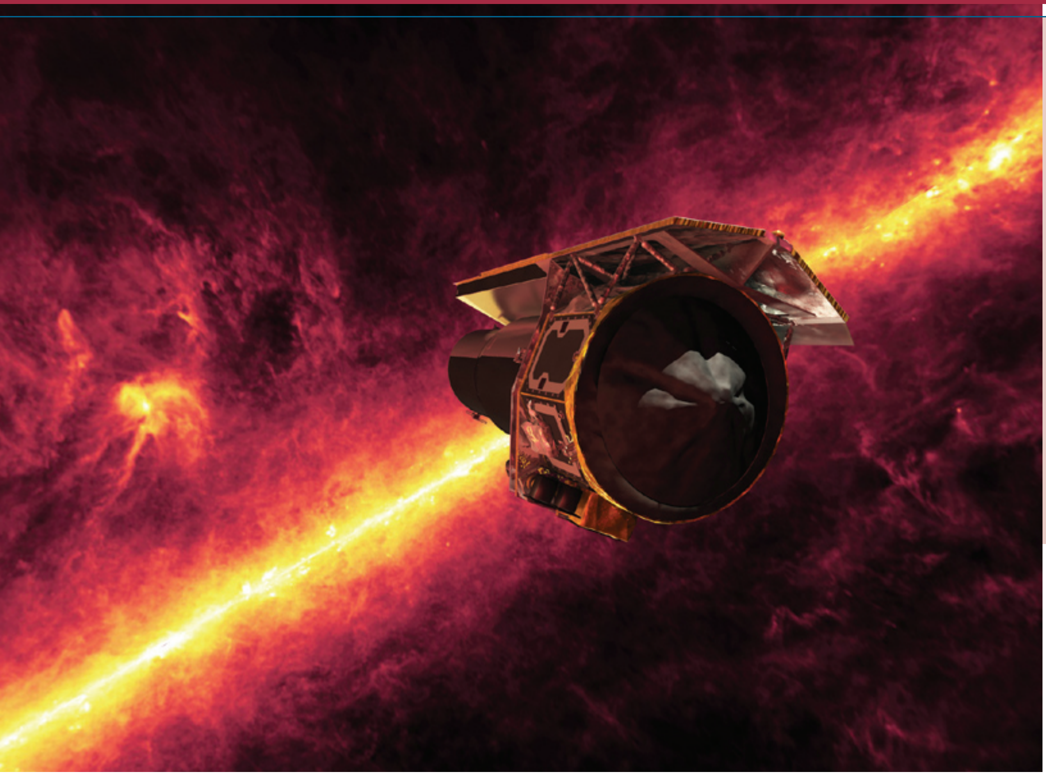
# Spitzer Warms to the Task



Spitzer in the infrared heavens, looking at a star-forming region called Rho Ophiuchi. The band of light is dust in the Milky Way glowing at a wavelength of 100 microns.

The Spitzer Space Telescope ends its primary mission when the last of the liquid helium used to cool its infrared detectors runs out. Here's a look at just a few of the observatory's accomplishments, and a quick preview of what lies ahead as Spitzer moves into the extended "warm" mission.

Things are getting a little balmy for NASA's Spitzer Space Telescope. After almost six years, the infrared observatory's liquid mojo, its coolant, will run dry any moment now. But don't reach for the Kleenex—it will continue to peruse the cosmos in a "warm" mode for at least two years, with one of its three instruments still usable. (Incidentally, the so-called warm mode is still quite chilly. For most of the mission's life, it has been a frosty 1.5 kelvins—nearly absolute zero, or the temperature at which all atomic motion ceases. The warm mode is 25–30 kelvins—still far more glacial than an ice cube, which freezes at a toasty 273 K.)

Spitzer's frigid life has warmed the hearts of astronomers around the globe. "Spitzer has been enormously productive and gratifying," says JPL's Michael Werner, Spitzer's project scientist. JPL manages the mission, and the Spitzer Science Center, which schedules observations and processes and disseminates the data, is on the Caltech campus. "For those of us who work on it, as Bobby Rydell sings, 'Every day's a holiday, and every night is Saturday night.'"

Spitzer's launch, in August 2003, ended a nearly 30-year journey to get the telescope off the ground—a circuitous trek around budget cuts and other roadblocks that involved four top-to-bottom redesigns into successively smaller, less-costly spacecraft. [See *E&S* 2003, No. 4.] All that rethinking has proved to be good thing. The spacecraft has operated incredibly efficiently, filling the plates of astronomers from an all-you-can-eat buffet of data guaranteed to give overindulging grad students heartburn for years to come. The mission's sweetest treats include making the first direct measurements of light from planets circling other stars, finding signs of planets in very strange places, creating a new map of our Milky Way, and unmasking hundreds of "missing" black holes.

