today. As a natural consequence, programs started to spring up at many additional places around the world as well. A time capsule of this era is preserved in reviews by Neugebauer, Becklin, & Hyland (1971) and Soifer & Pipher (1978), and in David Allen's (1975) somewhat eccentric book, "Infrared, The New Astronomy." Curiously, detector development and instrument performance stood still until the introduction of high performance InSb systems in 1975 (Hall 1975).

4.1 Mid-Infrared Surveys

Neugebauer and Leighton's survey had proven a rich hunting ground for new types of infrared source, yet it only extended a factor of two to three beyond traditional optical wavelengths. The first sensitive all-sky survey for longer infrared wavelengths was conducted by the Air Force, using seven rocket launches to get small, cold telescopes above the atmosphere (Walker & Price 1975). At Arizona, I was supposed to conduct groundbased observations to verify and support this effort. This work mostly drove home the incredible advantage of using cold telescopes above the atmosphere; in a number of years of hard work, we found exactly one mid-infrared object that was not previously known. Since it was in the Camelopardalis constellation and was found late enough in our effort that we knew we were unlikely to find more, we whimsically named it "Giraffe 1."

In comparison, the rocket survey found about 2000 objects in a net exposure time of less than an hour. Not all of these objects were easy to confirm. Part of the problem was the huge advantage at detecting extended sources with cold telescopes compared with the methods used on the ground, as had been found previously by the Cornell group. Another part was the same difficulties they had experienced with spurious detections of dust particles and other debris associated with the rocket launch. Nonetheless, the survey was immensely useful in opening up the mid-infrared regime (Kleinmann et al. 1981). My former student Susan Kleinmann and others were able to use this rich new catalog of mature, mass-losing stars to document how stars evolve toward planetary nebulae and how the interstellar dust is constituted and ultimately distributed to make new stars and planets. The survey also set the stage for more ambitious projects using cold telescopes in earth orbit.

4.2 Cool Stars

Work on evolved, cool stars centered at CalTech (where many prototypes had been discovered in the 2.2μm survey) and at Minnesota, since monitoring their behavior was a nice project for the O'Brien Telescope. Working together, the two groups studied the most spectacular infrared-emitting star in the entire sky, eta Carina (Gehrz et al. 1973, following up on the original infrared detection by Neugebauer & Westphal 1968). Identifications with optical counterparts and early infrared spectroscopy indicated that a typical very cool infrared star was in late and extreme phases of mass loss. In some cases, the surrounding envelope was so thick that the star itself was virtually invisible in the optical, although the envelope might be among the dozen brightest sources in the sky in the near infrared! Infrared spectra demonstrated, however, that the objects in the cores were extreme stars similar to the less obscured visible analogs (McCammon et al. 1967;

Hyland et al. 1969). There were a few exceptions where the shells hid all traces of a star (Becklin et al. 1969), but by analogy they were thought to be similar but more extreme objects. Gehrz and Woolf (1971) 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. This picture was confirmed by modeling of the radiative transfer in the circumstellar dust, based on airborne spectra covering from 2 to 40μm (Forrest et al. 1978)

A related topic was to trace the evolution from these extreme mass-losing stars. Many were destined to become planetary nebulae. RV Tau stars were a phase in this metamorphosis, and there were extensive studies of their infrared excesses (Gehrz and Woolf 1970; Gehrz 1971). The AFCRL survey revealed two very bright objects that represent the early phases of planetary nebulae themselves, GL 618 and GL 2688. Planetary nebulae are also bright infrared sources, and half a dozen appear in the AFCRL catalog (Kleinmann, Gillett, & Joyce 1981). Airborne observations showed their continuum to be dominated by small graphite grains embedded in a surrounding cloud of about a solar mass (McCarthy et al. 1978).

