A new era dawns in astronomy

At wavelengths from gamma rays to microwaves, astronomers are exploring the universe with a variety of new tools.

Thomas V. Higgins
Contributing Editor

As the millennium draws to a close, an extraordinary surge of creative energy is coursing through the astronomy community. Not since 1610, when Galileo trained his primitive spyglass on Jupiter, have astronomers witnessed such a fertile renaissance of technical innovation and scientific discovery.

With gigantic ground-based telescopes and sophisticated orbiting observatories, scientists are exploring the cosmos at nearly every wavelength of the spectrum. Their discoveries have been nothing less than startling and reveal in exquisite detail a universe of unimaginable violence and complexity. The pace of discovery is breathtaking, as capabilities advance by orders of magnitude and a variety of breakthroughs blaze the trail toward further discovery. The most important accomplishments have been the advent and continued development of charge-coupled-device (CCD) imaging arrays for sensitive detection, very large telescope mirrors for unprecedented light-gathering power and angular resolution, precision active control of the position and shape of large optics, adaptive optics to compensate for atmospheric turbulence, and space-based platforms that can completely escape earth and its air.

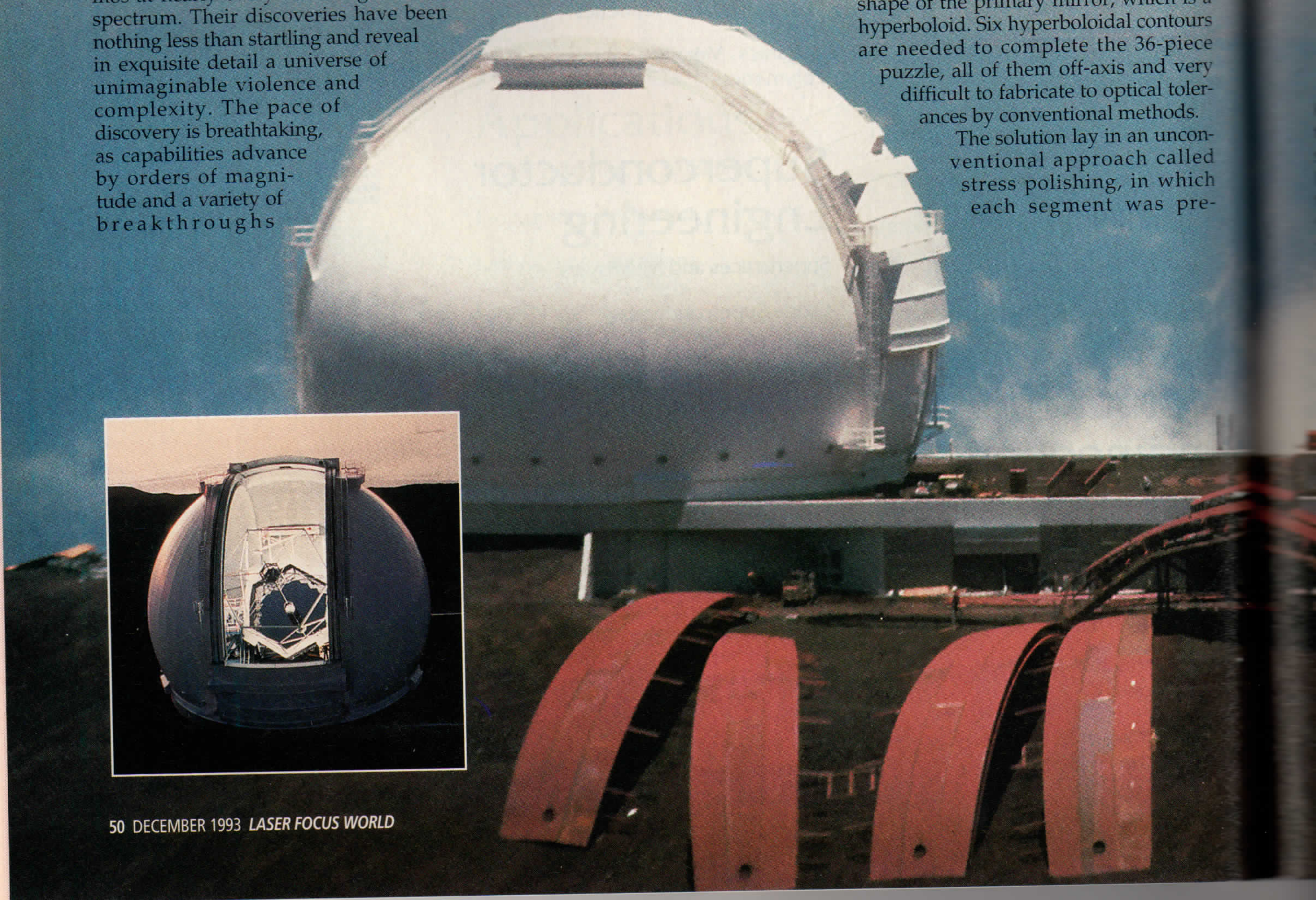
The big kahuna

Many of these technologies are embodied in a single colossal telescope located on the summit of an extinct volcano—Mt. Mauna Kea—above the island of Hawaii. Almost everything about the Keck is big (see inset photo). It is the largest telescope in the world, with a primary mirror spanning 10 m, twice the size of the venerable Hale telescope on Mt. Palomar in California.

The 10-m primary mirror is actually a mosaic of 36 hexagonal segments arranged edge to edge. Each 1.8-m segment is only 75 mm thick and is secured in an actively controlled mount that keeps the mirror aligned with its neighbors to within 5 nm and maintains the overall shape to approximately 50 nm. Position information, acquired by sensors placed along the edges of each mirror segment, is fed 50 times per second to a computer, which then corrects any misalignments twice per second via commands sent to hydraulic actuators on the mounts.