The carving knife, serving fork, and slotted

By Whitney Clavin

spoon that serve our astronomical gastronomes are a short-wavelength infrared array camera, a long-wavelength multiband imaging photometer, and an infrared spectrograph. These three instruments together span wavelengths from 3.6 to 160 microns (millionths of a meter) in the infrared region, which we humans can't see—infrared light lies just beyond red in the rainbow, starting at about 0.78 microns. Humans perceive infrared radiation as heat, and that's what it is: objects that are too cold to glow visibly shine in the infrared. Equally importantly, unlike visible light, infrared wavelengths are just right to sneak through much of the dust that chokes our galaxy and blocks our view. Thus Spitzer can have its cake and eat it, too. Depending on the wavelength being observed, the telescope can both see the dust that envelopes newborn stars and cloaks the farthest galaxies, or see through the dust to the stellar nurseries and other objects hidden within. Spitzer pries open the cold and dusty places where the universe's "dirtiest" secrets hide.

## WEATHER ON EXOWORLDS

Millennia from now, when orbiting observatories litter the sky like space junk, Spitzer will ultimately be remembered for its pioneering research on exoplanets, planets circling stars beyond our sun. Spitzer is the first telescope to ever see the actual light from an exoplanet—an accomplishment that took everyone by surprise. "I was astonished that Spitzer could do this," says Werner. "We had no idea that this would be possible when we were designing and building it."

The first exoplanets were discovered in the early 1990s, well before Spitzer's launch, and now more than 350 are known. Astronomers typically learn of these alien worlds indirectly; for example, the most common planet-hunting tool is the radial-velocity technique, in which a planet is detected via the friendly tug it exerts on its parent star. The wobble is seen as a subtle shimmy in the position of the star's spectral lines. Most of these planets are "hot Jupiters"—portly balls of gas so close to their suns that their temperatures can be as high as 2,300 K. The tighter the orbit, the faster they go, so these hopped-up heavyweights whip feverishly around their stars in just days. Their masses make them easier to detect, but their speed helps too—since they complete each lap in a short time, you don't have to watch very long for them to betray their presence.

When it comes to telescopes, bigger is usually better. Bigger mirrors catch more light. How then did Spitzer, with its relatively small, 85-centimeter primary mirror, see the shine of planets that bigger telescopes had not? The trick is to watch an exoplanet pass in front of, then disappear behind, its star. Currently, astronomers know of several dozen planets whose orbital planes just happen to be oriented edge-on to our point of view.

When a planet passes in front of its star, an event called a transit, some of the star's light travels through the planet's atmosphere en route to us. By comparing the starlight when the planet is in the way—like a rude moviegoer walking in front of the screen—with the starlight when the planet has taken its seat, as it were, astronomers can identify atoms in the planet's atmosphere. This is possible because every chemical has a unique spectral "fingerprint," absorbing a specific pattern of wavelengths of light—in this case, the light of the star shining through from behind. (NASA's Hubble Space Telescope first used this technique to identify sodium, carbon, and oxygen in a hot Jupiter called HD 209458b.)

Spitzer, on the other hand, can also watch planets slip around behind their stars. First, the total light from the star and planet is measured, followed by the light of just the star as the planet disappears from view. By subtracting the star's light from the system's combined light, astronomers are left with the

This false-color Mardi Gras mask is two galaxies, NGC 2207 and IC 2163, caught in the act of merging. The blue eyes are the galaxies' cores. Spitzer discovered the mask's strings of pearls, glowing red—dusty clusters of newborn stars that formed when the galaxies began their embrace 40 million years ago.

planet's contribution. The method works because planets, particularly hot Jupiters, are relatively bright in the infrared, where they yell, "Hey, look at me!" This lets us identify chemicals in a planet's atmosphere directly, and even take its temperature. Every body, including human ones, radiates over a range of wavelengths, and the colder the body, the longer the wavelength at which it emits the most energy. These ranges of wavelengths—so-called black-body curves—let astronomers act like exoplanet weathermen.

Not surprisingly, the weather varies widely from planet to planet. Some have split personalities—for example, a team led by Joseph Harrington of the University of Central Florida, and including Brad Hansen (PhD '96) of UCLA and six colleagues, measured a whopping 1,400-K temperature difference on the two faces of Upsilon Andromedae b. This planet, like all hot Jupiters, is thought to be tidally locked. Like our moon, it always presents the same face to the body around which it orbits. In this case, one side perpetually boils in its star's heat, while the other side never sees the light of day.

