Astronomy's Rosy Revolution

Infrared detectors open a new window onto the universe

By RON COWEN

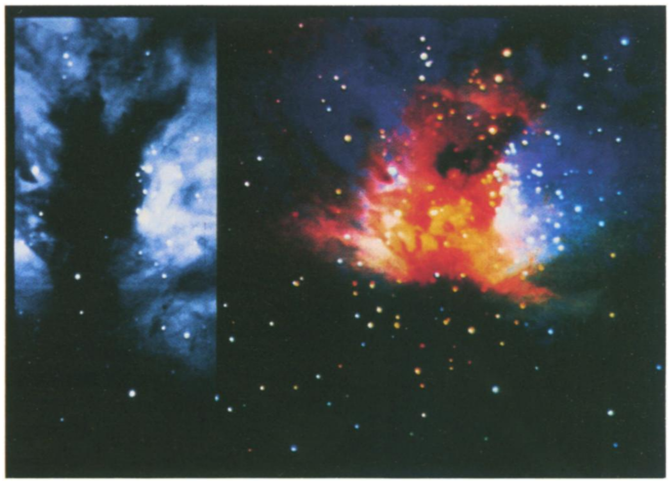
The heavens look different in the infrared. Ancient stars, dim and dull in visible light, take on a fiery glow; familiar-looking galaxies dramatically change their shape; dust-shrouded regions blaze brightly, revealing the birthing places of stars.

Astronomers have long known that infrared observations could open a new window onto the cosmos. At some of these wavelengths – just three to 10 times longer than those of visible light – dust becomes transparent, allowing researchers to peek at the hidden centers of galaxies. Infrared deep-sky maps reveal galaxies more distant than those seen in visible light. Closer to the Milky Way, only infrared viewing clearly images the long-lived population of cool stars, which make up the bulk of a galaxy's mass and ultimately determine its fate.

But for years, scientists lacked the tools they needed to fully explore the infrared frontier – even at the shorter range of wavelengths clearly visible from Earth. Simply put, the available detectors could not meet the challenge.

Too small and lacking the high sensitivity of devices used to view visible light, the typical infrared detector of the 1970s relied on a single, solid-state sensor to capture streams of incoming photons. That created an astronomer's nightmare: To obtain one full image of a nearby galaxy, researchers had to slowly slew their telescopes back and forth across a patch of sky over dozens of nights, then piece together the thousands of small images generated by a detector attached to the back of the instrument. And because the sensor's field of view exceeded the size of a single star image, the resulting picture often lacked the small-scale detail that the astronomers had labored so carefully to grasp.

"The frustration that has underpinned infrared astronomy ever since it began was that we knew very well what we wanted to do but we didn't have the instruments to do it," says Ian Gatley of the National Optical Astronomy Observatories (NOAO) in Tucson, Ariz. "A lot of the things we aim to do are really very, very simple conceptually. The issue has always been one of technology."


NOAO

Left: Visible-light view of the Milky Way cloud NGC 2024 shows a dark band across the region. Right: Color-coded composite of three near-infrared images made with one of the new arrays reveals a litter of young and newborn stars. Blue, green and red denote infrared wavelengths of 1.2, 1.6 and 2.2 microns.

Things started looking rosier in the 1980s. By then, the U.S. military had developed some large, heat-sensitive detectors for viewing infrared-bright objects such as rockets moving in the night sky. Astronomers began adapting these devices to record the far fainter infrared emissions of distant stars and galaxies.

"There were a lot of things that for years and years I said, 'Gee, I wish we could do this; wouldn't this be neat?'" Gatley recalls. "Suddenly, along comes this amazing technology that's telling us, 'Okay, fine – go do it!'"

Since no single material can sense all infrared radiation, designers vary the metal alloys used in detectors, depending on the specific wavelengths astronomers seek to study. So far, researchers have made the most progress in developing devices sensitive to near-infrared wavelengths between 1 and 5 microns – a region of the electromagnetic spectrum in which dust becomes transparent.

Their efforts were spurred by the push to develop a new infrared detector that NASA plans to install aboard the Hubble Space Telescope in 1997. Scientists at the University of Arizona in Tucson and the Rockwell Science Center in Anaheim, Calif., collaborated on the design of the instrument, known as NICMOS (near-infrared camera and multi-object spectrograph). Since 1990, research teams at the University of Hawaii in Honolulu and the University of Arizona have used prototypes of the new instrument to explore the heavens.

