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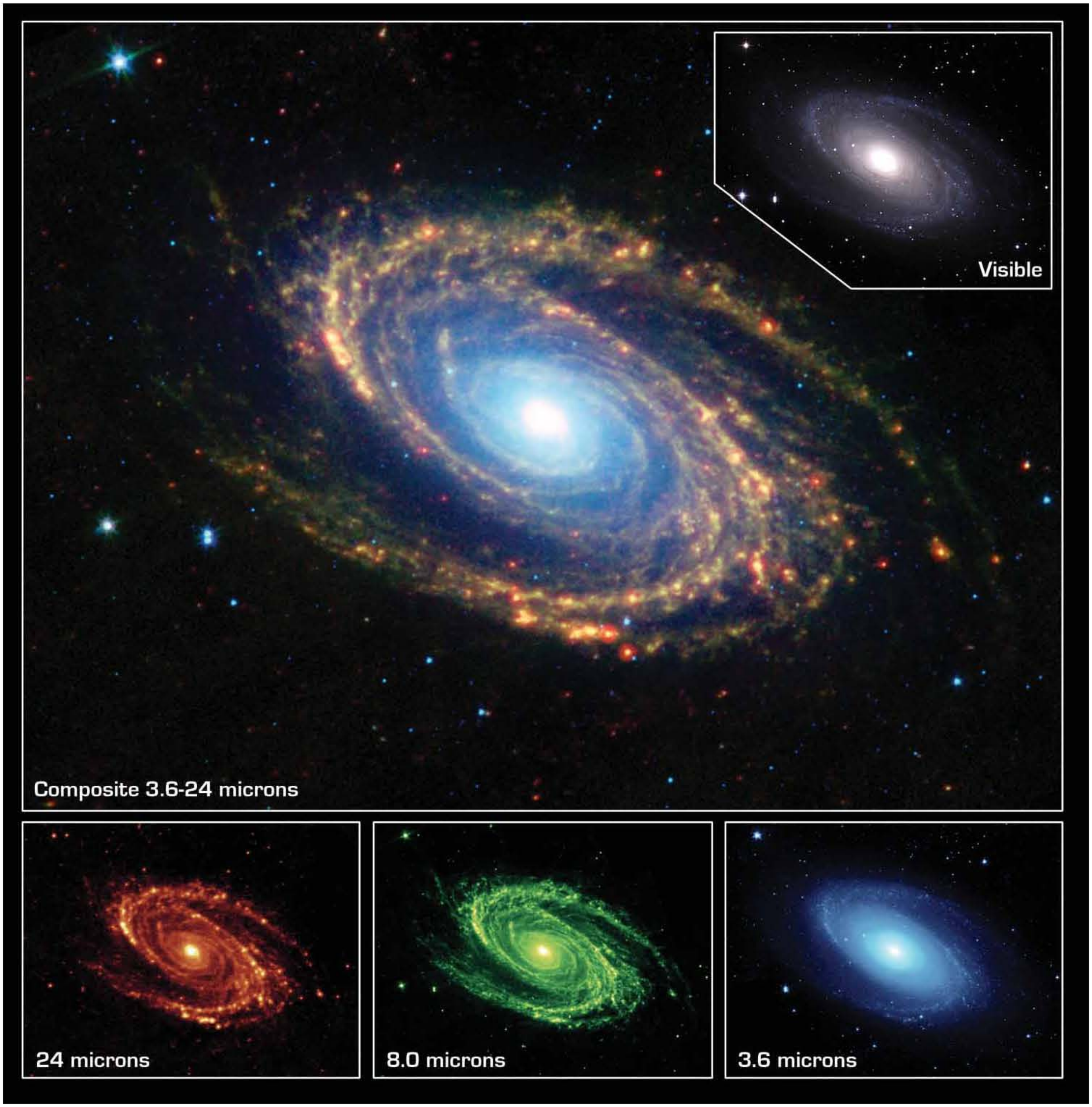


NASA/JPL-Caltech/K. Gordon (University of Arizona) & S. Willner (Harvard-Smithsonian Center for Astrophysics)

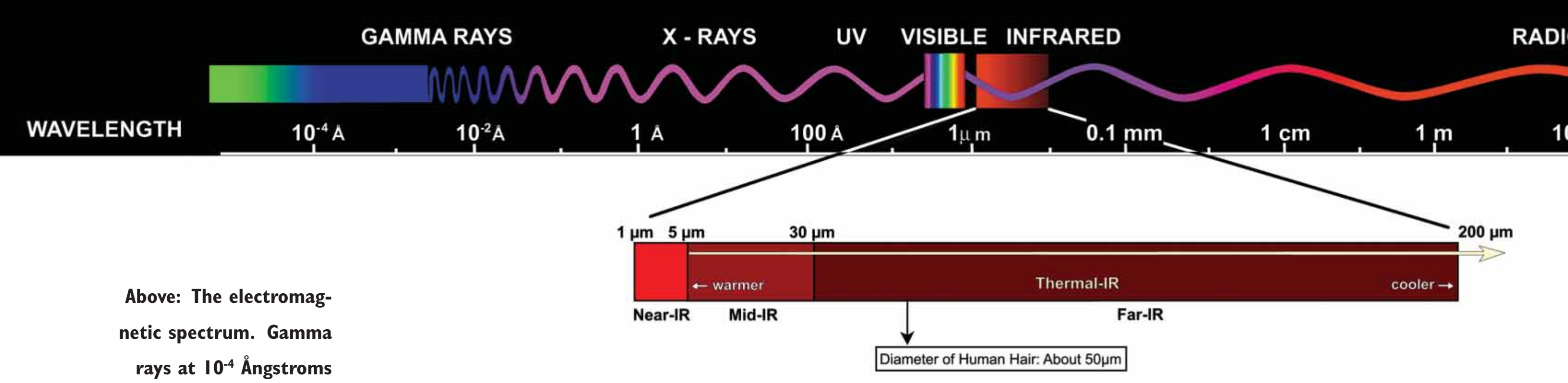
The Far, the Cold, and the Dusty

by Douglas L. Smith

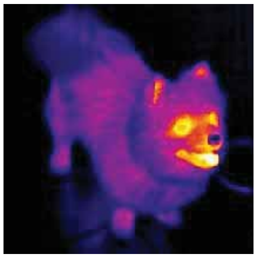
M 81, a spiral galaxy 12 million light-years away, is as big as the full moon and is easily visible through binoculars as a cosmic Fish and Wildlife Service tag on the ear of Ursa Major, the Great Bear. Being so big and near, if M 81 were Paul Newman, the Spitzer Space Telescope could see his nose hairs. In the words of the Smithsonian Astrophysical Observatory's Giovanni Fazio, "for the first time Spitzer allows us to dissect a galaxy like a kid in the biology lab with a frog." Each infrared band (insets at bottom) shows different anatomical details, and the three bands were composited to make the main image. A smooth distribution of mature stars shows up in the near-infrared (blue). Things get clumpier in the mid-infrared (green), and the spiral arms where the young stars live become more prominent. In the far-infrared (red), we see dust clouds heated from within by these stellar adolescents; the bright jewels are stellar nurseries. Besides gritty silicates chemically similar to beach sand, the dust contains organic molecules called polycyclic aromatic hydrocarbons, which, says Fazio, "are the black stuff on your toast and the burnt crud on your barbecue grill." The Spitzer can tell the difference between the two, as well as how much of each is where, and can survey the stellar demographics. Combining this with gas maps from radio astronomers will give us a much better understanding of how stars form. The visible-light image (inset, top right) is courtesy of Nigel Sharp of the Kitt Peak National Observatory.