Optical fabrication of the mirror segments presented one of the most difficult challenges to Keck designers because the surface of each segment must conform perfectly to the overall shape of the primary mirror, which is a hyperboloid. Six hyperboloidal contours are needed to complete the 36-piece puzzle, all of them off-axis and very difficult to fabricate to optical tolerances by conventional methods.

The solution lay in an unconventional approach called stress polishing, in which each segment was pre-



stressed or distorted in a jig before grinding and polishing. With the right amount of predistortion, all six segments could be ground and polished as spheres—the easiest shape to make optically. After polishing, the jigs were released and the surface relaxed to the desired off-axis hyperboloid.

When the circular segments were cut into their final hexagonal profiles, however, problems arose from the added stress relief introduced by cutting. But engineers surmounted the difficulty by incorporating a permanent stress harness for each segment.

The completed primary mirror, the last segment of which was installed in April 1992, gathers four times more light than the Hale telescope yet weighs the same—about 15 tons. With that kind of light-gathering power, astronomers hope to probe as far as 14 billion light years into space. And in April 1993, Keck astronomers captured an image of the most-distant known galaxy (4C41.17) some 12 billion light years away.

The galaxy was caught by one of Keck's "first-light" instruments, the near-IR camera (NIRC). Other inaugural instruments include a long-wavelength IR camera, high-resolution spectrograph (HIRES), low-resolution imaging spectrograph, long-wavelength spectrograph, and the NIRC itself. All of these instruments house sensitive state-of-the-art CCD imaging arrays, and together they span the spectrum from 0.3 to nearly 30 µm, taking full advantage of Mauna Kea's superb IR seeing conditions.

Size isn't everything

Because any telescope is really only as good as the instruments attached to it, great care has gone into the design and construction of the five Keck instruments. "In general, it's not how big your telescope is, it's what you do with the light that enters it," says Steven Vogt, professor of astronomy and astrophysics at the University of California, Santa Cruz (UCSC, Santa Cruz, CA).