A sandwich of two semiconductor chips, each serving a separate but critical function, forms the heart of these new, thumbnail-sized devices, known as large-format arrays. The top layer consists of an infrared-sensitive chip divided into individual sensors called picture elements or pixels. A bottom layer of silicon, also divided into pixels, records the electronic signal induced when light strikes the top layer. Tiny metallic "bumps" electronically connect the two layers. The newest arrays contain some 65,000 infrared-sensing pixels; the sensitivity of a single pixel surpasses that of an entire infrared detector built only a decade ago.

The resolution of these detectors still pales alongside state-of-the-art optical devices, which contain some 4 million pixels. And infrared astronomers still must slew their telescopes to capture an image of most sources. But they slew less often, and in just one night they can produce images that would have taken centuries to make with the old, single-element infrared detectors, notes Stephen E. Strom of the University of Massachusetts at Amherst. Best of all, Strom says, these pictures offer unprecedented clarity and detail.

Already, the new detectors have generated a feast of new findings, ranging from surveys of distant galaxies to glimpses of starbirth in our own Milky Way.

Shaping up a distant galaxy

Viewed in visible light, the galaxy NGC 309 appears similar to the Milky Way. Like our galaxy, it has three brilliant arms that spiral out from a central disk. The luminous arms represent regions where massive, hot stars currently concentrate and where astronomers believe starbirth takes place.

But infrared images paint a different

portrait of NGC 309.

Viewed in the near-infrared, one of the galaxy's three arms vanishes and the central disk appears transformed into an ellipsoid, report David L. Block of the University of the Witwatersrand in Johannesburg, South Africa, and Richard J. Wainscoat of the University of Hawaii. The researchers surveyed NGC 309 with a large-format detector attached to the University of Hawaii's 2.2-meter telescope atop Mauna Kea. They describe their results in the Sept. 5 NATURE.

Visible-light images originally led astronomers to characterize NGC 309 as a classic spiral galaxy. But the near-infrared observations, made at a wavelength of 2.1 microns, suggest it may belong in an entirely different class, the barred spirals. These galaxies, named for their elongated or "barred" central region, differ from classic spirals in several ways, including their rate of starbirth.

Infrared detectors pick out cool stars with a mass comparable to that of the sun, Block explains. These represent the dominant stellar population in any galaxy because they last longer than the hotter, more massive stars that produce the bulk of visible-light emissions. The hotter stars typically burn out after about 50 million years, Block says, whereas the cool stars seen in the infrared burn their fuel slowly enough to endure for billions of years — about the lifetime of the galaxy.

The stellar populations viewed in the infrared coincide with a galaxy's oldest star clusters as well as with the regions likely to have a high density of gas and dust. Such locations favor starbirth. Moreover, observations by other researchers suggest that barred central regions pull in surrounding mass, an activity that may trigger star formation. Thus, NGC 309's two stubby arms and elongated nucleus, as seen in the infrared image, may actually depict the clustering of gas and ancient stars that ultimately drives starbirth, Block says.

As far back as the 1950s, astronomers had predicted that some spiral galaxies would appear substantially different in the infrared, but they lacked the images to support their theory. "Large-format infrared arrays . . . now open a new era in the classification of disk galaxies," Block and Wainscoat conclude in their report.

Cosmology in another light

The cosmological landscape still mystifies astronomers. How did the Milky Way and similar galaxies originate? When did most galaxies burst onto the scene with their very first glow of starlight? How much mass do they contain?

Recent infrared surveys, using large-format detectors to image hundreds of the faintest galaxies ever observed, are beginning to answer these fundamental queries. Indeed, the new work has generated several perplexing findings that may force researchers to rethink standard theories about galactic evolution.

Lennox L. Cowie and his colleagues at the University of Hawaii surveyed four small patches of sky using two telescopes atop Mauna Kea: the 3.9-meter U.K. Infrared Telescope, equipped with an array containing some 3,600 pixels, and the University of Hawaii's 2.2-meter telescope, using the state-of-the-art NICMOS array with about 65,000 pixels. These arrays enabled the researchers to image hundreds of dimly glowing galaxies without needing to piece together a myriad of images from smaller, less sensitive detectors.

The infrared surveys detected sources as dim as the faintest galaxies ever imaged in visible light. The maps reveal sky regions so crowded with galaxies that the solar disk, as viewed from Earth, would cover 50,000 of the objects.