Other hot Jupiters are more even-keeled. Take HD 189733b, which has fairly uniform temperatures globally, though it too is locked in place. The team that made this discovery, led by Heather Knutson of the Harvard-Smithsonian Center for Astrophysics, included her Harvard colleague David Charbonneau, a former Caltech postdoc; Adam Showman (MS, PhD '99) of the University of Arizona at Tucson; Tom Megeath (BS '86) of the University of Toledo; and five other collaborators. They concluded that atmospheric circulation must carry the heat from the planet's sunlit side to its dark side, and forecast steady, supersonic winds of some 36,000 kilometers per hour. Chicago seems becalmed by comparison.

Spitzer also witnessed the fiercest storm ever seen. HD 80606b—a wildly eccentric planet whose orbit shuttles it nearly as far out from its star as Earth is from our sun, then back in to a distance much closer than from the sun to Mercury—was found to have a temperature swing of more than 700 K over the six hours when it passed closest to the furnace. Computer models predict this extreme heating triggers winds on the order of 18,000 kilometers per hour. The planet's rotation—HD 80606b is not tidally locked, rotating some 65 times per orbit—would curl these winds into megahurricanes that could toss all of Florida into Louisiana.

## PALE BLUE DOTS

Just as biologists began by collecting trays of insects on pins and then moved on to classifying and studying individual species, astronomers are now sorting and cataloging populations of exoplanets. "This is brand-new science," says Werner. "At this early stage, the differences between our specimens loom larger than any underlying similarities." In a few years, NASA's James Webb Space Telescope will saunter onto the scene, and we'll get an even better look at many more specimens. The Webb should be able to pick out cooler gas planets farther from their stars, and possibly even analyze the atmospheres of planets only a few times larger than Earth.

But finding pale blue dots like our own will require different sets of eyes. Kepler, whose development was managed by JPL, was launched on March 6. [See Random Walk, page 6.] Kepler will look for Earth-sized planets in the habitable zone—that perfect-day-at-the-beach part of a solar system where water is liquid—by watching 100,000 nearby sunlike stars for the periodic dimming due to transiting planets. After clocking the intervals between several transits, a process that will take a few years, Kepler scientists will be able to calculate each planet's orbital period and determine whether it is basking in the warm glow of the habitable zone.

Kepler won't do spectroscopy on the planets' light, however—that job will fall to NASA's Terrestrial Planet Finder (TPF), now in the very early stages of development at JPL. TPF's mission is to photograph small, rocky, Earth-like worlds and look for chemical signs of life in their atmospheres. The giveaway will be finding oxygen, water, and methane coexisting: water and oxygen for obvious reasons, and methane because it can be a metabolic byproduct. (See the SETI article on page 12 for more about this.) "The exoplanets we've been able to study in detail so far certainly don't have any beachfront property to buy up," says Charles Beichman, the executive director of Caltech's NASA Exoplanet Science Institute and a Spitzer scientist. "But we will build on these studies to search for life in the universe."

## PLANETS HERE, THERE, AND EVERYWHERE

For those of you who gaze up at the stars and hope with all your hearts that friendly little green aliens do exist, Spitzer has good news. It didn't discover life, or habitable planets, but it has revealed that building planets is as easy as growing weeds; and if planets are ubiquitous, chances are pretty good that life is too. Planets, like dandelions, crop up in the darnedest places—the infrared glow of planetary dust gives them away. Dust is a lot easier to see than a planet, because dust has more total surface area. Imagine that you're standing in the end zone at the Rose Bowl, and a pal under the

Top: This dusty star-forming region, called W5, covers four full moons' worth of sky in the constellation Cassiopeia. The two caves were hollowed out by the radiation pressure and stellar winds from the bright blue stars in their centers; this compression triggered a second burst of star formation—the pink dots on the tips of the dust pillars. A third wave of star formation is now happening in the white knotted regions. Right: A simulation of the swirling winds on the night side of HD 80606b after its closest approach to its star, based on Spitzer temperature data. The frames are spaced six hours apart.

Planets, particularly hot Jupiters, are relatively bright in the infrared, where they yell, “Hey, look at me!”

opposite goal posts is holding up a stick of chalk. You’d really have to squint to see it . . . if you could make it out at all. But if your friend used that chalk to color in an entire chalk board, the white rectangle would be as plain as day.

