



Frank J. Low

1933–2009

BIOGRAPHICAL

Memoirs

*A Biographical Memoir by
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FRANK JAMES LOW

November 23, 1933–June 11, 2009

Elected to the NAS, 1974

Frank Low is acclaimed as “the father of infrared astronomy.” His technical contributions enabled scientists to overcome barriers to collecting accurate data. Frank’s contributions to the field came from great enthusiasm and energy together with deep technical insight, a combination that allowed him to solve daunting problems almost intuitively. Frank was intensely competitive, but at the same time he was unfailingly generous. He founded a small company that sold his innovations and instruments to others more or less at cost. Frequently he gave them away if he was interested in the science that could be accomplished. His career was marked by many breakthroughs that enabled infrared astronomy to contribute to our understanding of stars, galaxies, and the universe.



Photography by Lori Stiles

A handwritten signature of Frank J. Low in dark ink, written in a cursive style.

By George H. Rieke

Early life and career

Frank Low was born Francis James McFadden in Mobile, Alabama, on November 23, 1933. His father died two years later, leaving his mother in modest circumstances. She married Albert Low in 1941. She had made an excellent choice in a stepfather for her son, whose name was changed to Frank James Low. As vice-president of The Austin Corporation, Albert Low had sufficient resources to send his new stepson to high-quality private schools.

Frank entered Yale in 1951 with his direction already set. He wrote:

So when I went to Yale, I had already decided to be a physicist. I came out of having the experience of learning first biology, then chemistry and then physics — which is the way it was always taught in those days — and each science was marvelous, wonderful and mind-expanding, but when I got to physics it was sort of clear that that was where it all ends up. And there isn't anything beyond physics. That's it.¹

Frank did his graduate work at Rice Institute, which he entered in 1955. He had worked the previous summer at the Shell Oil Development Laboratory in Houston, where he met Edith Morgan; they were married in September of the following year. At Rice, his thesis on “Nuclear Spin Relaxation in Liquid Helium 3” was under Harold Rorschach, a new faculty member with a specialty in low temperature behavior of helium. The thesis was completed in 1959 and was published the following year as Low & Rorschach. Judging by the number of citations, it had only modest impact. However, Frank had been forced to solve a number of challenging issues in low temperature cryogenics, a background that served him well soon after.

He took a position at Texas Instruments Central Research Laboratory (CRL) after completing graduate school. At that time, Texas Instruments was riding high. Under Gordon Teal, it had demonstrated silicon transistors just following their invention at Bell Labs. Jack Kilby had recently invented the integrated circuit, shortly after joining the company. These advances opened the way to modern electronics, and Texas Instruments took full advantage of its leadership to dominate the industry. To maintain a place at the cutting edge of technology, Teal had set up the CRL in 1955, on the model of Bell Labs. Employees were given great freedom there to pursue nearly pure research. Low decided to develop a new bolometric photon detector, exploiting the very rapid change of resistance with temperature at the superconducting edge as a sensitive temperature sensor. However, after some experimentation he decided that the transition was too



Figure 1. Low's first bolometer.
(Photo by George Rieke.)

unstable to control (a correct decision at the time, although advances in superconducting electronics have made transition edge bolometers the current state of the art). There was a lot of expertise at the CRL on semiconductors, which also have rapid changes in properties with temperature. In that era germanium was better characterized than silicon, so Frank gravitated toward using germanium as the temperature sensor for his bolometer. Things moved quickly; by late 1960, he had a working prototype, as shown in Figure 1.² Texas Instruments decided that the invention did not have sufficient commercial promise to obtain a patent, allowing Frank to promote it freely.

Frank had become aware of the shortcomings of glass cryostats during his thesis research; he had built a brass nitrogen cryostat surrounding a glass one for the liquid helium. He dealt with these issues at CRL by developing an all-metal helium cryostat. This device was not just a translation of the glass cryostats of the time into metal. He replaced the nitrogen stage completely with a carefully placed radiation shield that was in part cooled by the effluent helium gas, making a compact, efficient, and rugged package that could hold a liter of liquid helium for nearly a day.