The infrared faintness of many of the galaxies led Cowie's team to assume that they were very distant. Since looking into deep space is essentially the same as looking back in time, this would mean that the galaxies formed early in the history of the universe. But in analyzing the visible-light spectra emitted by some of these galaxies, Cowie and his coworkers found that many of them lie only 6 billion light-years from Earth — fairly close, in cosmological terms. In fact, the astronomers detected the largest number of galaxies at this distance rather than farther from Earth. This, they say, supports the notion that many galaxies formed relatively *late* in the history of the universe.

In 1989, a few other research teams, working with visible-light images, started spotting a similar clustering at about 6 billion light-years. But infrared studies have a special advantage, Cowie says.

Cowie

Galaxies blanket this composite deep-sky image. Blue and green denote images taken at two visible-light wavelengths; red denotes image taken at the near-infrared wavelength of 2.2 microns.

That advantage involves the phenomenon of redshift, in which light emitted by objects that speed away from Earth faster than those nearer our planet get shifted to longer, or redder, wavelengths — just as the wail of a receding ambulance siren appears to shift to a lower pitch. In an expanding universe, objects farther from Earth recede faster than those closer to our planet. Thus, more distant objects appear redder. So surveying a distant galaxy in visible light actually detects the radiation emitted by stars at shorter, ultraviolet wavelengths. Stars that radiate most of their light in the ultraviolet burn their fuel rapidly, fizzling out long before a galaxy dies.

In contrast, infrared maps of distant galaxies highlight emissions from the much larger population of longer-lived stars that radiate primarily in visible light. Viewed from Earth, that light gets shifted to the infrared. Since astronomers infer a galaxy's mass by measuring its brightness, detecting infrared emissions thus provides a more reliable mass estimate. And once researchers have an accurate mass estimate, they can identify the galaxy's subtype.

The new infrared results leave astronomers baffled, however. Instead of portraying a mixture of many galaxy types, these sky maps — snapshots of the universe as it existed 6 billion years ago — show primarily one class, a group of compact, low-mass "dwarf" galaxies. Dwarfs contain billions of stars rather than the hundreds of billions typical of most galaxies, including the Milky Way. But the number of distant dwarfs detected in the infrared survey appear about 10 times greater than the total number of *all* galaxies seen in glimpses of the more modern universe.

"The finding is quite shocking," Cowie says, because few dwarfs now reside in the "local" cluster of galaxies — those within some 60 million light-years of the Milky Way. Most of this nearby population consists of larger, more massive galaxies — classified as spirals or ellipticals depending on their shape, and collectively known as "normal" galaxies.

Did the dense collection of small galaxies viewed in the infrared surveys perform a vanishing act, self-destructing in more recent times? And when did the "normals" begin to form?

"I don't think anybody really quite knows what's happening," says Cowie. "We're still a little bit muddled."

However, he and his colleagues do propose several possibilities, which they will detail in an upcoming ASTROPHYSICAL JOURNAL. The apparent abundance of dwarfs in the past, combined with the present abundance of normal galaxies, suggests that the dwarfs may once have dominated the universe and served as seeds for future normal galaxies. Cowie's group speculates that collections of these small galaxies may have merged in the cosmologically recent past to form the spiral and elliptical galaxies seen today.

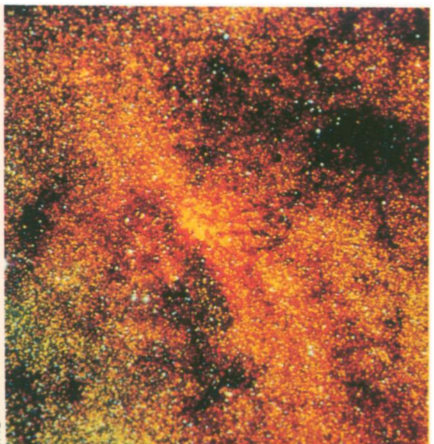
One clue favoring this scenario: The total mass of the old dwarf population appears similar to that of the present-day normals. More significantly, says Cowie, an analysis recently begun by his team suggests that the dwarfs clustered in groups, a prerequisite for mergers to occur.

Several difficulties still plague the merger model, however. If dwarfs formed the present-day spiral galaxies, says Cowie, the spirals should have thicker disks than those observed. In addition, observed light emissions from elliptical galaxies do not appear to match the spectra that dwarf mergers should produce.

The idea that millions of galactic fragments assembled over a relatively short time to form the bigger galaxies we see today presupposes a cosmological drama that few astronomers had imagined, Cowie notes. "It really is a little radical," he says, "but I think many people now prefer it."