Luckily for astronomers, planetary systems are dustier than the floor underneath your bed. As stars form, swirls of gas and dust begin to take shape in the so-called protoplanetary disks surrounding them. Denser regions—dust bunnies—become the seeds of planets. These seeds collide, sometimes sticking together to form larger bodies called planetoids. The planetoids, in turn, keep running into each other. Gentle fender benders result in mergers, eventually leading to full-grown planets. More violent encounters shatter the planetoids, forming debris disks of fresh dust.

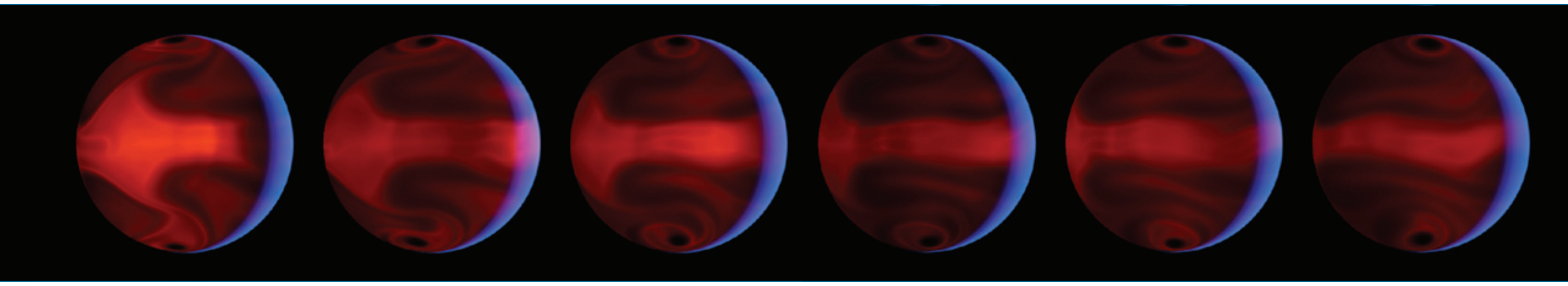
Planets and debris disks can coexist, and the disks may be handy signposts for future planet hunters. Spitzer surveyed 26 nearby sunlike stars known from radial-velocity studies to have one or more planets, and found faint debris disks around six of them. These disks were 10 to 100 times thinner than protoplanetary disks—what Beichman, the study leader, calls “leftover piles of rubble.” His 12 coauthors include JPLers Geoffrey Bryden, Karl Stapelfeldt (PhD ’91), Christine Chen (BS ’96), and Werner. More evidence for the link between disks and planets came from images from the W. M. Keck Observatory atop Mauna Kea and from the Hubble, when a nine-person team led by UC Berkeley’s Paul Kalas and including Eugene Chiang (PhD ’00), Stapelfeldt, and fellow JPLer John Krist spotted a Jupiter-mass planet orbiting the star Fomalhaut just inside a dust ring detected by Spitzer.

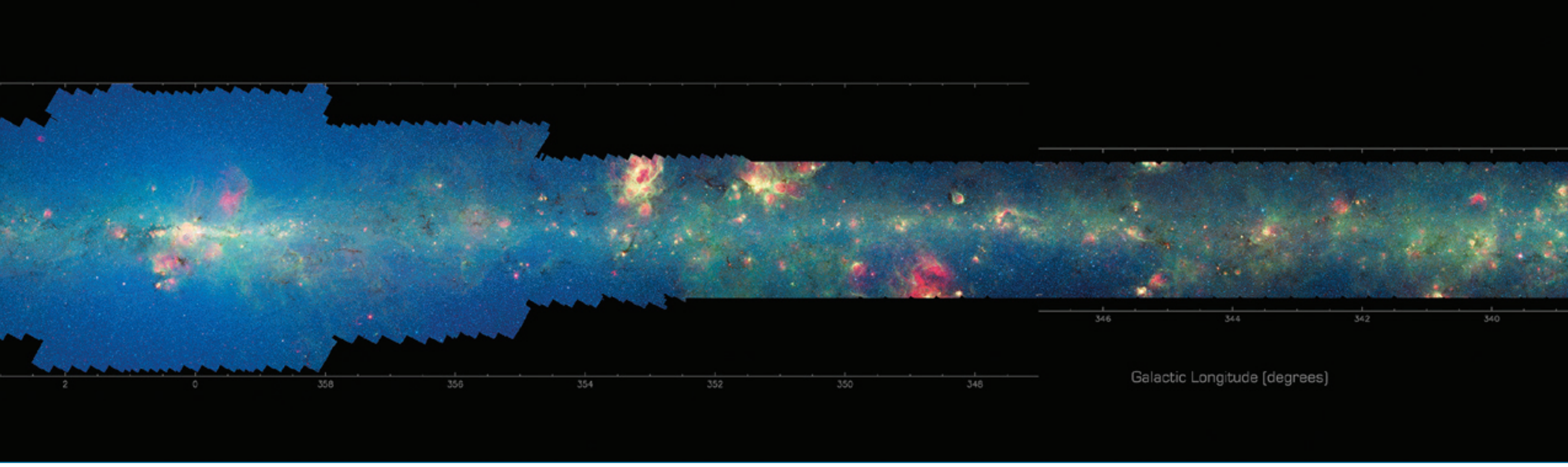
Another group, led by Michael Meyer of the University of Arizona at Tucson and including Caltech senior research associate in astronomy John Carpenter, associate professor of astronomy Lynne Hillenbrand, and member of the professional staff John Stauffer (plus 10 other people), looked at 309 stars of all ages but about the same mass as our sun, and found that at least 20 percent of them were swimming in dusty debris disks. The real number could be far higher—up to 60 percent, in some interpretations—and there are undoubtedly some stars whose dust is too faint for Spitzer to see. Other large studies have shown similar results. The inevitable conclusion: most stars are likely to have planets.