Turning to astronomy

Texas Instruments' commercial judgment about the germanium bolometer was understandable; it required cryogenic equipment to hold it at 4K or colder, and the wavelength range over which it provided a unique advantage, 5 microns to 2 mm, is largely absorbed in the atmosphere. Even today, there are few commercial applications. Although TI was not interested, Frank wanted to find something to do with his invention. He learned about a faculty member interested in infrared astronomy at the University of Texas, 180 miles away. This was Harold Johnson, whom Frank visited in mid-1961. Harold was the best astronomy contact that Frank could have made; unlike Johnson, most astronomers have proven indifferent to opening new spectral windows.^{3,4} Johnson and Frank immediately established a close friendship and collaboration that underpinned the growth of infrared astronomy for the next decade. By February, 1962, Johnson had accepted a position with Gerard Kuiper at the University of Arizona Lunar and Planetary Laboratory, so the meeting might not have occurred had Frank not gone looking for Johnson during the remarkably narrow window of opportunity between the invention of the bolometer and Johnson's departure for Arizona.

Not long after, word reached the National Radio Observatory (NRAO) in Green Bank, West Virginia about a fellow in Texas with a very sensitive detector. It operated near a wavelength of 1 mm, the high frequency fringe of the radio range but a spectral region where the Russians were beginning to show interesting results. NRAO felt they should get into the field, since as a national observatory they should provide capabilities across the entire radio range.⁵ Frank Drake came to CRL to recruit Frank, and in 1962, the Lows (Frank, Edie, and daughters Valerie and Beverly) moved to NRAO in West Virginia. Frank was assigned an exceptionally skilled technician, Arnold Davidson. Drake later recalled that when he Frank came, "he just took over. He ran the project like he was an independent operator."⁶ Frank and Davidson experimented with a 5-foot reflector at Green Bank to develop capabilities at 1mm, but could only achieve detections of the

brightest sources such as Jupiter and the Moon.⁷ The telescope was too small and the atmosphere at Green Bank not sufficiently transparent to accomplish much astronomy.

Frank explored ways to build a bigger telescope. He reconnoitered the Newport News Shipyard, where there was a vertical lathe with a 36-foot swing, used to machine accurate ribs for the pressure hulls of nuclear submarines. It looked to Low like the perfect way to make an accurate telescope surface out of a giant billet of aluminum. Just on a chance, Drake inserted a paragraph into the annual NRAO budget to build the bigger telescope. As he remembered, “There was no discussion. That’s so weird. It was a last minute thing and it was....decided to just try it, we can’t lose.”⁸ The budget went through, but the contract for study of the concept, and eventually to build the telescope, went to the Rohr Aircraft Corporation rather than the Newport News Shipyard. The design that was implemented was a thin aluminum membrane supported on a steel backup structure; the diameter remained at the 36 feet that could have been machined at Newport News. During the machining, the tool punched through the membrane and the hole had to be welded shut; this area played havoc with achieving the desired figure. Worse, there was a fundamental design flaw; the steel backup and aluminum surface acted like a bi-metallic strip and the figure of the mirror changed with ambient temperature.⁹

While the Rohr Corporation was working on the 36-foot mirror, Harold and Frank set out in 1963 to extend stellar photometry to 10 microns. Harold was assigned two weeks to observe on the McDonald 82-Inch Telescope, right in the middle of the July rainy season. There was a huge obstacle to success, what Frank called the “mountain” of infrared radiation from the telescope. Harold knew the astronomical signal, minute relative to this foreground, could only be detected by switching the beam rapidly from the source to a nearby reference field. For this purpose, they used a cam-driven mirror near the focus of the telescope, chopping at 10 repeats per second. However, the slightest deviation from perfection in the mirror motion caused huge amounts of excess noise. To be sure it would work, Frank first perfected this system on the 21-inch telescope on Mt. Bigelow in Arizona. There was still the rain to contend with, but one night on the telescope run was beautifully clear and relatively dry, and Frank and Arnold Davidson measured 10 micron photometry of 24 stars as well as of Mars, Jupiter, Saturn, and Titan.¹⁰