As principal designer of the HIRES for Keck, Vogt should know. The high-resolution spectrograph is a remarkable instrument that ventures beyond the customary limits of optical design. Despite its very high spectral resolving power ($\lambda/\Delta\lambda$), which can approach 200,000, the HIRES can record the spectra of objects 10 to 100 times fainter than previous spectrographs.

In its present configuration, the spectrograph is built around a huge 12 × 48-in. echelle diffraction grating (actually a mosaic of three echelles) and a 2048 × 2048 Tektronix CCD array. Inside an enclosure the size of a living room, giant optics—some extending 30 to 44 in. in diameter—collimate, disperse, and focus the light from the entrance slit onto the CCD (see Fig. 1).

One of the triumphs of the HIRES optical design is the lightning-fast, *f*/1.0 camera that does the focusing. All the optical surfaces of the camera (which was designed by Harland Epps, professor of astronomy and astrophysics at UCSC) are spherical, yet it attains an image resolution of 12.6 µm (rms) and is color-corrected over the enormous spectral range of 0.3–1.1 µm. This makes the HIRES adaptable to future improvements in CCD technology and accommodates the often rigorous spectral demands of celestial observations.

Despite the huge cost of the Keck and its instruments ($94 million), funding for a second 10-m telescope has been received and construction has begun just 85 m

Keck II, Keck Telescope's twin, is now under construction 85 m away from Keck I. Plans call for the two telescopes to be joined together by a coudé light tunnel, forming the world's largest optical interferometer.

The Keck Telescope (left), largest in the world, crowns the summit of Mt. Mauna Kea on the island of Hawaii. Its 10-m primary mirror resembles a jigsaw puzzle with 36 separate mirror segments.

ROGER RESSMEYER

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FIGURE 1. High-resolution spectrograph (HIRES) for Keck telescope is about the size of a living room. Steven Vogt, principal designer of the instrument, is seated atop the HIRES.

from Keck I (see photo p. 50). Keck II is slated for completion in 1996.

Astronomers plan to optically link the twin telescopes via an underground coudé light tunnel, thus forming the world's largest optical interferometer and boosting the angular resolution of a single Keck scope by nearly ten times. (The diffraction limit of a 10-m mirror is 0.01 arcsec.) Radio astronomers have perfected baseline interferometry into a high art (the Very Large Array west of Socorro, NM, routinely achieves angular resolutions of 0.1 arcsec), but difficulties grow by a factor of 10^5 at optical wavelengths.

Air turbulence alone limits Keck's angular resolution to 0.4 or 0.5 arcsec at best, even with the outstanding conditions atop Mauna Kea. Air turbulence also would play havoc with the phase information important to interferometric observations, so astronomers plan to use adaptive optics to minimize this atmospheric smearing.

Many other technical obstacles must be overcome, but the prospect of milliarcsecond resolution has attracted the interest of astronomers worldwide. As part of its TOPS (Toward Other Planetary Systems) program, NASA is particularly keen on applying these interferometric techniques at IR wavelengths to search for embryonic planetary systems around neighboring stars.

But big is in

The Keck is just one of many large telescopes that will see first light this decade. By the early 21st century, about ten 8-m-class telescopes will dot the globe. Just a stone's throw away from Keck on Mauna Kea, the National Astronomical Observatory of Japan is building an 8-m telescope for the 0.3- to 30-µm spectral region. Scheduled for completion in 1999, the Subaru telescope will feature a new concept in primary-mirror design. Shaped like a gigantic contact lens–aptly called a meniscus–the 8-m primary measures just 200 mm thick.

At 35 tons, the mirror weighs about twice as much as the 10-m Keck but does not have the bothersome edge effects of a segmented mirror. And because of its slender profile, the optical distortions caused by thermal mass (an unhappy byproduct of immense mirrors) should prove acceptable. Corning Incorporated (Canton, NY) is fabricating the giant Subaru mirror from 88 hexagonal boules of ultralow-expansion glass. The boules are melted together in a huge kiln, then slumped over a convex mold to attain the proper meniscus shape. When mounted in the telescope, 264 precision hydraulic actuators will hold the mirror's shape to within 100 nm.