The Spitzer Space Telescope, né the Space InfraRed Telescope Facility (SIRTF), has just released its first batch of pictures, including the stunning view of M 81 at left. The name change honors Lyman Spitzer, Jr., the Princeton astrophysicist who proposed putting a telescope in space in 1946 and who was the first to recognize that the inky interstellar dust clouds that annoyed other astronomers were worthy of study in their own right as the birthplaces of stars. The Spitzer is the fourth and final of NASA's "Great Observatories," each of which looks at a different portion of the electromagnetic spectrum, and the new name rounds out an astronomical Mount Rushmore that includes the Hubble Space Telescope, the Compton Gamma Ray Observatory, and the Chandra X-ray Observatory. The Spitzer Space Telescope is managed for NASA by Caltech's Jet Propulsion Laboratory, and the Spitzer Science Center, which will run the mission's scientific program and process and disseminate its data, is located on the Caltech campus.

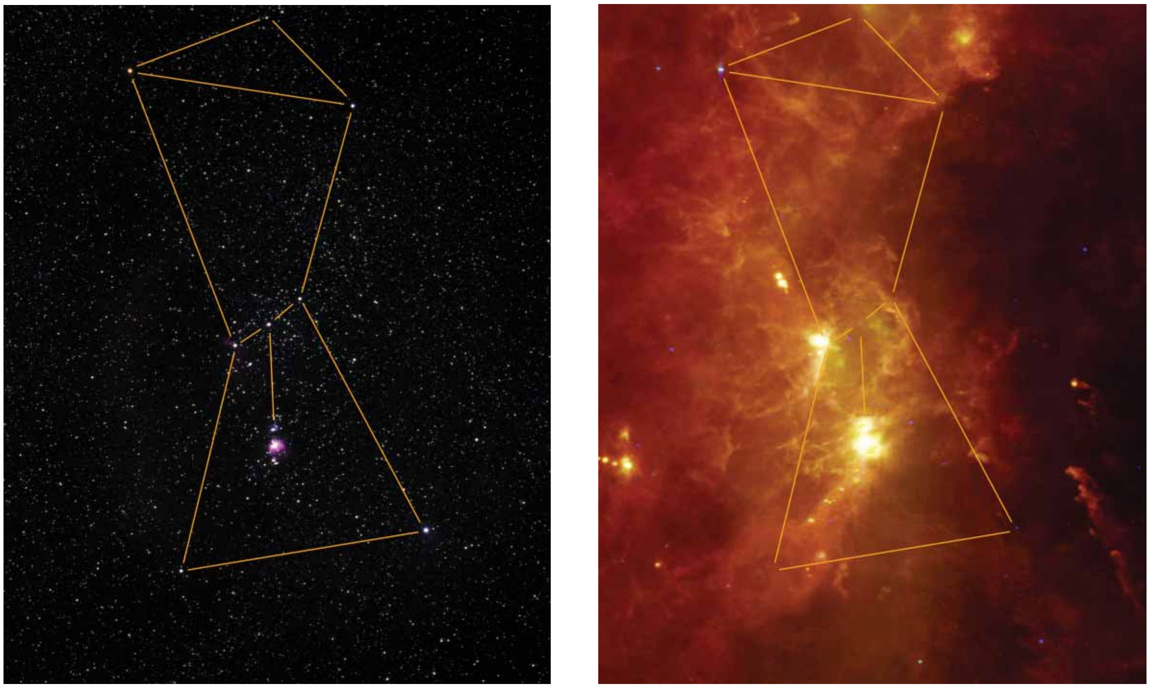
Space is the place for infrared astronomy. Most infrared light never makes it to the ground, but gets absorbed by water vapor and carbon dioxide in Earth's atmosphere. And because infrared radiation is actually heat, it's just too darn balmy here—yes, even in the Antarctic—to see much. As the University of Arizona's George Rieke remarked, "Observing in the infrared from the ground is like trying to observe in the visible with the lights still on in the dome." The telescope is looking at signals measured in quadrillionths of a milliwatt—so faint that the warmth from the tiny trickle of electrons through the camera chips themselves would mess things up, were it not instantly whisked away by the liquid-helium cooling system that keeps the detectors at a frosty 1.5 Kelvins. (Room temperature, 25°C, is 298 K; absolute zero, at 0 K, is as cold as it is theoretically possible to get.) Spitzer is not the first cryogenically cooled infrared observatory in



Above: The electromagnetic spectrum. Gamma rays at 10^{-4} Ångstroms have a wavelength about 10 times the diameter of a proton, while radio waves can run hundreds of times Earth's diameter; the infrared portion (inset) lies comfortably in the middle.



Above: Because infrared radiation is heat, things look very different. Rusty appears cold because of his nice, thick, insulating coat. But his eyes and open mouth betray his body temperature. And he's healthy—look how cold his nose is!



Right: Similarly, Orion's body has bright stars at the neck, shoulders, belt, and knees, plus two bright stars and a fuzzy blob in the sword. And infrared picture from IRAS (far right) reveals vast dust clouds from which stars are coalescing; that fuzzy blob is merely the bright nucleus of one such cloud.

space—a 1983 mission named IRAS had that honor—but it is by far the most sensitive.

Why bother? Because only in the infrared can one simultaneously see the veil of cosmic dust and lift it to look within. The dust is transparent at wavelengths beyond some 20 microns, or millionths of a meter, so you can see right through it to the nascent sun within. That's because the longer an infrared wave, the colder its source. The stuff from which stars and planets condense is very cold and radiates in the far infrared. Temperatures from a couple of hundred Kelvins up to about 1,000 K correspond to the mid- and near-infrared, say 20 to three microns; the exact spectral boundaries, like the dust clouds themselves, are fuzzy. (Your eye begins to see red light at about 0.78 microns.) The Spitzer can see suns whose visible and ultraviolet light is blotted out by the dust, and can also see brown dwarfs—stellar wannabees bigger than Jupiter but too small to start burning hydrogen.