In 1964, Frank (with Edie and now three children; Eric had been added) moved to Tucson, Arizona to help supervise completion of the 36-foot telescope on Kitt Peak. However, the telescope ran far behind schedule and did not make its first astronomical

observation until October, 1967. By then, the problems with its mirror had become apparent. The telescope efficiency was only 10 - 15%, meaning that the effective aperture had only been increased from 5 foot to about 12 foot relative to the Green Bank telescope. In addition to the issues with the telescope figure, the computer control system could not point the telescope accurately. Little came of Frank's efforts to use the telescope. He reported an upper limit for the galactic center¹¹ and a detection of the Orion nebula. The cause was taken up by another group with similar equipment, but their main result was that the 36-foot was not going to make many discoveries in this manner.¹² Further progress depended on development of better detectors. In total, the bolometric observations with the 36-foot Kitt Peak telescope netted less than two dozen publications and only about 700 citations.

Breakthroughs in unexplored spectral regions, such as radio, and X-ray, had occurred when pioneer experimenters had stumbled over unexpectedly bright sources; such luck was not going to favor the mm-wave region. It appeared that NRAO had built itself a white elephant. The situation was saved, however, with the detection of interstellar molecular lines, starting with carbon monoxide (CO). After that, the 36-foot telescope became one of the most productive in the history of NRAO.¹³

Once in Tucson, and with the 36-foot telescope beset with problems, Low quickly gravitated to the Lunar and Planetary Laboratory (LPL). LPL was unique; it was the only infrared-friendly observatory in the world. The Laboratory had been founded by Gerard Kuiper, who was pioneering infrared studies of planets. Kuiper had made LPL a second astronomy department at the University, rivaling the official one across the street. Frank's mentor, Harold Johnson, had joined LPL and was carrying on a vigorous program of infrared observations. In 1965, Frank accepted a research faculty position at the University of Arizona. In 1966, he was also appointed to a position in the newly formed space science department at Rice University.

An explosion of advances

Frank's migration to infrared research was marked by an explosion of advances over the next decade. He was instrumental in the development of airborne astronomy, great advances in astronomy conducted from the ground, ballooning, and thermal mapping of the moon from space, as well as development of the Infrared Astronomical satellite (IRAS).

1. Airborne astronomy

Gerard Kuiper was using the Convair V 990 aircraft at NASA's Ames Research Center to obtain infrared spectra of the planets free of terrestrial atmospheric absorption. As a result, there was general interest at LPL in astronomy data gathered from airplanes. Carl Gillespie was Kuiper's administrative assistant. Carl had served in the Navy and he used his contacts to arrange for Frank an experimental series of flights in a Navy Douglas A3 Skywarrior bomber. The objective was to measure the sun in the millimeter-wave. The approach was very simple; one of Frank's metal dewars with a bolometer was bolted to an aluminum tube that had a ball joint at the other end. The ball joint was mounted to the sextant port of the airplane so the one-inch lens that doubled as the dewar window could be pointed directly at the sun.¹⁴

Frank describes how they approached these flights: "So we carried all of our gear in a station wagon...[the] two of us, and set these experiments up, calibrated this thing, flew it, did it several times, made sure that everything repeated, and I published it."¹⁵

The experiment pioneered "open port" infrared astronomy, with no aircraft window to intervene in the view of space. However, the A3 was not suitable for a larger telescope. NASA had just purchased a Lear Jet for aeronautical research at Ames Research Center at Moffett Field. The Lear Jet design was a further development of the Swiss FFA P-16 fighter jet; it was capable of climbing above 16 km. In addition to its high-altitude capabilities, it was spacious enough to accommodate a reasonably large telescope. It was ideal for exploring the promise of airborne far-infrared astronomy.