4.3 Young Stars

This period marked the first full infrared surveys of star forming regions and the realization that infrared excesses were useful signposts of youth. Starting with the nearby ρ Ophuichi dark cloud (Grasdalen, Strom, & Strom 1973), a large number of nearby molecular clouds were scanned in the near infrared to locate large populations of embedded stars, mostly of relatively low mass. In parallel, it was shown that nearly every previously known form of young star had infrared excess radiation (Cohen 1973a,b,c; Strom et al. 1975). The current paradigm of protoplanetary disks does not seem to have been widely proposed at this time, but a variety of other possibilities for the excesses were discussed (Strom, Strom, & Grasdalen 1975). An interesting controversy surrounded the status of the luminous, heavily embedded objects being discovered, of which the Becklin-Neugebauer object was the prototype. Was it a true pre-main-sequence protostar (Neugebauer, Becklin, & Hyland 1971; Becklin, Neugebauer, & Wynn-Williams 1973; Grasdalen 1976) or a heavily reddened young star (Penston, Allen, & Hyland 1971; Gillett & Forrest 1973)?

Massive star forming sites were copious sources of far infrared radiation (Low & Aumann 1970; Harper & Low 1971; Hoffmann, Frederick, & Emery 1971b; Fazio et al. 1974). The bright mid and far infrared fluxes from these regions acted as a beacon to searches for forming massive stars, although it is likely that the young stars lie in the neighboring (and superimposed) molecular clouds as much as in the HII region (see, e.g., Wynn-Williams, Becklin, & Neugebauer 1972). The first examples of major far infrared cooling lines were also detected (Ward et al. 1975).

4.4 Starburst and Ultraluminous Galaxies

We had a mid-infrared sensitivity advantage at Arizona over any other telescope, due to the low background and chopping-secondary-equipped 61-Inch Telescope. We used it to survey what were then faint sources (our limiting detections are now reached in a couple of milliseconds with *Spitzer*). We quickly discovered that the nuclei of many spiral galaxies were detectable at 10μm (Kleinmann & Low 1970; Rieke & Low 1972). In a couple of the brightest cases, M82 and NGC 253, we were successful with the Learjet in extending the observations to 100μm (Harper & Low 1973); we also detected NGC 253 at 350μm from the ground (Rieke et al. 1973). The 10μm signals were indicating huge luminosities from cool dust! We showed that this excess arose from relatively short-lived episodes of massive star formation, on the basis that the available dynamical mass could not sustain the luminosity of the regions for long (Rieke & Low 1975). This process was eventually dubbed a "starburst."

These early surveys revealed starbursts with luminosities up to 10^{12} Lsun and more, the first ultraluminous infrared galaxies (ULIRGs). The most dramatic example at the time was Mrk 231, found independently by a student at Stony Brook, Erick Young (Young, Knacke, & Joyce 1972) and by us (Rieke & Low 1972). The best evidence of the rapid growth of the field was that significant discoveries could be made independently! Originally, the large luminosities we attributed to such objects were greeted with skepticism, since they were deduced by analogy to Galactic sources and to a few nearby starbursts with huge far infrared fluxes. However, on exceptionally dry nights we could peer through a very poor atmospheric window at 34 μm, and were able to confirm the rapid rise of the spectrum of Mkn 231 to that wavelength, enough into the far infrared that the high luminosity was firmly established. (Rieke & Low 1975).

4.5 Active Galactic Nuclei (AGN)

It was established quickly that AGN have large infrared luminosities. However, Mother Nature played an elaborate practical joke on infrared astronomers in this instance. A number of spectral components - cool stars, hot dust, warm dust - somehow aligned themselves to give the appearance of a unified power-law spectral energy distribution (e.g., Oke, Neugebauer, & Becklin 1970). It was often taken almost for granted that such a spectrum demonstrated the presence of non-thermal radiation.

However, there was a simple test. There was a minimum plausible size for a thermal source, set by the thermal equilibrium of dust grains heated by a single central object. If the infrared outputs varied too fast to match this size, then the nonthermal hypothesis would be confirmed. Such variability was observed. In a few cases, the variability behavior appeared to contradict the nonthermal hypothesis and support the idea of a multiple component source (Penston et al. 1974), but in general it appeared to require non-thermal emission. Unfortunately, good variability measurements were scarce because of the overall difficulties in obtaining accurate photometry, particularly given the small apertures used to reject the thermal background radiation (see, e.g., Pacholczyk 1970 and Neugebauer et al. 1971). Most of the early reports now appear to have been erroneous. It took a decade or more to sort out fully the dominantly thermal emission of AGN.