First-light instruments for the Subaru are still under consideration, but one intriguing design, the Infrared Mosaic Camera, would use a mosaic of sixty-four 1000 × 1000 CCD arrays for wide-field sky surveys. Other proposed instruments include a coronagraph imager with adaptive optics, an IR camera and spectrograph, a mid-IR spectrograph, and an OH airglow suppressor.

Using the same mirror-casting process, Corning also will supply two 8-m meniscus mirrors for a dual telescope project called Gemini, a $176 million cooperative undertaking of the USA, UK, Canada, Chile, Argentina, and Brazil. The Gemini consortium will construct one telescope on Mauna Kea and another at Cerro Pachon, Chile. Both telescopes will feature active optical control of the primary-mirror figures, as well as adaptive optics. To keep the telescope mirrors squeaky clean, a novel excimer-laser system has been proposed for Gemini that is under evaluation at STI Optronics (Bellevue, WA).

One of the most ambitious telescope projects under construction is the European Southern Observatory (ESO) Very Large Telescope (VLT) in the high, dry mountains of northern Chile. When completed, the VLT will comprise four 8.2-m telescopes operating as one to synthesize the light-gathering power of a single 16-m mirror with ten times the area of the Hale telescope.

The first of these four gargantuan meniscus mirrors was cast by Schott Glaswerke (Mainz, Germany) in June 1993. Despite being only 177 mm thick, the mirror weighs more than 24 tons. As with other thin-mirror telescope designs, hydraulic actuators will control the shapes of the VLT's four primary mirrors. Adaptive optics also have been proposed for all four telescopes.

Many of the technical difficulties of multimirror telescopes and meniscus mirrors were first tackled on a smaller scale at the Multi-Mirror Telescope (MMT) on Mt. Hopkins, Arizona, which was dedicated in 1979, and at the ESO's 3.5-m New Technology Telescope (NTT) in La Silla, Chile, which began operating in 1989. The successes and failures of these two telescopes paved the way for the larger projects under way today. Plans are now being made to reconfigure the MMT with a single 6.5-m primary mirror and the latest in adaptive optics technology. Optical engineers have already molded the primary mirror at the Steward Observatory Mirror Laboratory (SOML) using spin-casting techniques (see Fig. 2).

> *By the early 21st century, about ten 8-m-class telescopes will dot the globe.*

With spin-casting, very large, lightweight mirrors with steep curvatures can be economically fabricated by rotating them in a specially designed mold at temperatures above the melting point. The technique, pioneered by SOML founder and director Roger Angel, avoids the cost of having to remove tons of glass during the grinding stage and generates rigid mirrors with hollow honeycomb cores that can be air-cooled for thermal stability (see *Laser Focus World*, Oct. p. 15). The shorter focal lengths also make for stiffer, lower-cost telescope support structures and compact domes.