Frank proposed to NASA to mount a 15-cm telescope in the emergency escape exit of the airplane. George Aumann, his first graduate student at Rice, used a metal wastepaper basket for illustration, and convinced Gillespie and Frank that a 30-cm telescope would fit.¹⁶ However, the performance of the telescope was very disappointing because the chopping mirror used to switch the signal on and off the detector was also switching a lot of the radiation coming from the telescope tube and the turbulence from the airplane made this signal very noisy. This problem had to be solved or there would be no airborne astronomy. Frank describes how they went about it:

[We set up the telescope] right outside the Lunar and Planetary Laboratory....There was really no need to take it up the mountain. We weren't going to measure anything...we wanted the sky noise. When we ran our conventional chopper...we were seeing huge amounts of up and down fluctuation...The telescope [secondary mirror]...was mounted firmly to

spiders. The spiders were held [with a ring]. So I loosened the screws in such a way that I could wiggle the ring up and down...And as I moved the secondary to a small angle...nothing changed." Interviewer: "Hmm. How did you get the idea?" Low: "Well, desperation. Just pure desperation."¹⁷

Modulating the signal by chopping the secondary mirror was the third key invention that Low made to enable sensitive infrared observations. Unlike the bolometer and the metal dewar, which were carefully thought through and designed, this one was made almost by chance. The virtue of moving the secondary mirror was that it allowed switching the view of the detector without changing the path of the light through the telescope, whereas the choppers mounted near the telescope focus had generated two completely separate light paths. The differential thermal activity in these two paths was the dominant source of noise.

Among other observations, the Lear Jet telescope (Figure 2) characterized the huge infrared outputs of regions of star formation, due to energy from hot stars absorbed by interstellar dust and reradiated in the infrared. It also detected similar radiation from nearby galaxies.¹⁸ This discovery led to one of the primary applications of infrared observations: they are an indicator of populations of very young stars embedded in interstellar clouds of gas and dust. The Lear Jet also was the parent of the Kuiper Airborne Observatory, with a 91.5-cm telescope, which in turn led to the Stratospheric Observatory for Infrared Astronomy (SOFIA), with a 250-cm telescope.



Figure 2. Low flying with the Lear Jet telescope.
(Photo by Philip Daly.)

2. Infrared astronomy from the ground

Initially LPL was a virtual laboratory. Frank and Harold set up shop in a storefront a mile and a half off the university campus. They made use of the 28-inch telescope put into service on Mt. Bigelow north of Tucson in 1963, and for larger glass they still managed to gain access to the McDonald 82-inch. Kuiper had secured funding from NASA for a dedicated planetary 61-inch telescope, and it started making observations on October 8, 1965. One of the early observers was Frank with his still rather crude bolometer-based photometer. Incredibly, a month later Kuiper could report that Frank had discovered that Jupiter emits more energy than it absorbs from the sun; energy trapped in its formation is slowly leaking out.¹⁹ The result was soon confirmed and the first quantitative measurements of the total emission were made observing in the far infrared from the Lear Jet.²⁰

The sky was supersaturated with discoveries to be made in infrared astronomy! Others were also leaping at the opportunities. Gerry Neugebauer at Caltech and his graduate student, Eric Becklin, found the first example of a protostar, bright in the near infrared but not detectable in the visible, lying in the Orion nebula.²¹ Frank and then-inexperienced graduate student Doug Kleinmann followed up to see if the star could be detected at longer wavelengths. It was a cold night and Frank took refuge in the warm room until Kleinmann reported that the photometer had broken and hit its limit; he could not get it on scale no matter what he tried. Kleinmann had serendipitously discovered an exceedingly bright dust cloud heated by young stars in the same area as Becklin and Neugebauer's protostar.²²