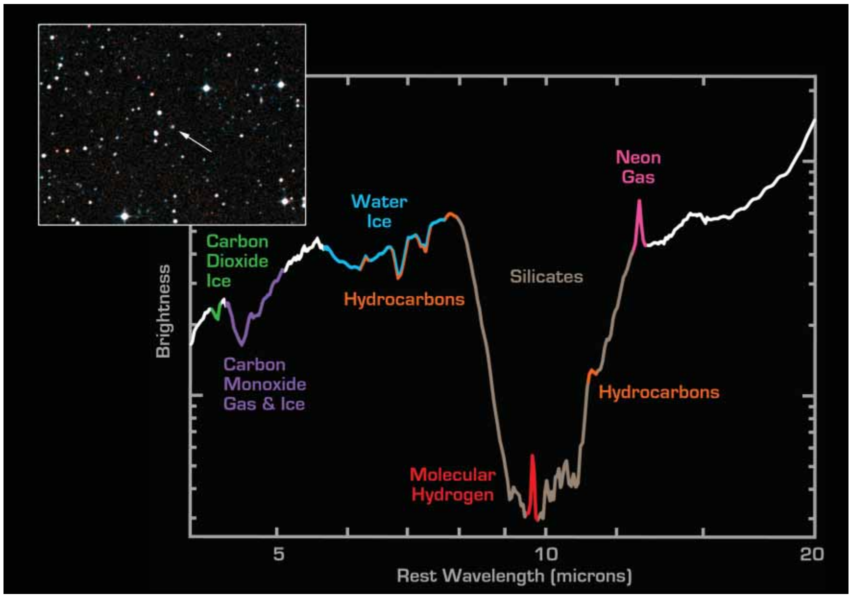
So that's the cold and the dusty. The "far" comes in because the universe is expanding, stretching the light that passes through it. Thus the light from stars in young, faraway galaxies gets redshifted down to where the Spitzer can see it. (The infrared light from their dust, meanwhile, just becomes infrareder.) And since light travels at a finite speed, looking outward in space is equivalent to looking backward in time. Galaxies close at hand also shine brightly in the near-infrared, says JPL's Michael Werner, the Spitzer project scientist, "because much of their light is produced by cool, red-giant stars. Even though a star doesn't spend much of its life as a giant, while it does, it's very luminous." By comparing galaxies at different distances and therefore ages, we can trace their life cycle.

Among the oddities to be spied on by the Spitzer are ultraluminous infrared galaxies, several hundredfold brighter in the infrared than the visible, each of whose "total energy output is

The spectrum revealed that those burnt-food hydrocarbon molecules—essential precursors of carbon-based life as we know it, in the immortal words of Mr. Spock—existed there at the same time they existed here.

Below: Spitzer's infrared spectrum, or chemical fingerprint, of the 3.2-billion-year-old galaxy IRAS F00183-7111 (the arrowed dot in the visible-light inset, from the Palomar Digital Sky Survey) shows a big dip where silicate dust absorbs most of the light from the stars embedded in it, revealing its presence. Hydrogen- and carbon-containing molecules called hydrocarbons can be seen at slightly shorter wavelengths, and as a "shoulder" in the silicate peak. Other carbon-containing molecules and various ices are also visible, none of which were visible before. And the purple peak is light emitted by singly-ionized neon, which is used to calculate star-formation rates.

This galaxy is 1,000 times more luminous than our own, rivaling quasars in its prodigious energy release. But because it's so dust-choked, something like 99 percent of its short-wavelength light gets absorbed by the dust and re-emitted in infrared.

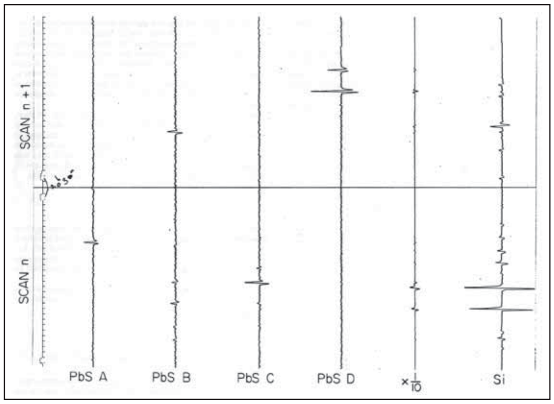


NASA/JPL-Caltech/Lee Armus (SSC/Caltech)

hundreds to thousands times that of our own galaxy," says Werner. "This energy is generated in a very tightly confined space, less than a few hundred light-years across [our own galaxy is about 100,000 light-years in diameter], and emerges in infrared wavelengths, presumably because there's some embedded energy source heating the dust. We don't really know whether that energy source is a dense starburst, a black hole, or some combination of both." Werner hopes that the Spitzer will be able to tell the difference by examining the makeup of the gas near the energy source, and in the process "study the balance between the universe's two fundamental methods of energy release that we know of: nuclear burning—the conversion of hydrogen to helium—and gravitational collapse."

The biggest science news from the Spitzer's holiday gift pack wasn't an image at all, but a spectrum of a galaxy 3.2 billion light-years away known as IRAS F00183-7111. Earth is about 4.5 billion years old, so this light started toward us around the time when terrestrial life was beginning to gel from the primordial soup. The spectrum revealed that those burnt-food hydrocarbon molecules—essential precursors of carbon-based life as we know it, in the immortal words of Mr. Spock—existed there at the same time they existed here. (Every atom and molecule absorbs or emits light at a set of characteristic wavelengths, as identifiable as fingerprints.) The European Space Agency's Infrared Space Observatory had spent a couple of hours collecting a mid-infrared spectrum of IRAS F00183-7111 in the mid-1990s. But, says Lee Armus, a member of the professional staff at Caltech, "ours is much, much better—more signal and less noise—and has a more complete wavelength coverage." And the Spitzer took only 14 minutes to collect it—one can only imagine what we'll find when the telescope *really* stares hard at something!

Whether a civilization in IRAS F00183-7111



Above: The late Robert Leighton sculpts the 62-inch-diameter epoxy mirror for the first infrared telescope in 1962. He cast it in the back of his office in Bridge Lab. The telescope, once the second largest at the Mount Wilson Observatory, was used for the Two-Micron Sky Survey (*E&S*, 1998, No. 4) and is now in the Smithsonian Museum in Washington, DC.

is looking out at us and wondering if they're alone in the universe is, of course, an open question. As James Houck, the spectrograph's principal investigator, said, "We see a bunch of bolts, screws, and maybe a horn button. That doesn't mean a car will appear soon; it just means we have found some things that are characteristic of cars."

Astronomy has come a long way since the first infrared survey, begun in 1965 by two Caltech physics professors. Gerry Neugebauer (PhD '60) and the late Robert Leighton (BS '40, PhD '47) used a simple array of eight lead-sulfide photocells to sweep the roughly 70 percent of the sky visible from nearby Mt. Wilson Observatory, collecting the data as squiggles on a strip-chart recorder. The resulting Two-Micron Sky Survey, published in preliminary form in 1969, contained 5,612 infrared sources, the vast majority of which had been previously uncataloged. One project member was an undergrad named Thomas Soifer (BS '68), now himself a Caltech physics professor and director of the Spitzer Science Center.