This includes binary, or twin, stars. Another Spitzer survey found that twins are at least as likely to host planets as are loners like our sun. There are more twins than singletons in the Milky Way, and therefore presumably in other galaxies, which means more prime real estate for planets. The universe may well be teeming with Tatooines, where a Luke Skywalker would see a stunning double sunset.

It turns out that the distance between the stars determines the likelihood of planet formation. Snug binaries like Luke’s home system, separated by distances of under three astronomical units, and binaries that prefer a lot of personal space, with 50 or more astronomical units between them, are the most likely to parent planetary disks. (An astronomical unit is the distance between Earth and the sun.) Binaries at intermediate distances are nowhere near as planet-friendly, with very few of them having disks. This makes sense, as a planet could orbit a tight pair as if it were a single star, while a companion star 50 astronomical units away would be comfortably beyond Pluto’s orbit, allowing planets to form undisturbed. “Binary stars may have to be very close, or very far apart, for planets to arise,” says coauthor Stapelfeldt. “Location is everything.” This seven-person effort, led by David Trilling at the University of Arizona at Tucson, also included Bryden; Andrew Boden, a member of the Caltech professional staff; and Beichman.

Spitzer even found disks swirling around brown dwarfs. Starting at about 10 times the mass of Jupiter, these lukewarm balls of gas could intimidate even the mightiest of planets. But compared to stars, they’re downright puny, having only a few percent of the sun’s mass. Brown dwarfs start out like stars, but never quite ignite. Yet the telescope not only found dust disks around brown dwarfs, it also detected signs that the planet-formation process is under way. And in one oddball discovery, Spitzer found a potentially planet-forming disk around a brown dwarf that itself could pass for a planet. At eight times the mass of Jupiter, the clumsily named Cha 110913-77344 is smaller than some known exoplanets. Could this little dude eventually become a





parent? And if so, what would you call the offspring—moons or planets? This team, led by Penn State astronomer Kevin Luhman, also included Tom Megeath.

"These brown-dwarf discoveries demonstrate the ubiquity of the planet-forming process and further blur the distinction between stars and planets," says Werner. "Brown dwarfs are about as common in our neighborhood as are all other types of stars put together, so it's entirely possible that the nearest exoplanets orbit brown dwarfs, not sunlike stars." Given that brown dwarfs may have entourages, could they be so gracious as to host life? A planet would have to snuggle up awfully close to be in the cozy habitable zone. "Our knowledge about planets and life is so rudimentary that anything is possible," says Beichman.

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### REIMAGINING THE MILKY WAY

At this point, you might be forgiven for thinking Spitzer is an exoplanet monomaniac. Not so—the telescope has also spent a lot of time on the rest of the cosmos, starting with our own Milky Way galaxy. For decades, astronomers have used radio telescopes to map out its structure—a difficult task, considering that we can't step outside it to see it whole. Worse, the galactic center is clogged with dust that blocks our view, not only of the middle but of what lies beyond. Trying to map the Milky Way from here is a bit like trying to draw a blueprint of a house when you can only see the insides of a few rooms.

Nevertheless, a picture eventually emerged of an elegant spiral galaxy with four long arms—named Norma, Scutum-Centaurus, Sagittarius, and Perseus after prominent constellations within them—wrapped around a slightly elongated core. Our sun sits in a relatively empty region between the Perseus and Sagittarius arms, in a small nub of an arm called Orion-Cygnus. Some astronomers suspected that the core was elongated enough to make the Milky Way a barred spiral, a hunch that was confirmed in the early 1990s when the first generation of infrared telescopes revealed the starlight from this bar.