Although not all discoveries came so easily, these two examples illustrate the great potential that was finally being tapped. Once the 61-inch had been outfitted with a chopping secondary mirror, it became the premier thermal infrared telescope and held that position for nearly a decade.²³ Frank and Kleinmann used it to discover that some galaxies are very luminous in the infrared.²⁴ Frank and postdoc George Rieke opened up the study of such galaxies. They discovered the extent of the starburst phenomenon, in which the luminosity of a galaxy is dominated by young, massive stars formed over a period of only a few tens of millions of years. They also found the first examples of ultra-luminous infrared galaxies with energy outputs similar to those of quasars.²⁵

Later, Frank's focus from the ground (with graduate student Don McCarthy and others) was on techniques to obtain high-resolution imaging, including interferometry (McCarthy and Low 1975) and freezing the image motion by scanning the source image rapidly over a narrow slit.²⁶ This work ultimately took full advantage of the 6.8-m

diameter of the Multiple Mirror Telescope (MMT). The MMT concept itself grew from a suggestion by Low to build large telescopes as arrays of smaller ones, made after he visited the 4.2-meter segmented-mirror telescope being developed by Pierre Connes (Connes' telescope was ultimately unsuccessful).²⁷ When Aden Meinel was able to secure multiple 1.8-meter lightweight mirror blanks as military surplus, the concept for the MMT arranged as six independent telescopes with a combined beam took shape.²⁸ In addition to the infrared and optical capabilities of the large effective aperture, Meinel had considered how to use this arrangement for aperture synthesis. Low participated in realizing this dream through the first phased array observations.²⁹ These techniques were limited by the necessity of using single detectors, but they anticipated many of the approaches now used in adaptive optics with high performance detector arrays.

3. Ballooning

Frank's interest in infrared astronomy from balloons stemmed from a sabbatical visit by Bill Hoffmann. Following up on a number of suggestions that the interstellar dust should be heated sufficiently by stars to create a detectable far infrared signal, Bill and Carl Frederick used a bolometer and dewar supplied by Frank and a rudimentary balloon gondola and telescope to discover the far infrared emission of the galactic center.³⁰

Frank initiated his own balloon program, which eventually mapped the entire central zone of the Milky Way in the far infrared. These maps showed dramatically the interrelation between the radio and infrared emission, and measured a total of a billion or more solar luminosities of output of the young stars toward the inner galaxy. He also provided Giovanni Fazio with a telescope mirror (a reject from a ground-based 40-Inch telescope) and detectors for an ambitious far infrared balloon project. This instrument was flown repeatedly through the 1970s and produced the first set of reasonably high resolution (1 arcmin at 69 μm) maps of the center of the Milky Way galaxy and of many star-forming complexes.³¹

4. Apollo 17 infrared scanning radiometer

The moon had been an attractive target for infrared astronomers frustrated by insensitive equipment since Lord Rosse studied it in 1870. Frank and Arnold Davidson observed it when not much else was detectable from Green Bank. The culmination of their efforts was the selection of Frank as the principal investigator on the Infrared Scanning Radiometer to map the moon in thermal output on the Apollo 17 mission. The instrument was built by Barnes Engineering. The work became the Ph.D. thesis for Frank's last Rice graduate student, Wendell Mendell. The detailed maps primarily traced changes in

thermal inertia, differentiating for example old craters from young (the latter with more exposed high-inertia rock). The instrument was noteworthy for its ability to measure very cold regions with an uncooled thermistor detector.