The photocells were surplus from the defense industry; they had been developed for the Sidewinder missile's heat-seeking guidance system. Says Soifer, "The infrared has been sort of a poor stepchild to the optical in terms of photon detection, and the major funder of infrared-sensitive chips over the past decades has been the military. But their interests stop halfway through the wavelength range we're interested in, and they don't care about the kind of very-low-light-level detection that we need. A battlefield is pretty bright, even on a dark night, and jet exhaust shows up at fairly short wavelengths."

Says Werner, "We invested a lot of time, money, and brain power in building on the infrastructure provided by the military to develop Spitzer's detector arrays. For example, previous missions' infrared spectrographs have had a small number of detectors and a lot of moving parts, so that different portions of the spectrum had to be dropped successively on the array. Our spectrograph, built by Ball Aerospace under the guidance of Jim Houck and his team at Cornell, has *no* moving parts and gets the whole spectrum at once, so we observe all of the spectrum all of the time. It's extraordinarily powerful." The multiband imaging photometer provided by the University of Arizona's George Rieke has three cameras, including what Soifer calls "the first true camera at 70 microns. It has 32 by 32 pixels, or a thousand individual sensors." At lower resolution, the instrument can see out to 160 microns. And the camera provided by Giovanni Fazio at the Smithsonian Astrophysical Observatory provides four simultaneous images at 3.6, 4.5, 5.8, and 8 microns. Each of its arrays has 256 by 256 pixels, which is not particularly large any more—technology has marched on, and ground-based infrared telescopes today have cameras in the 2,000 by 2,000 pixel range. But, says Werner, there hasn't been a corresponding increase in per-pixel efficiency—the newer chips just have more of them. And the vantage point of outer space more than makes up the difference. Says Soifer, "the cold background gives you *so* much more sensitivity. Our sensitivity is at least a factor of 10 better, and often more, than Keck at any wavelength where we take the same kind of measurement."

So it's a really good thing that the Spitzer got built, because it almost didn't. It was originally conceived in the 1970s as the Shuttle InfraRed Telescope Facility, or SIRTF—the space shuttle, remember, was going to stay aloft for up to 30 days at a time, with forty-some launches per year. In May 1983, NASA issued an "Announcement of Opportunity" for SIRTF as a multi-instrument payload-bay package to be managed by NASA's Ames Research Center up near San Jose and expected to take its first flight in 1990. (Werner, who had joined Caltech as an assistant professor of physics in 1972, had left for Ames in 1979 to

Left: A portion of the Two-Micron Sky Survey data. The eight photocells were arranged in a 2 × 4 array oriented north-south, with each pair feeding a single pen (A-D) on a strip-chart recorder. All four signals were added together and divided by 10 on the fifth channel, in case a really bright source was found. The sixth pen (Si) recorded the signal from a photocell sensitive to light at 0.84 microns, just to the red of visible, in order to see if the source would appear on photographic plates from previous surveys. The ticks along the chart's left edge mark each minute of right ascension, or celestial longitude. At the end of each scan, the telescope automatically clicked poleward by 15 minutes of declination, or celestial latitude, and reversed its direction. So the star that shows up on Channel A near the end of scan *n* reappears in Channel B at the beginning of scan *n* + 1. The position and brightness information was digitized by hand and fed on paper tape into an IBM 7094, a transistor-based computer designed for large-scale scientific calculations that could perform a whopping 100,000 multiplications per second.

become Project Scientist in early ’80s.) In retrospect, this was not a great idea, as the 12.5-centimeter InfraRed Telescope (IRT), also built by the Smithsonian Astrophysical Observatory and flown on the *Challenger* in 1985, showed that the shuttle flew in its own cloud of vapor and small particles that, while not as bad as Earth's atmosphere, was still pretty tough to see through.

In any case, SIRTF got scooped. The InfraRed Astronomical Satellite (IRAS), a joint project of the US, the UK, and the Netherlands, was launched in January 1983. In the 10 months before its 127 gallons of liquid helium ran out, it scanned more than 96 percent of the sky at 12, 25, 60, and 100 microns. It logged some half-million infrared sources in what was, at the time, one of the largest data sets ever assembled. IRAS was so successful that in September of the same year, NASA broadened SIRTF's scope to include the possibility of a free-flying spacecraft, and, in 1984, selected Fazio, Houck, and Rieke to build the instruments for what was now the *Space* InfraRed Telescope Facility. This proved to be prescient when the *Challenger* exploded in 1986, grounding the shuttle fleet. The observatory had dodged a bullet, but the firing squad was just warming up.

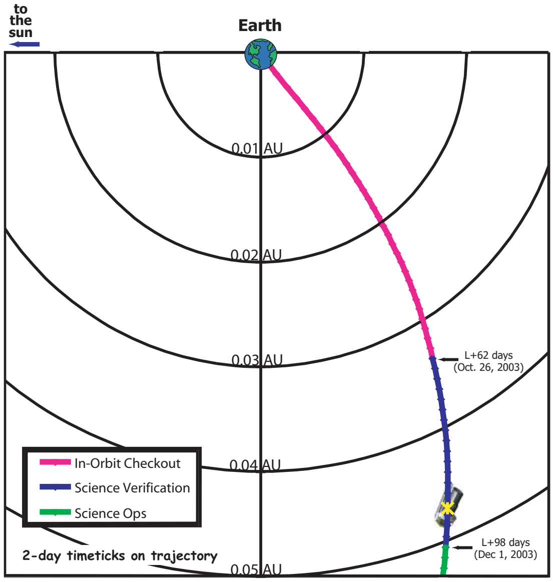
Meanwhile, back at Caltech, a special facility was being set up to digest and catalog IRAS's flood of information. JPL managed IRAS for NASA, but it made sense to move the data analysis to campus because of JPL's access restrictions and because of the intense scientific interest. It didn't hurt that Neugebauer was the American cochair of IRAS's joint science working group, and that Soifer had overseen the development of the data-processing software that turned pixels of light into catalogs and atlases. Caltech's Infrared Processing and Analysis Center (IPAC) and the Hubble Space Telescope Science Institute would serve as the model for the Spitzer Science Center.

Then in April 1990, the Hubble Space Telescope was launched; the flaw in its mirror was discovered in June. “That was our darkest moment,” Soifer recalls, “because we were about to begin the Phase B study, which is a serious commitment by NASA to industry to do the project. The Hubble spherical aberration was announced maybe a week or two before our request for proposal was to come out, and that just stopped everything in its tracks.” At that point, SIRTF was a $2.2 billion mission carrying 3,800 liters of helium, and, with a launch weight of 5,700 kilograms, would have “strained the capabilities of a Titan IV/Centaur launch, which costs another $400 to 500 million,” says Werner. That same year, NASA moved SIRTF (and Werner) south to JPL.