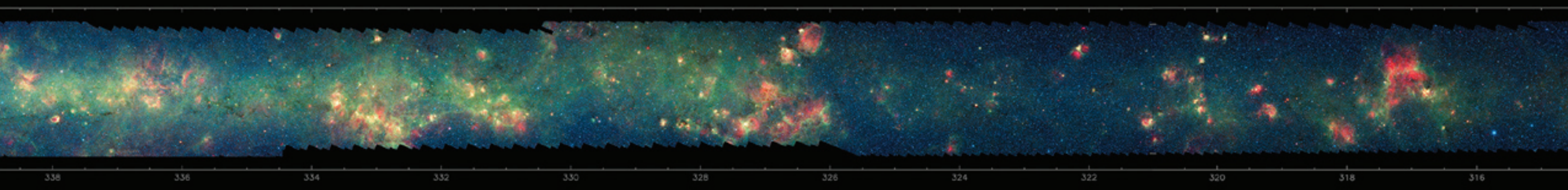
Spitzer's observations confirmed and extended this elongation—and then came the bombshell. In a survey stretching almost halfway across the sky, Spitzer was able to get the best picture yet of three of the four arms. (Perseus was outside the field of view.) As expected, Scutum-Centaurus was jam-packed with stars old and young. However, Norma and Sagittarius proved to be mostly gas, with scattered clusters of young stars. Just like that, two big arms became vestigial, leaving Scutum-Centaurus attached to one end of the central bar, and Perseus attached to the other. But before you drop a bunch of money at your local observatory's gift shop on a shiny Milky Way map, keep in mind that it's still subject to change. Team leader Robert Benjamin of the University of Wisconsin–Whitewater, says, "We will keep revising our picture in the same way that early explorers sailing around the globe had to keep revising their maps."

### ECHOES FROM THE BEYOND

Dying stars can go out with a bang. Literally. The details vary, but in general when a star more than about eight times the mass of our sun starts to run out of hydrogen fuel, it begins to implode until it gets hot and dense enough to start fusing pairs of helium atoms into carbon. When the helium runs low, the cycle begins again, turning carbon and helium into oxygen. The star works its way through the periodic table all the way up to iron, which won't burn. (Caltech physics professor Willy Fowler, PhD '36, shared the Nobel Prize in 1983 for working out the sequence of fusion reactions involved in this process.) The star implodes for the last time, crushing its interior into a neutron star or a black hole, while the outer layers rebound in a supernova explosion that can be seen across the galaxy.

But some of the explosion's light can reverberate around the neighborhood, revealing secrets the star would otherwise have taken to its grave. We are intimately familiar with Cas A, as one supernova remnant is affectionately known, because at a mere 11,000 light-years away it is close enough for us to make out its fine details. Even so, we don't know what type of supernova it was, and thus what class of star Cas A was in life. The tangled, spherical structure we see today is a tombstone bearing a date of about 9300 BCE, when the star blasted itself into smithereens. And while this funerary monument has been carefully examined, the coroner's report was written in the light from the explosion that swept past Earth around 300 years ago. But Spitzer found that the blast had heated up adjacent dust clouds, causing them to reradiate infrared light that is just now reaching Earth.

By following the trail of the infrared echoes, astronomers were able to find similar visible-light echoes that solved the mystery of how Cas A died. The visible spectrum toe-tagged Cas A as a rare Type