4.6 Infrared Spatial Interferometry

Prior to spatial interferometry the diameters of a few bright infrared stars were measured through lunar occultations (Zappala et al. 1974; Ridgeway, Wells, & Carbon 1974; Ridgway, Wells, & Joyce 1977). However, this method was very specialized. Charlie Townes was developing interferometers using coherent (heterodyne) detectors (Sutton et al. 1977), but the very narrow spectral bandwidths limited them to the few brightest stars in the infrared sky. More general approaches were needed.

In 1973 and 74, when Donald McCarthy was a second year graduate student, we explored various research projects. He chose to pursue an all new field of research, ground based IR spatial interferometry. We decided to begin by building a classic 5 μm

Michelson interferometer attached to the 21-inch campus telescope; soon Don had his first fringes. By demonstrating his lab setup to Peter Boyce from the NSF Don had won his first NSF grant; and we had initiated a new era in high spatial resolution research.

Don describes our early results taken from 1 to 20 μm on the two local SO telescopes and later on the NOAO 4-meter telescope: "We measured the first-ever angular sizes of evolved stars (VY CMa, NML Cyg, IRC 10216, etc) and published initial results (McCarthy & Low 1975). We also resolved α Ori, measuring not only the angular size of the star's dust shell but also the flux ratio of star/shell versus wavelength" (McCarthy, Low, & Howell 1977). We then followed with the same for Mira and could see the ratio change vs. phase in the light cycle (McCarthy, Howell, & Low 1978). With our novel instrument and incoherent techniques we were able to compete effectively with the coherent techniques used by Towne's group.

In 1977 Robert Howell joined our small group as a graduate student and he contributed a fundamental instrumental enhancement by switching from our standard beam switching technique to scanning the fringes across a slit. Note that both signal modulation techniques require articulation of the secondary mirror; only the pattern changes. Howell also developed speckle techniques that used a servo-controlled f/45 secondary to scan the speckle pattern across a narrow slit (Howell, McCarthy, & Low 1981; see also Foy et al. 1979). This method allowed us to measure the full spatial frequency spectrum of a source up to the diffraction-limit.

With infrared arrays and adaptive optics, the methods to get diffraction-limited images have changed beyond recognition. Still, our early work was the prelude to current capabilities and to the striving for even higher resolution in the future.

5. Meetings with NASA Headquarters and Perfect Results

By 1975, it was clear that there was a lot to learn in the infrared. Many of us had begun to appreciate the significance of the far infrared contributions produced by aircraft, balloons, and sounding rockets; it was time to move to earth orbit. Nancy Boggess, the head of infrared astronomy at NASA, wanted to set the ground for investments in more powerful facilities. In July 1975, she assembled a group of representative infrared astronomers at Snowmass, a Colorado ski resort. To our surprise we learned Headquarters had already determined to build a space facility for infrared astronomy and operate it from within the Shuttle Bay, and they had given it a name, the Space IR Telescope Facility or just SIRTF. With at least tacit approval from Nancy, our titular leader, the representative scientists held firm with an alternative plan that ultimately prevailed. To summarize briefly, we argued for a small Earth satellite that could quickly survey the infrared sky in a few weeks.

The Snowmass meeting resulted in another decision—NASA was encouraged to authorize a two-meter class telescope to be sited on Mauna Kea, Hawaii, and operated by the state of Hawaii for the scientific community. Gerry Neugebauer, Fred Gillett and I were charged to oversee the design and construction of the 3-m Infrared Telescope Facility (IRTF). At the same time, Bob Gehrz and John Hackwell convinced the Wyoming State Legislature to provide them a $1 Million dollar capital appropriations bill (supplemented by $0.6M from NSF) to build a 2.3-m infrared telescope. It was completed on this shoestring budget in October of 1977 (Gehrz & Hackwell 1978), followed within two years by the IRTF and the 3.8-m United Kingdom Infrared Telescope (UKIRT). No longer was the 61-Inch the only infrared-optimized telescope—there were suddenly many larger options.