This second slug would probably have been fatal if not for the Bahcall report. Commissioned by the National Academy of Sciences as a road map for astronomical research for the coming decade and printed in November 1991, it was named for Princeton's John Bahcall, the committee chair. It called the ’90s the “Decade of the Infrared,” where answers were most likely to be found to the compelling questions of how galaxies, stars, and planets form and evolve, and how matter and galaxies are distributed in the universe. It went on to designate SIRTF the highest-priority mission for American astronomy in the 1990s. It was enough to keep the mission alive.

Even so, “SIRTF went into hibernation for two or three years,” Werner recalls. It was jolted awake when a third shot rang out that splintered the headboard: in August 1993, JPL lost contact with the Mars Observer just as it was preparing to enter orbit around the red planet. As a result, NASA adopted the “Faster, Better, Cheaper” mantra, and a six-ton observatory—or even the smaller, Atlas-launched version that had been developed in the interim—didn't stand a snowball's chance. “We got out of the doldrums in the fall of 1993 when two things happened. The scientists realized that we had to take the situation into our own hands, so we had a couple of retreats in which we developed this ‘warm-launch’ idea put forth by Frank Low from the University of Arizona. We also hit upon the idea of focusing on a very small number of science objectives tied into the Bahcall report—anything that wasn't required to do them was no longer going on board.”

SIRTF's luck was indeed turning, because that fall Larry Simmons, who had led the team that had successfully refurbished Hubble's Wide-Field/Planetary Camera, became the project manager. Says Werner, “He came just at the right time, and helped us turn things around a lot. He brought with him a very good team from the wide-field camera, and he really operated Spitzer as a team. That's an easy thing to say, but it's not so easy to do. He encouraged a lot of interaction within the project, and developed a culture of openness that made it easier to deal with problems when they arose. It all paid off, because he built a reservoir



Above: Spitzer undergoing final assembly at Lockheed Martin's plant in Sunnyvale, California in 2002. The solar panel, which runs the length of the spacecraft down its shiny side, is not yet in place. The telescope proper fits into the narrow upper part of the barrel, which also contains two more heat shields. The cryostat lives in the bulge in the lower part of the barrel. The eight-sided box below the barrel contains the instruments' electronics, the power systems, and the equipment that aims the telescope and communicates with Earth, and is the only warm part. Above, right: Spitzer's location on November 24, 2003. The spacecraft is now over 8,000,000 kilometers away. An AU, or Astronomical Unit, is the mean distance from Earth to the sun, or 149.6 million kilometers.

of goodwill, and then when things got tough, we could draw on that reservoir."

And they would get tough again—the project took one last hit in 1994. "Larry kept open books so everybody knew how much money everybody else was getting. So when we had to descope, *again*, everybody knew where we were, and where we had to get to, and we were able to come to agreement on how our rather skimpy reserve was to be allocated." The result led to what actually got launched—a $700 million mission that rode a Delta, carried 350 liters of helium, and weighed only 850 kilograms. "And here we are," says Werner. "*With* our original three science instruments, much modified by the passage of time. All through these delays, we were improving the core technologies. So we have a system with the same size telescope that costs, in as-spent dollars, only a quarter of what the earlier concept would have cost in 1990 dollars." Simmons's management style was so effective, says Werner, that he's been asked to write it up for future missions.

Many technological advances kept the Spitzer alive, but Low's warm-launch idea was the key. Previous infrared observatories had put the telescope as well as the camera equipment in a huge cryostat, or cold chamber—basically a giant Thermos bottle—which was chilled to operating temperature before launch. This took a big, heavy flask and a tanker truck full of liquid helium. But only the instruments really need to be kept cold, said Low, so why not launch everything else at room temperature? (This also makes the testing of the launch process a lot easier.) So the Spitzer's cryostat is just big enough for the multi-instrument chamber, where the infrared chips live, and the helium tank. After launch, the spacecraft simply loses heat to the bone-chilling void of space until it reaches the ambient temperature of about 35 K. Meanwhile, valves on the tank open at launch, allowing the liquid helium to begin evaporating and sucking any stray heat out of the

Left: The telescope itself. The primary mirror is 85 centimeters in diameter. Below: Not frat boys praying to the beer god, but technicians mounting a mock-up of the telescope on the cryostat for a vibration test. The cryostat's rounded top houses the Multi-Instrument Chamber, which is only 20 centimeters, or about two handsbreadths, high. The helium tank fills the rest of the keg.

cryostat. The coolant lines run between the telescope's heat shields as well, so once outer space has done its part the helium chills the superstructure to 5 K. It's like popping open a soda can—which are the main products of the Ball Corporation, which built the cryostat—and when the soda goes flat, the mission is over, unless a couple extra years of near-infrared work can be eked out in a "lukewarm" mode. The telescope also hides behind its own solar panel, which doubles as a sunshade, and a spiffy two-tone paint job of silver and black (any Raiders fans on the project?) reflects heat off the shiny sunward surfaces and radiates heat from the shadowed side.

The Spitzer also travels in an innovative orbit designed to conserve coolant. Why snuggle up to a nice, warm planet, asked JPL engineer Johnny Kwok, when there's an infinite deep freeze just beyond? So the observatory was set adrift, as it were, into an orbit around the sun that's slightly larger, and therefore slightly slower, than Earth's own. The spacecraft is gradually falling behind us—it's now more than 8 million kilometers away, far enough that its radio signals take nearly half a minute to reach us. When its coolant runs out in five to six years, it will be some 150 million kilometers away, and in about 60 years, we'll overtake it. Not that there would be any point in trying to retrieve it, unless perhaps the Smithsonian wants it—if detector technology has advanced so far in the last couple of decades, who knows what we'll be able to do by then?

The telescope—mirrors, supports, light baffles, and all—is made entirely of lightweight beryllium, as was IRAS's telescope before it. The slightest warping would throw the optics out of alignment, and different materials contract at different rates as they cool. "Beryllium has favorable cryogenic properties," explains Werner. "It cools down repeatably, if not predictably. So to get the mirror to the shape we wanted, we had to cool it down, watch it deform, and then polish into its surface the inverse of the deformation, so that when it cooled down next time, it would end up in the desired shape. This is called cryo-null-figuring, which had never before been done to such a high level of precision." In fact, it took two cycles of cryo-null figuring, plus a fine-focus adjustment once in orbit, to produce the razor-sharp images we're receiving.

Because of its distance from Earth, the Spitzer is being operated like a deep-space mission. The Hubble Space Telescope is in a low-Earth orbit, and we are in more or less continuous contact with it through the Tracking and Data Relay Satellite System, which also handles communications with the space shuttles and a whole flotilla of other nearby craft. But Spitzer is on its own. It gets its observing instructions once a week, and once or twice a day it disgorges the results—up to eight billion bits of data; for comparison, the Mars Global Surveyor's camera has 11 million pixels

of memory for a day's worth of pictures—in 30 minutes to an hour of talking to JPL's Deep Space Network. It's like the Voyagers' visits to the outer planets, says Werner, "but for Spitzer, every day is an encounter. We're working 24 hours a day, seven days a week." This store-and-dump data-transmission system is likely to become standard operating procedure for future observatories.