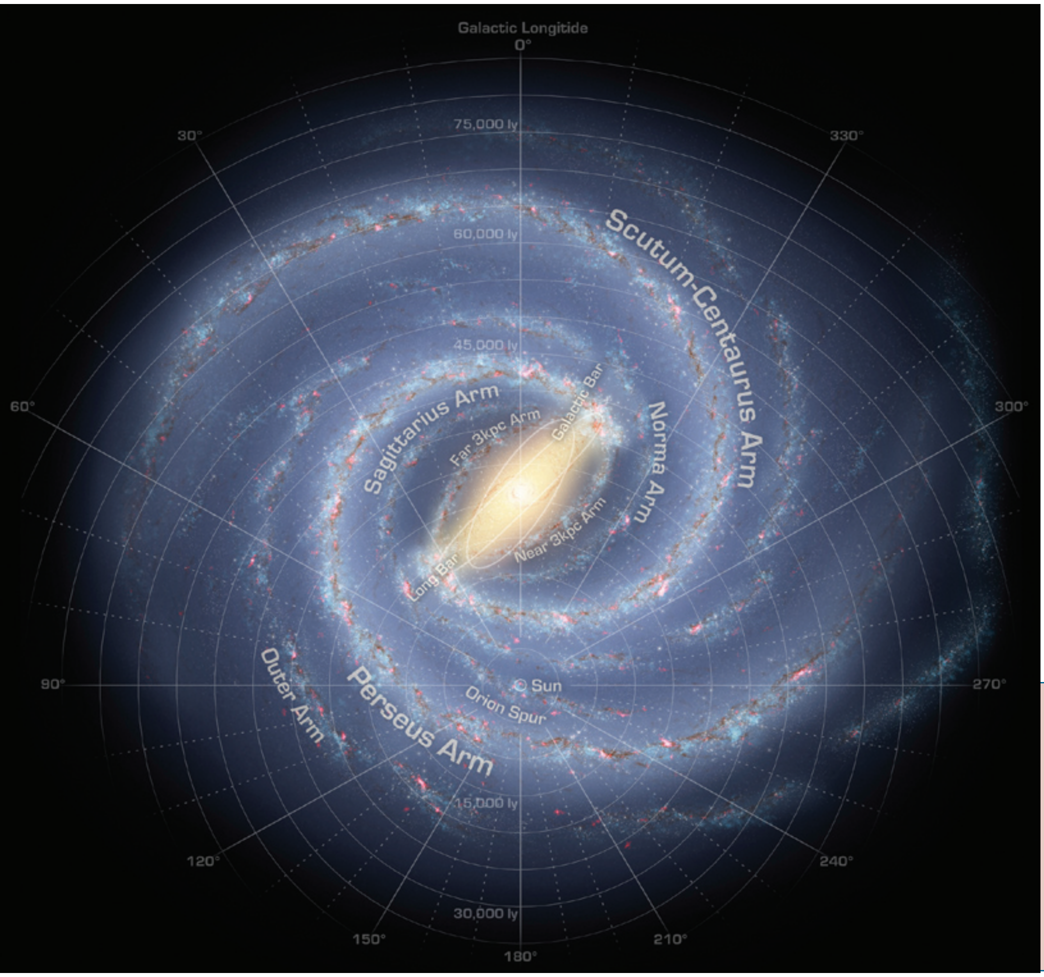


IIb supernova. This means that in life, Cas A was a bloated red supergiant star—ironic for a denizen of a constellation, Cassiopeia, named for a notoriously vain queen in Greek mythology. Fortunately, perhaps, for her self-image, Cas A shed several dress sizes before dying, shucking off her hydrogen envelope before her core collapsed in her final blaze of glory. Astronomers have since listened to similar ghostly whisperings from the remnants of other supernovas, describing the eerie details of their deaths.

## WE ARE SUPERNOVA DUST

Joni Mitchell was right when she sang, "We are stardust, billion-year-old carbon," at Woodstock. The carbon, and essentially any other atom in our bodies that's not hydrogen, was smelted in the nuclear furnaces deep within stars—foundries that take about a billion years to work their alchemy. This stardust is then seeded through the universe in the explosions of dying stars that themselves formed out of gas clouds seeded with the dust from other dying stars. We can trace the dust all the way back almost to the very beginning of time . . . but here we have a problem. The primordial universe was hydrogen and helium. Nothing else. Stars are born out of swirls of gas and dust when the force of gravity pulling in overwhelms the pressure of the gas pushing out. As the gas cools, the cloud collapses, and when it gets dense enough, nuclear fusion ignites. A thick blanket of dust speeds up the cooling by reflecting the ambient heat from other stars in the neighborhood that have already lit up, meaning that gravity triumphs more quickly and today's stars can begin to shine with relatively little mass. Bereft of dust, the earliest pioneers, called Population III stars, would have needed inordinate amounts of gas in order to collapse. They would have been behemoths that, when they did finally ignite, would have burned fast and furiously before their fiery demise.

Which brings us to the second part of the problem. When a star blows up, most of the heavy elements it has made remain in its former core. Proving that those first explosions would kick out enough dust to grow future generations of stars has been tricky—until now. In another study of Cas A, Spitzer detected 10,000 Earths' worth of fresh dust in the clouds around her—3 percent of the sun's mass, and enough dust, in proportion, to have been an enormous help in the early universe. Since Cas A is so close, the team, led by Jeonghee Rho at Caltech's Spitzer Science Center, was able to map the dust onto the gaseous ejecta known to have come from the explosion, proving the two have a common origin. Member of the Professional Staff William Reach participated in the work, as did seven people from other institutions.