5. The Infrared Astronomical Satellite (IRAS)

In July of 1974, NASA invited proposals for research on an Explorer class astronomy mission. It attracted 121 proposals. An all-sky infrared sky survey was selected, taking advantage of the immense sensitivity gains enabled by a cold telescope in space. Dutch scientists had also started developing ideas for an infrared space telescope, but it proved too expensive for funding within the Netherlands. In September 1974, they brought it to NASA as a possible collaboration.³² US infrared astronomers reviewed strategies at the Snowmass Ski Resort in July 1975 and recommended such an all-sky survey to precede a pointed infrared telescope.³³ Later that year an agreement was reached with the Dutch to study the possibility of a collaborative mission. In January 1977, a science working group was formed to oversee the construction of the Infrared Astronomical Satellite (IRAS), with twelve US and sixteen European members.

An underlying assumption of the project was that many of the key technologies for IRAS were already developed by the military but were not known to astronomers because they were classified. However, it turned out that the military technology was inadequate for IRAS. There were multiple reasons: the military concentrated on detecting threats with bright infrared signatures very fast, not on long integrations to reach faint sources. The two sets of detectors needed for the far infrared bands in IRAS (wavelengths longer than 30 microns) needed to be manufactured in germanium, and the aerospace firms had virtually no relevant experience with this material. Also, the aerospace contractors were not prepared for the development effort required to address these issues. When Rockwell delivered the final focal plane of detectors, it was “essentially a box of non-functional parts,” in the words of Erick Young.³⁴

NASA works most comfortably in collaboration with aerospace industry, but in this case it was the IRAS science team that had the expertise to save the mission. Frank became the leader of a technology development effort. Jim Houck at Cornell showed how to build the far infrared detectors, and then had to smuggle the detector material and the technician who knew how to use it around the NASA procedures at JPL to get flight units manufactured. Frank adapted an amplifier design developed by Rieke’s group for ground-based instruments so it could be used with IRAS, and built all the flight units at Infrared Laboratories. Erick Young recalled that although he “violated most traditional NASA flight hardware guidelines, Frank’s amplifiers worked beautifully.”³⁵

Myriad other issues were solved by members of the group— particularly Houck, Fred Gillett, Young, and Neugebauer—under Frank’s leadership. These issues included high efficiency optics, bandpass filters, and recovery from radiation effects (a last-second key contribution by Young). Nonetheless, IRAS was pushing the envelope of established technology very hard and was frequently in crisis; as a result, it was very hard on managers. One of the successful ones, Bob White, led the rebuilding of the detectors to include Houck’s and Frank’s contributions. Afterwards he reported: “IRAS was the only time in my experience where the engineers and scientists worked well together. I think they realized that without each other they would both fail, and it was a unique challenge.” This statement is remarkable, considering Frank’s chronic impatience in contrast to the innate caution of aerospace engineers.

IRAS was launched on January 25, 1983. Whether it would work was in question right up to when the fuse was lit (and even until the cover successfully detached from the telescope in orbit). Significant items (e.g. a case of Scotch) were wagered by members of the science working group on both sides of the question. In the end it worked beautifully, thanks in large part to the technology developed by the scientists. It observed more than a quarter of a million infrared sources and set the stage for the rapid advance of infrared astronomy over the next two decades. Frank took a particular interest in the discovery with this satellite of “infrared cirrus,” wispy clouds of dust tracing matter well out of the galactic plane.³⁶

After IRAS

The assumption within the infrared community was that IRAS would be followed by a cold space telescope with a suite of instruments that could study individual sources. A call for proposals for participation in this Shuttle Infrared Telescope Facility (SIRTF— later renamed Space Infrared Telescope Facility) was released as soon as the success of IRAS was apparent. Three instrument teams were selected under Houck, Fazio, and Rieke, and Frank was picked as Facility Scientist. As with IRAS, the selections included veterans of the early development of infrared astronomy who had substantial expertise in the technology.

However, competition within NASA was fierce and the Space Science budget was over-committed. Although a European mission, the Infrared Space Observatory (ISO), did get under way in 1986, SIRTF made no headway. One instrument engineer at Ball Aerospace summarized the frustration succinctly: “If it’s May, we must be redesigning MIPS [the acronym for one of the SIRTF instruments].”