JPL sends the data to Caltech's Spitzer Science Center, where about 100 people work, for processing and distribution. (The center also manages the selection of the winning proposals for instrument time and programs their execution.) The data and its ancillary pointing and calibration information goes into one of seven "pipelines," depending on the instrument and its observing mode. The pipelines, which took five years to create, are written as modular code, so that they can easily be updated or modified as needed. Each pipeline automatically transforms the raw numbers into images or spectra, removes cosmic-ray hits, attaches the supporting information, and so on. The center processes 10 to 20 gigabits per day on a "farm" of some two dozen high-end workstations, says Member of the Professional Staff Lisa Storrie-Lombardi, "and the drones write their output to the 'sandbox,' which is six terabytes of online disk space, for a human to look at it before it goes to the archives." A terabyte is a trillion bytes; 6 terabytes would store about 13 million snapshots from that cool little digital camera you got for Christmas.

Half of the first year's observing time—more than 3,000 hours—will go to six so-called Legacy Projects organized around the themes of the Bahcall report. These projects are large surveys—sets of atlases, really—that will be published on line immediately for all to use. In a radical departure from standard astronomical practice, Soifer eliminated the proprietary period during which only the scientists who did the work get to look at the data—usually for a year after it's been processed and delivered. Furthermore, the Legacy teams have agreed to repackage all the data into large mosaics, label each celestial feature by its position and brightness, catalog it, cross-reference it to previous catalogs, and generally make the work as useful as possible.

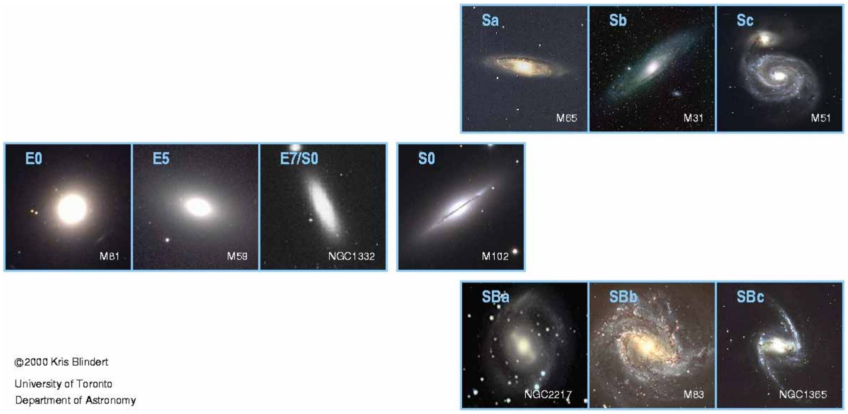
So why would anyone want to clean the stables when everyone else gets to ride the horses, too? Replies Soifer, "That's a very good question, and one that I had to struggle with in order to make these projects attract really good people. I found two answers. Number one is the chance to be in the driver's seat, defining the program—as you know, all of us astronomers believe that we have the best ideas and know best how to advance the field. And the other motivation is that these projects are well-enough funded to not only do the service work of producing these refined, processed catalogs, but also to hire grad students and postdocs and do breakthrough science along the way. We expect that. We understand that. We *want* them to do the science that motivates the service work."

About 1,000 hours' worth of Legacy data should be on line by May, and the balance six months later. Here's a quick look at each project, starting with the farthest reaches of the universe.

The Great Observatories Origins Deep Survey, or GOODS, led by Mark Dickinson at the Space Telescope Science Institute, will peer out to the limits imposed by the telescope's diameter. GOODS will revisit the region near the Big Dipper that Hubble stared at for 10 consecutive days back in 1995 to make the so-called Hubble Deep Field image. Chosen for its apparent emptiness, it proved to contain hundreds of galaxies, from 2.5 to about 12 billion light-years away. In the southern celestial hemisphere, GOODS will look at the Chandra Deep Field, where the X-ray telescope fixed its eye for 278 hours and which Hubble has since surveyed as well. The GOODS observations will be combined with ground-based ones to trace how galaxies evolved from the relatively small aggregations of stars we see beyond about eight billion light-years to the giant galaxies like our own that we see today. Says Werner, "We can't follow a single galaxy, but we can look at different redshift slices to learn how galaxies grow and age, which is not yet very well understood. At almost all epochs we can see what appear to be fairly mature and well-developed galaxies coexisting with obstreperous infants."

In the middle distance, the Spitzer Wide-area InfraRed Extragalactic survey, SWIRE, led by IPAC's Carol Lonsdale, will do "what for Spitzer is a shallow survey," says Soifer. "But it's still far deeper than anything else that has ever come about." SWIRE will go out to a redshift of 2.5, or about 10 billion years ago, encompassing the universe's peak star-formation period, says Soifer. "Most of the action happened between now and back to a redshift of about 2, or nine billion years ago. This will complement work by Professor of Astronomy Chuck Steidel [PhD '90] and others, who are looking at redshift 3 and beyond, before star formation slipped into high gear." Like GOODS, SWIRE will collaborate with telescopes on the ground. SWIRE will cover about 50 square degrees, or roughly 250 times the area of the full moon, and is expected to reveal some two million new galaxies, or a staggering 40,000 per square degree.

Locally, SINGS, the Spitzer Infrared Nearby Galaxies Survey, helmed by Robert Kennicutt Jr. of the University of Arizona, will take extreme close-ups of 75 large, nearby galaxies, like the shot of M 81 at the beginning of this article. These intimate portraits were chosen to represent all parts of the Hubble sequence, which is sort of a periodic table of galaxies. SINGS will also collect detailed spectral data with anatomical precision,



Left: A portion of the Hubble Deep Field. Almost everything you see is a galaxy—the two things that look like starbursts are, in fact, foreground stars in our own Milky Way. The entire Deep Field covers a patch of sky the diameter of Roosevelt's eye on a dime held at arm's length.

Above: The Hubble sequence was invented in 1936 by Edwin Hubble, who based his classification scheme on a galaxy's apparent shape—elliptical, spiral, or irregular (not shown). Elliptical galaxies go from E0 (almost spherical) to E7 (very flat). Lenticular galaxies (S0) are intermediate between ellipticals and spirals. Spirals range from Sa to Sc as their arms become less tightly wound and their central bulges become smaller. Hubble also distinguished between normal spirals and barred ones (SB) that have a prominent bar through the central bulge to form shoulders for the spiral arms. (Graphic courtesy of Kris Blindert.)

inventorying what chemicals are present where and in what quantities, and mapping the dust distribution and measuring how brightly it shines. "We'll examine places that are in different stages of the star-formation cycle to try to identify what distinguishes each phase, and learn how the dynamics of the process work," explains George Helou, deputy director of the Spitzer Science Center and a SINGS team member. By looking at a collection of face-on galaxies, SINGS hopes to figure out how bursts of star formation propagate—do they get triggered by something and then radiate like the ripples from a pebble dropped in a birdbath, as is thought to happen in the arms of spiral galaxies? Or do stars just break out all at once all over the place like that birdbath freezing up, as may happen in ellipticals? And what factors inhibit the process, or even shut it down? "Why do some galaxies experience one big burst of star formation," Helou asks, "then go to sleep for the rest of the ages? Why do others experience repeated episodes, and others yet a more steady rate?"