Top: A swath of the Milky Way from the galactic center (zero longitude) through the Norma and Scutum-Centaurus arms. The blue specks are stars, the green swirls are clouds of organic molecules, and the red and yellow knots are dust-rich star-forming regions.
Left: The new, improved map to the stars' homes.

The Cas A supernova remnant, as seen by Spitzer (red), Hubble (yellow), and the Chandra X-ray Observatory (green and blue). The three telescopes are mapping temperatures ranging from a few hundred kelvins (Spitzer) to about 10 million K (Chandra).

## AS FAR AS SPACE TELESCOPES CAN SEE

Spitzer has also uncovered hundreds of millions of hidden, ravenous black holes. You can't see a black hole directly because it's, well, black, but when feeding, it betrays itself by belching. If a bright beam of visible light or X-rays makes it to Earth, we call the unruly diner a quasar. Other black holes are more discreet, concealing their gluttony behind blankets of dust, like Lewis Carroll's Walrus "holding his pocket handkerchief before his streaming eyes" so that the Carpenter couldn't count how many oysters he had eaten. These "missing" quasars have been at the top of astronomers' "most wanted" list for almost two decades.

Spitzer fingered many of the fugitives by picking up the glow of dust warmed by the X-rays, allowing NASA's Chandra X-ray Observatory to go back and find the faint, telltale signatures of the quasars lurking within. They turned up in droves—hundreds of them were found between 9 and 11 billion light-years away in one relatively small patch of sky. "Active, supermassive black holes are everywhere in the early universe," says Mark Dickinson of the National Optical Astronomy Observatory in Tucson, Arizona. "We had seen the tip of the iceberg before. Now, we can see the iceberg itself." Other team members included Spitzer Science Center staff scientist Ranga-Ram Chary, then-postdoc Minh Huynh, Member of the Professional Staff David Frayer, Niel Brandt (BS '92) of Penn State, and 14 others.

Once upon a time, before the age of black holes, the universe itself was black. Almost completely black—no stars and no galaxies, just the remnant glow of the Big Bang, the colossal explosion that brought the universe into being. These "dark ages" arrived some 400,000 years after the Big Bang, when things had cooled enough that free-roaming electrons and protons could combine to form hydrogen atoms. As the cosmos continued to expand and cool, the young universe got socked in with a fog of cold hydrogen gas. And so things stood until the universe was about a billion years old, when the collective light of the very first star-making galaxies burned through, heating the mist like a warm spring sun. Spitzer, working with the Hubble Space Telescope and the W. M. Keck Observatory atop Mauna Kea, Hawaii, has spied some of these dark-age denizens—small galaxies compared to our Milky Way, yet teeming with stars. The infrared signatures show that many of these stars were already over 100 million years old when seen by Spitzer, meaning that star formation had kicked in surprisingly early.

Richard Ellis, the Steele Family Professor of Astronomy, has led several of these hunts, which have also variously included Daniel Stark (PhD '08), Member of the Professional Staff Mark Lacy, then-postdoc Johan Richard, visiting associate Jean-Paul Kneib, Michael Santos (PhD '04), and assorted people from other institutions. The galaxies lie so far back in time that the light they originally emitted at ultraviolet and visible wavelengths has been stretched into infrared by the expansion of space itself—in fact, they can't be seen at all with visible light. You find them by comparing an image from the Hubble or Keck, where they don't appear, with one from Spitzer, where they do. Because these galaxies are so far off, and thus so faint, Ellis and his colleagues often exploit a phenomenon Einstein predicted called gravitational lensing. If the ancient galaxy happens to lie behind a massive cluster of galaxies, the cluster's gravity will bend the light on its way to us, acting like a giant magnifying glass.

Studies like these will be a big part of Spitzer's "warm mission." The two shortest wavelength channels (3.6 and 4.5 microns) on the infrared array camera will remain fully functional, and in these wavebands Spitzer will still have the most sensitive infrared eyes around. The telescope will finally have the leisure to kick back and survey larger patches of sky for longer periods of time. In the process, Spitzer will continue to attack such questions as the fate of our expanding universe, whether Earth-like planets are common, and even how often we can expect big asteroids to bruise Earth. "We like to think of Spitzer as being reborn," says Werner. "The warm mission is very exciting because much of the science will be totally different from anything that we've done before—it's a brand new observatory." e&s

*Whitney Clavin is a science writer who shares her time between the Public Affairs Office at JPL and the Spitzer Science Center at Caltech.*

*This article was edited by Douglas L. Smith.*