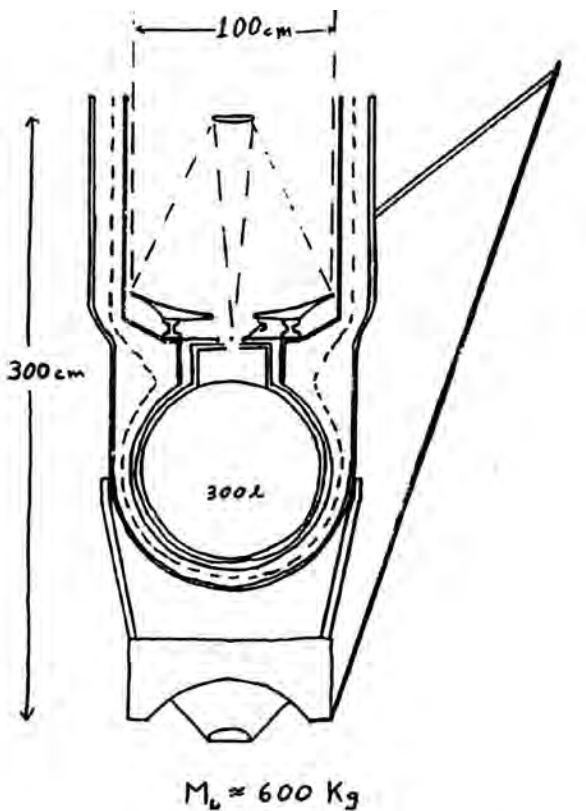


Figure 3. The helium/radiatively cooled SIRTf concept.

The SIRTf team was very resourceful. They developed seven distinct mission concepts sequentially, trying to sell something to Congress. The seventh was canceled in September, 1993. In desperation the team arranged a retreat at the Ball Aerospace Conference Center, November 6-7. On the second morning, Frank emerged with a new mission concept (Figure 3). It extended and simplified an idea for a telescope that would cool by radiation into space augmented by cryocoolers (e.g., Hawarden et al. 1992). Frank had realized that the effluent from a small reservoir of liquid helium that would cool the instruments could also cool the telescope. The instruments could operate below 2K and the telescope at 6K without resorting to cryocoolers, which at the time were not well-demonstrated for spaceflight. This concept preserved the far infrared capabilities of SIRTf but made it far smaller and less expensive than the previous version. Politically this was critical, because it allowed promoting an entirely new approach rather than the overly familiar old ones (Rieke 2006). Radiative cooling, demonstrated dramatically with the success of *Spitzer* (as SIRTf was renamed after launch), later enabled a major NASA initiative for space astronomy, the James Webb Space Telescope.

Retirement

Spitzer was approved in 1996. That same year, Frank retired from the University of Arizona. In retirement, he focused his effort on the instrument company he had founded three decades earlier, Infrared Laboratories, which also in 1996 brought out the first of a new product line of infrared emission microscopes. These devices utilized near-infrared detector arrays developed for the NICMOS instrument on the Hubble Space Telescope to identify warm areas in integrated circuits, which were indicative of incipient failures. The microscopes represented a major addition to the infrared detectors, metal dewars, and custom instrumentation that had been the product line for the company for thirty years. By 2007 Frank was noticeably failing from Alzheimer's Disease, and he died from this cause on June 11, 2009.

Frank Low's contributions were recognized through the Helen Warner Prize in 1968 (given to an outstanding young astronomer), the Rumford Prize in 1986 (for research on light or heat), the Joseph Weber Award in 2003 (for astronomical instrumentation), the Jansky Lectureship in 2006 (for contributions to radio astronomy), the Bruce medal in 2006 (for lifetime contributions to astronomy), and an exceptional public service medal from NASA in 2008. He was elected to the National Academy of Sciences in 1974.

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