In our own galaxy, the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE—"They really worked hard to get an acronym," observes Soifer), with the University of Wisconsin's Edward Churchwell in charge, will answer an age-old question once and for all by counting all the stars in the Milky Way. Well, most of them, anyway—the Spitzer can't look directly at the galactic core, says Soifer, "because it's just too bright, even with our very shortest integration times." But in the portion of the galaxy that they will see, GLIMPSE will inventory every last star in all stages of life, from dusty fetuses to dying cinders—over 100 million sources are anticipated, which will map the Milky Way in unprecedented detail. Even though it's our own galaxy, we're still unclear on such basic questions as how many spiral arms it has, or whether there's a bar in the central region. At visible wavelengths, we can't see through to the other side for the dust in the middle, and previous infrared surveys weren't always fine-grained enough to distinguish between nearby things and ones along the same line of sight but on the far side of the galaxy.

The final two Legacy projects will look very close to home. They will follow, with unprecedented acuity, the process by which a cloud of gas and dust collapses, turns into a star surrounded by a disk of material, and eventually evolves into a solar system. The dividing line is basically at the birth of planets: Neal Evans from the University of Texas heads a project called From Molecular Cores to Planet-Forming Disks, and Michael Meyer of the University of Arizona runs one called Formation and Evolution of Planetary Systems. Geoffrey Blake (PhD '86), professor of cosmochemistry and planetary sciences and professor of chemistry, and Professor of Astronomy Anneila Sargent (MS '67, PhD '77) are members of the

Evans team, which is examining embryos up to about three million years old, such as Herbig-Haro 46/47, at right. And Assistant Professor of Astronomy Lynne Hillenbrand is on the Meyer team, which picks up from there and runs out to a billion years or so. Fomalhaut, bottom right, is an example—the ring of dust surrounding it suggests that planets have already formed in the hole.

But first things first. Soifer has an allotment of what's known as Director's Discretionary Time, and he's called dibs for the First Look Survey. The idea is to find out what the Spitzer's sharp eyes can see, so that other folks can plan their own observations. So in the first two weeks of December, Storrie-Lombardi's team aimed the telescope for 60 hours at four square degrees in the constellation Draco, about midway between the dragon's beak and its belly, in a kind of mini-SWIRE. Like SWIRE, First Look is collaborating with ground-based observers to get as much correlated information as possible, with telescopes at Kitt Peak and Palomar, and radio dishes at the Very Large Array, pitching in. There's a First Look at our galaxy as well, in which a group led by Member of the Professional Staff Alberto Noriega-Crespo took a sweep across the galactic plane in order to examine the galactic halo. They also probed a molecular cloud—a dense region of hydrogen, helium, and other gases from which stars condense—named L1228 that lies between Draco and Cepheus. And Victoria Meadows' group of First Lookers joined ground-based observers on an asteroid hunt.

The entire endeavor has been an excellent example of cooperation between JPL and Caltech, says Werner, "which is something that everybody recognizes as being a good thing in the abstract, but you can't just have {JPL director} Charles Elachi or {Caltech president} David Baltimore get up on a soapbox and say, 'There Shall Be Cooperation Between Caltech And JPL.' It only happens when there's a project like Spitzer that brings out the best in both organizations." Adds Helou, "The Spitzer Science Center will be crucial to the mission's ultimate success by making large-project resources accessible to the small-science researcher. Spitzer will reveal a new universe and rewrite the astronomy books, and it's appropriate for Caltech and JPL to lead a project that represents NASA at its best." ☐

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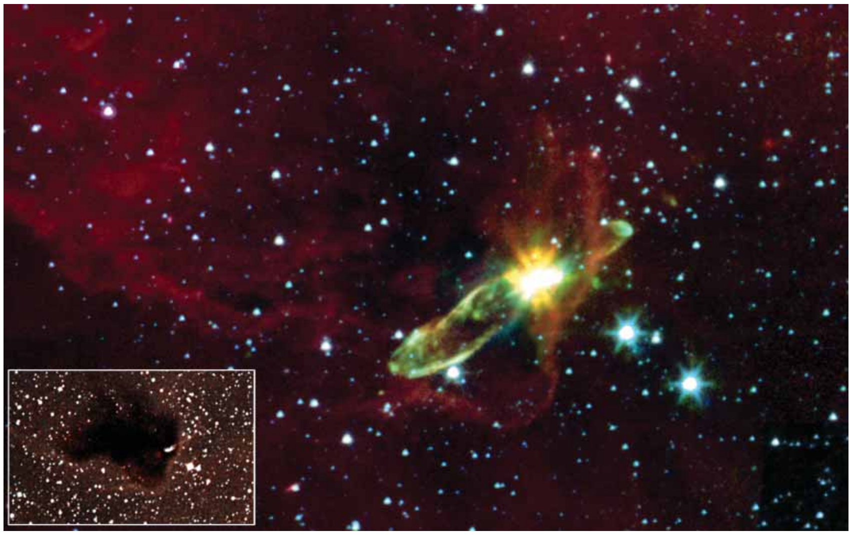
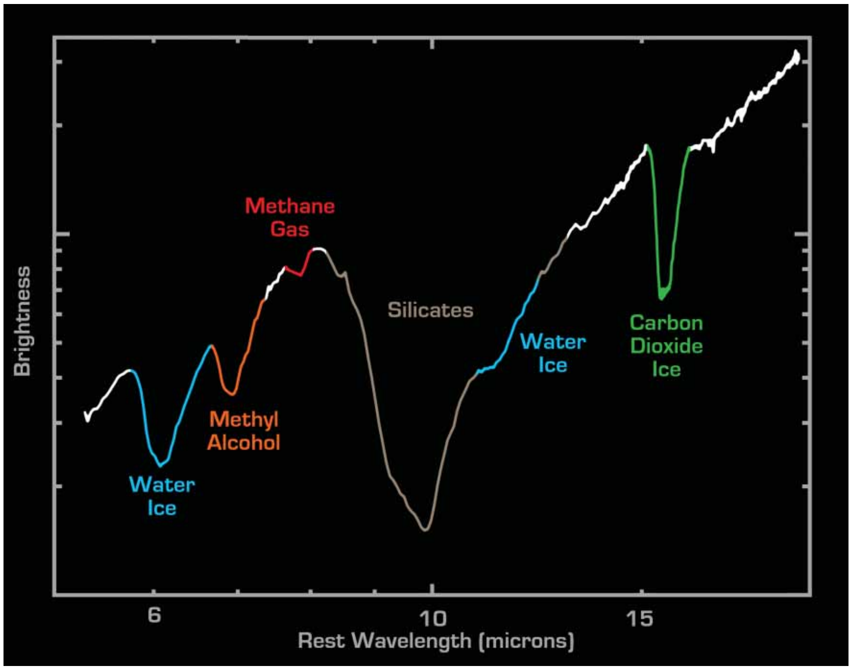