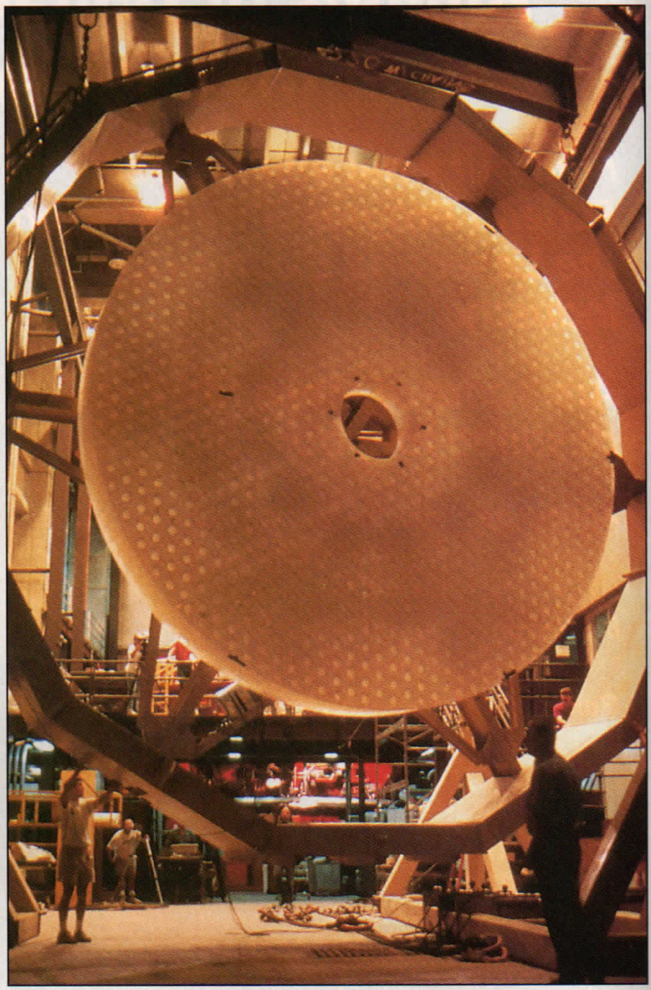
UNIVERSITY OF ARIZONA/LORI STILES

FIGURE 2. Ten tons of glass were used to spin-cast this 6.5-m mirror blank at the Steward Observatory Mirror Laboratory (University of Arizona, Tucson, AZ). The mirror will replace the six 1.8-m mirrors of the Multi-Mirror Telescope on Mt. Hopkins, Arizona.

Several future telescopes will use spin-cast mirrors 6.5 m or larger. One design calls for two 8.4-m, f/1.0 mirrors to be used in an immense binocular telescope atop Mt. Graham, Arizona.

When completed, the rebuilt MMT may include a 60-cm, fully adaptive secondary mirror for direct control of image quality. Angel has submitted proposals for the use of light from a laser guide star to sense atmospheric image distortion (see magazine cover). Signals would be fed to 36 individually controlled segments that make up the secondary mirror's reflective surface. Piezoelectric actuators would then correct each segment position with tip, tilt, and piston actions.

Out in space

Clearly, many of the large new-generation telescopes include plans for adaptive optics. Atmospheric absorption, however, is another matter altogether. In the visible- and radio-wavelength portions of the spectrum, where ground-based astronomy is traditionally done, the air is relatively transparent. But at IR wavelengths, atmospheric transmission resembles a picket fence, and everything, including the telescope, glows like a hot plate. Worse yet, our atmosphere looks like a brick wall at far-IR, extreme-ultraviolet (EUV), x-ray, and gamma-

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Major telescopes in space

Wavelength region	Telescope[1]	Agency[2]	Diameter (m)	Dates
Gamma ray	Compton Observatory	NASA		1991–
X-ray	Einstein Observatory	NASA	0.56	1978–1981
	Exosat	ESA		1982–1986
	Roentgen Satellite: ROSAT	German-NASA		1990–
	(Advanced X-Ray Astrophysics Telescope Facility)	NASA		(1998)
	(X-Ray Multiple Mirror Mission)	ESA		(1998)
Extreme ultraviolet	Extreme Ultraviolet Explorer	NASA		1992–
	(Far-Ultraviolet Spectroscopic Explorer)	NASA-Canada	0.6	(2000)
Ultraviolet	Copernicus	NASA	0.9	1972–1980
	International Ultraviolet Explorer	NASA-ESA-UK	0.41	1978–
	Hubble Space Telescope	NASA-ESA	2.4	1990–
Visible	Hubble Space Telescope	NASA-ESA	2.4	1990–
	Hipparcos	ESA	0.29	1989–
Infrared	Infrared Astronomical Satellite	Dutch-UK-NASA	0.57	1983–1984
	(Shuttle Infrared Telescope Facility	NASA		(2000+)
	(Infrared Space Observatory)	ESA		(1994)
	(Large Deployable Reflector)	NASA	10	
Radio	Cosmic Background Explorer	NASA		1989–
	(Orbital Very Long Baseline Interferometry)	NASA		(1995)

[1] Instruments in parentheses are planned or under construction, but not yet launched.