In an alternative model, Cowie and his colleagues suggest that the dwarfs represent an entirely independent group of galaxies that, for unknown reasons, have since faded from view. This possibility also has profound implications for cosmology. Cowie notes that light emissions from the dwarfs indicate they contain as many baryons (neutrons, protons and other fundamental components of atomic nuclei) as normal galaxies. Thus, if the two types of galaxies coexist, the universe may contain double the previously estimated amount of this matter.

Evidence of a larger number of baryons



NOAO

This near-infrared image of our galaxy's center — a mosaic of about 60 1-minute exposures taken with one of the new large-format arrays — reveals thousands of young stars that remain hidden by dust in visible light. If one of the old single-sensor detectors had taken the same picture, it would have required half a million separate pointings of the telescope and as long as a century of nightly observations.

NOAO

Left: Visible-light view of the Milky Way's Orion molecular cloud shows regions heavily shrouded in dust. Right: In this infrared image, never before published, the dust vanishes, unveiling young stars in several areas of the cloud. The reddest stars are those that lie behind the most dust.

could change the way cosmologists think about hypothetical material called dark matter — invisible mass that emits no light but exerts a gravitational force. Researchers use dark matter as a way to account for the formation of galaxies and other lumpy structures in the universe. But if the cosmos contains double the estimated number of baryons, astronomers might need slightly less dark matter to explain the large-scale structure of the universe, Cowie notes. Moreover, the dwarfs may contain hidden pockets and halos that harbor the bulk of dark matter in the universe.

Penetrating the dust

Gatley and his colleagues had a simpler task in mind for their infrared arrays. They wanted to image starbirth regions in the Milky Way — stellar nurseries hidden in cocoons of warm dust.

The dust absorbs visible light, rendering the star-forming regions opaque at visible wavelengths. And viewing these starbirth regions in the far infrared — as NASA's Infrared Astronomical Satellite (IRAS) did in 1983 — only shows the brilliant glow of warm dust. The starbirth areas remain impenetrable.

But near-infrared light passes through dust unimpeded, providing a window onto star-forming regions.

The year was 1988, and the newest arrays had yet to be perfected. Gatley and his colleagues contacted the Hughes Aircraft Co., which was manufacturing an infrared array for military use. Made of platinum silicide, these detectors offer only about one-tenth the sensitivity of today's mercury-cadmium-telluride arrays, but they match them in size, with an unprecedented 65,000 pixels.

The platinum-silicide arrays were well suited to his studies, Gatley says. Guided by the bright clouds of warm dust imaged by IRAS, he and his co-workers knew where to look for star formation. And the arrays would easily detect the brilliant blaze of near-infrared light emitted during starbirth, Gatley reasoned.

His team's recent images of starbirth in the Orion nebula, the molecular cloud M17 and other nurseries in the Milky Way offer graphic testimony to the value of the platinum-silicide arrays. The researchers report some of their latest findings in the June 20 ASTROPHYSICAL JOURNAL.

"We were not really aware of how rich these [regions] would turn out to be," says Gatley. "There are lots and lots of young stars in there. We had wanted to look at these areas since the 1960s, but we needed to see past the dust to find out what was going on."

Particularly striking are the color-coded images the team obtained. At Kitt Peak near Tucson, the researchers devised an ingenious system of detectors and filters that paints four simultaneous portraits of star formation.

A chilled canister bolted to the end of a 1.3-meter telescope contains four platinum-silicide arrays, each placed in a precise position. A special filter in front of each array allows infrared light of one specific wavelength to pass through; the rest is reflected to the next filter-array combination in the sequence. Once the images are formed, scientists in the computer laboratory assign a different color to each of the four infrared wavelengths detected; longer wavelengths get redder colors.

"If your eyes could see different colors in the infrared, this is what these regions would look like," Gatley says. "We see glorious variations in the colors of the surfaces of the newborn stars. Some radiate predominantly at the longer-end wavelengths, some at shorter wavelengths, and some at all [four] wavelengths."

In September, NOAO began allowing visiting scientists to use the experimental setup, called SQIID (simultaneous quad infrared imaging device). Requests to use the device have already exceeded the available observing time.

Meanwhile, Gatley and his colleagues continue their census-taking of stellar nurseries. Like many other infrared astronomers, they look forward to working with ever larger arrays. But for now, Gatley says, they're taking time to enjoy the payoff of their efforts.

"I'm sure we'll manage very quickly to make life complicated again, but right now [infrared astronomy] just has this tremendous, refreshing simplicity," he says. "There's been a kind of breakthrough here that is really quite unusual in the course of human events. I don't expect anything like this to happen to me again." □