NASA/JPL-Caltech/Alberto Noriega-Crespo (SSC/Caltech)



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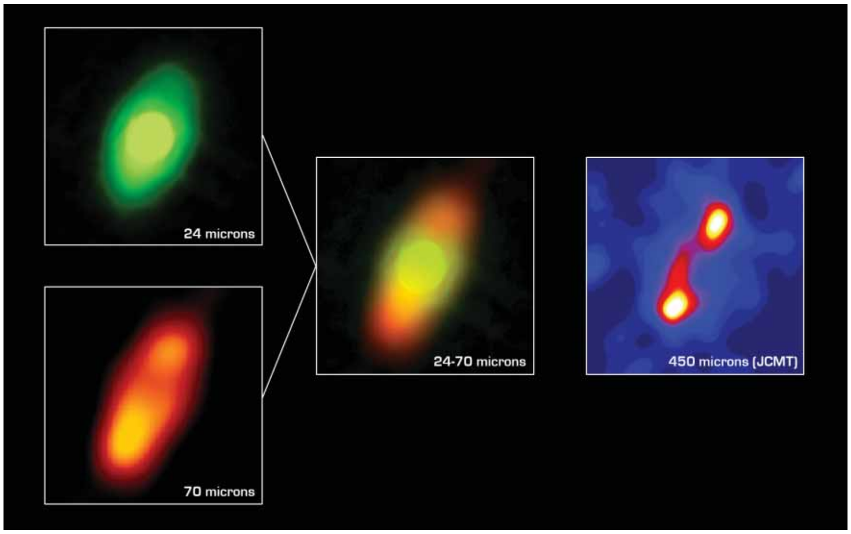
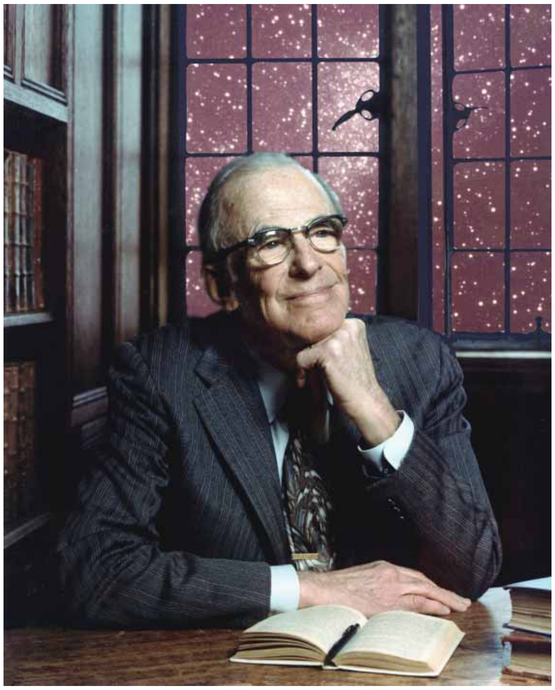


NASA/JPL-Caltech/Karl Stapelfeldt (JPL)

Top: Herbig-Haro 46/47 is 1140 light-years away in the constellation Vela, the Veil. In visible light (again, from the Palomar Digital Sky Survey) all you see is inky crud, which to Spitzer's eye at eight microns becomes a wispy cloud (red) marking where supersonic gas ejected by an embryonic star collides with the interstellar medium. The near-infrared reveals two previously undiscovered jets of gas (yellow-green) shooting out in opposite directions from the protostar. These jets emerge from a star's poles as part of the same processes that create a planet-forming disk around its equator—our sun probably had a similar pair once upon a time. In this composite image, 3.6-micron light is blue, 4.5 and 5.8 are green, and 8.0 is red.

Middle: The deep absorption feature for silicates shows the dust cocoon is really thick, and the dry-ice (carbon-dioxide ice) one shows it's pretty cold.

Bottom: Fomalhaut, the 18th brightest star in the northern-hemisphere sky, is only 25 light-years away. IRAS discovered that Fomalhaut was much brighter in the infrared than it ought to be, but couldn't tell if a disk of dust accounted for the excess. Later microwave observations (right) found a dust ring 56 billion kilometers in diameter—nearly five times the size of our solar system—hinting that planets may have already formed, sweeping the inner region clear. Now Spitzer has taken Fomalhaut's first infrared portrait (center composite). At 70 microns (bottom left), the ring's southern lobe is revealed to be one-third brighter than the northern—perhaps the wake of a comet being pulled into the inner solar system, or the debris from a recent collision between two moderate-sized asteroids. At 24 microns (top left), a faint cloud of warmer (dry-ice temperatures) dust fills the ring all the way in to about the orbit of Saturn, and possibly closer. This dust is thicker than our own so-called zodiacal cloud, but may come from the same source: comets visiting the inner solar system. Or it may be the debris of planetary formation. The submillimeter image was made at the James Clerk Maxwell Telescope.



Astrophysicist Lyman Spitzer, Jr. (1914–1997) contributed to stellar dynamics, plasma physics, and thermonuclear fusion as well as space astronomy. He earned his PhD from Princeton in 1938, and returned in 1946 after helping develop sonar during World War II. He spent the rest of his career there.

That same year, more than a decade before the first satellite was launched and twelve years before NASA was formed, he proposed an orbiting observatory that would be able to see a wide range of wavelengths unblurred by Earth's atmosphere. He would work for the next 50 years to make this vision a reality. His efforts led to the ultraviolet-observing Copernicus satellite, which he helped design in the early '60s, and the Orbiting Astronomical Observatory, which he shepherded through Congress (and past a bunch of reluctant scientists, who were afraid the expense would soak up all federal funding for astronomy) in the mid '60s. He would do this again for the Hubble in the early '70s.

*Spitzer was the first to study the interstellar medium—the gas and dust between the stars—and the magnetic fields therein. He literally wrote the book on the subject—*Diffuse Matter in Space*, published in 1968. He was among the first to suggest that the bright stars in spiral galaxies had recently formed from this stuff, and predicted the existence of a hot halo surrounding our galaxy.*

In 1951, Spitzer founded the Princeton Plasma Physics Laboratory. His Physics of Fully Ionized Gases*, published in 1956, is still a standard reference text, and he led Princeton's effort to harness nuclear fusion as a clean source of energy.*

His numerous honors included NASA's Distinguished Public Service Medal and the Crafoord Prize, equivalent to a Nobel in astronomy.