[2] NASA is the US National Aeronautics and Space Administration: ESA is the European Space Agency, a consortium of several countries.

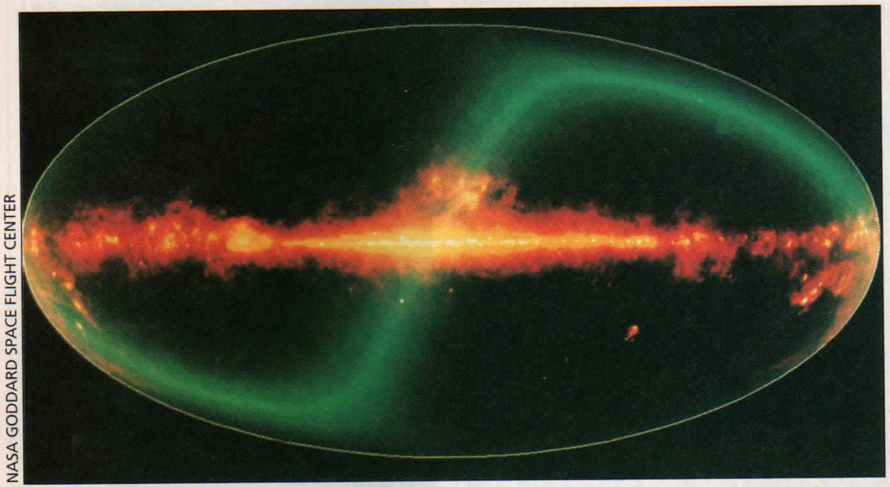
ray wavelengths.

The most effective way to compensate for atmospheric absorption and distortion is to rise above it, and the only way to do that is to drag instruments aloft on a balloon, sounding rocket, or spaced-based platform. It is costly and risky, but the potential rewards are alluring. Orbiting observatories such as the Compton Observatory, Roentgen Satellite (ROSAT), Extreme Ultraviolet Explorer, Hubble Space Telescope (HST), Infrared Astronomical Satellite (IRAS), and Cosmic Background Explorer (COBE) already have revolutionized our understanding of the universe (see table). And a cornucopia of future space-based observatories could dwarf those discoveries.

Last year, differential microwave radiometers on board the COBE detected minute spatial variations in the cosmic background radiation that represent temperature differences averaging 17 μK. The discovery shook the world of cosmology and furnished the so-called "inflationary" model of the Big Bang theory with experimental clout.

The anisotropy of the universe made headlines around the world, but few people realize that the COBE also carries two other instruments that endow it with a total spectral range of 1–10,000 μm. The Diffuse Infrared Background Experiment (DIRBE) provides absolute radiometric measurements of the sky in ten bands from 1 to 300 μm, while the Far Infrared Absolute Spectrophotometer covers the spectrum in two bands from 0.1 to 10 mm.

The instruments enable scientists to compare the cosmic background radiation with that of a perfect blackbody and to subtract the contributions of other sources from the true cosmic background. The ten spectral windows that DIRBE opened on the universe have caught a glimpse of stellar populations near the center of our galaxy and have exposed the dusty expanses of



NASA GODDARD SPACE FLIGHT CENTER

FIGURE 3. Dusty regions of our galaxy seem to burst into flame when viewed by Cosmic Background Explorer at 25, 60, and 100 μm, while the warm glow of interplanetary dust leaves an S-shaped signature across the galactic plane.

interstellar and interplanetary space (see Fig. 3).