There was sparse traction for the survey satellite until the Netherlands quietly proposed a joint infrared mission. Then, planning took root in both countries; and eventually the UK joined in to complete the triumvirate. The IRAS project was initiated formally as a joint program of the United States, the Netherlands, and the United Kingdom. Under the leadership of Gerry Neugebauer, the US was to provide the cryogenically cooled telescope equipped with the multi-spectral detector array. Ball Aerospace supplied talented engineering and good management for this purpose. Throughout this entire period the Dutch proved themselves to be skillful and almost error free in providing an excellent 3-axis stabilized spacecraft and an auxiliary IR instrument. The UK was to supply the data acquisition system and a reliable dedicated ground station was located at Rutherford Labs.

However, Gerry, as chair of the the IRAS Science Working Group (SWG), Nancy Boggess and Frank Martin, her superior at HQ, were faced with drastic dilemmas when the complex assemblies of 62 silicon and germanium detectors were delivered for their final testing. They failed one by one. There were many problems, but two major ones. Tests showed that the far infrared, germanium detectors provided by Rockwell had woefully poor response. Combined with the high noise of the cryogenic MOSFET amplifiers, we were threatened with a big loss of performance. NASA Ames Research Center had the entire cryogenic hardware responsibility. The Ames group depended on their contractor and they insisted that the contractor repair the defective hardware including the detector preamps and the germanium photodetectors. There was no evidence Rockwell knew how to do so. Fortunately, NASA's JPL lab had been acting as a technical and managerial consultant in tandem with the SWG. NASA transferred the project to JPL, where the problems still had to be fixed.

To replace the detectors, Jim Houck, a member of the SWG, donated what he describes as a $10 wafer of Ge:Ga from Eagle Picher. He sent a graduate student from Cornell to JPL to teach the technicians there how to cut detectors from the wafer and etch them to remove the damage, then solder leads on them (of course, he was not allowed to do these steps himself). Another major crisis arose when the potted MOSFET preamps were damaged by cutting off the wrong leads. Meanwhile, George and Marcia Rieke and I had developed a radically new preamp technology based on cryogenically cooled JFET preamps (Rieke et al. 1981). The failed MOSFET preamps were ultimately replaced by my company in Tucson, where we had recently completed work on the cryogenic JFET technology, well proven by Space Lab, another Steward Observatory project. Interestingly, a controversy developed among the international triumvirate with the two foreign partners adamantly opposed to NASA choosing my JFET technology as did a large majority of the SWG. Frank Martin chose to decide the issue by traveling to Tucson where I explained the situation to him in my back yard after dinner and Frank made an unpopular decision to go with the JFETs.

Another critical person in the recovery and operation of IRAS was Fred Gillett, who was an important member of the IRAS Tiger Team who calibrated the restored hardware. In addition, Fred and George Aumann, along with their families, moved to Rutherford outside Exeter in the UK for over a year. They shared the 10 month task of real time data verification and initial calibration, and in their spare time they searched for "surprises". Because of this extra activity they were able to discover the Vega phenomenon during the mission (Aumann and Gillett 1983) while pointed observations were being acquired. Finally, it should be remembered that Nancy Boggess insisted she serve as an infrared astronomer in addition to all of her other administrative duties and responsibilities (Boggess, Low and Harper 1973).

I wish to acknowledge the contributions of two younger scientists, Erick Young and Nick Gautier. Erick came to Steward from Stony Brook as a postdoc and he immediately took over the development of our extrinsic silicon and germanium detectors. Nick earned his doctorate degree at the University of Arizona. About that time the SWG recognized the lack of young talent within the project**,** and I solved the problem by hiring both Erick and Nick as members of the SWG team. Erick was responsible for the processing of the "Additional Observations", specifically he selected important pointed observations and managed their processing. Nick was responsible for producing the "Skyflux" data product, specifically the entire IRAS sky was reprocessed to calibrate the sky brightness over the entire celestial globe in all four wave bands.

Launched in 1983, IRAS proved to be fabulously successful in pioneering IR astronomy in space. A series of cryogenic space missions have built on the IRAS experience: COBE, ISO, *Spitzer*, and *Akari*. COBE enabled John Mather and George Smoot to carry out research now recognized with the 2006 Nobel Prize for Physics.

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