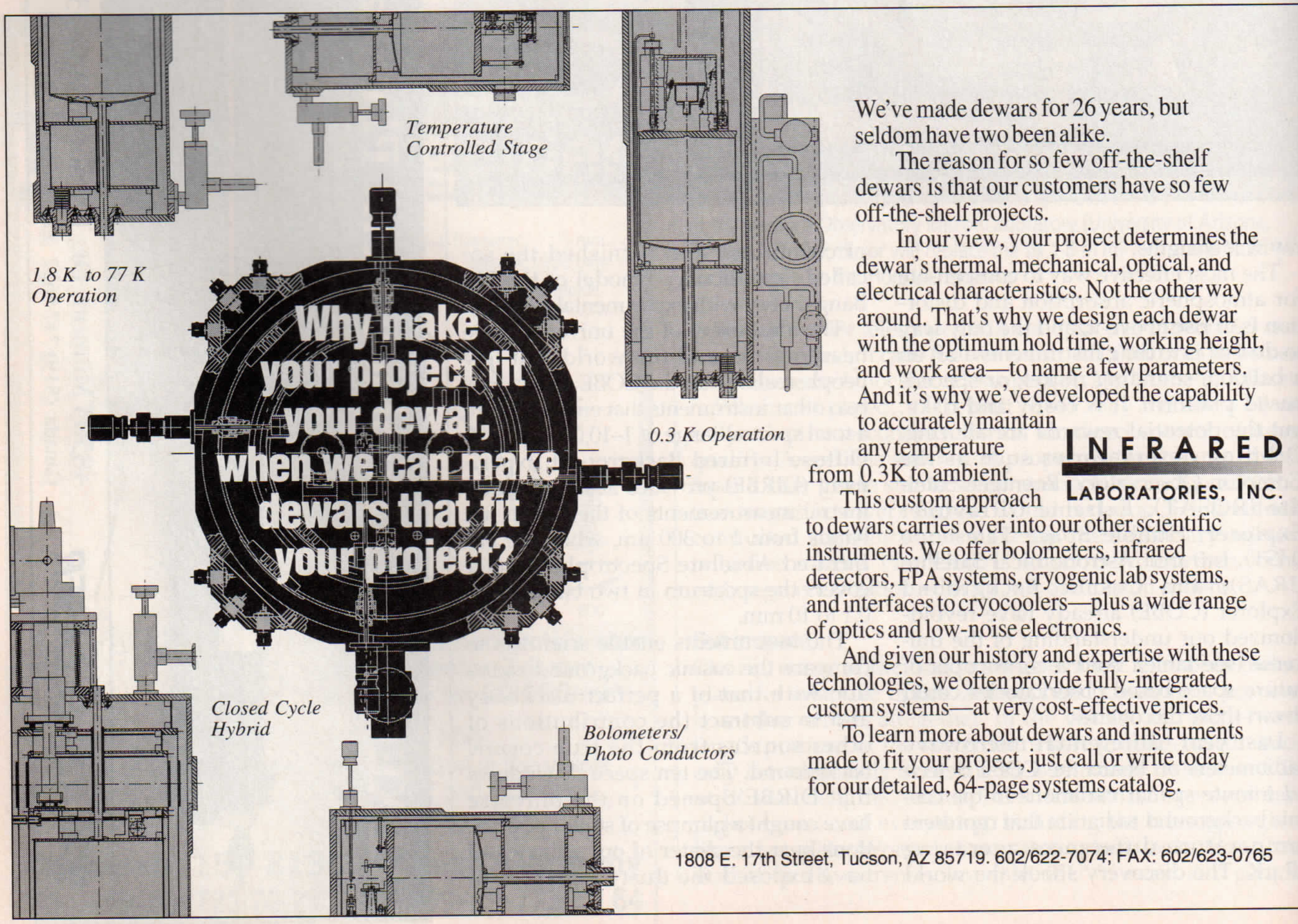
The heat of the night

The importance of IR spectra to astronomy was driven home by the dramatic discoveries made by the IRAS. During a ten-month period beginning in 1983, the IRAS surveyed the entire sky at 12, 25, 60, and 100 μm and uncovered scores of exotic objects, including large numbers of distant galaxies so obscured by dust that they can only be seen in the IR. (The most-distant known galaxy recently seen with the Keck was discovered by the IRAS.) The IRAS also showed that a typical spiral galaxy emits more than half its radiation between 40 and 120 μm.

From these and other IR discoveries has sprung the new frontier of IR astronomy, a field that owes much to the development of IR detectors and CCD imaging arrays. The CCD, which first appeared in 1970, already has earned a sterling reputation in ground-based visible astronomy by boosting quantum efficiencies far beyond the paltry 2% of photographic film to the incredible 80% of some modern CCDs.

Now, the spectacular gains once made in the visible are reaching into the IR. Two important missions planned for launch this decade hope to parlay these new IR technologies into another great leap in our knowledge of the universe: the Infrared Space Observatory (ISO) and the Space IR Telescope Explorer (SIRTF).

The European Space Agency (ESA)



plans to launch the ISO in September 1995. On board, four scientific instruments will study the sky from 2.5 to 200 µm. An imaging photopolarimeter will cover the ISO's entire spectral range using four subsystems: a multiband photopolarimeter (3–120 µm), far-IR camera (50–240 µm), spectrophotometer (2.5–12 µm), and mapping array (18–28 µm). Imaging will be performed in two bands from 2.5 to 17 µm by a camera and polarimeter called ISOCAM, which is built around two 32 × 32 IR arrays: an InSb CID array for 2.5–5.5 µm and a Si:Ga array for 4–17 µm (see Fig. 4). Finally, two spectrographs will analyze IR sources in two bands from 2.5 to 45 µm and 45 to 180 µm. A 60-cm telescope will gather IR radiation for the ISO instruments. And liquid helium will keep some of the IR arrays at 2 K throughout the observatory's expected lifetime of 18 months.

NASA's SIRTF is scheduled for launch in 2002 atop an Atlas IIas rocket. This observatory will house three instruments that cover the spectral range from 2.5 to 200 µm with five types of advanced imaging arrays: a 256 × 256 InSb array; a 128 × 128 Si:As IBC (Impurity Band Conduction) array; an 128 × 128 Si:Sb IBC array; a 32 X 32 Ge:Ga

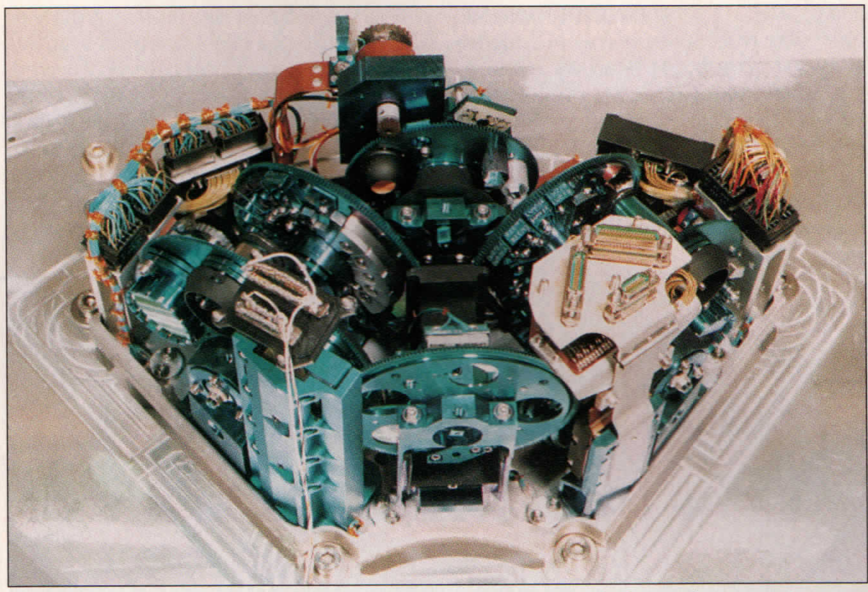

CATHERINE CESARSKY/CEN-SACLAY

FIGURE 4. Infrared Space Observatory camera (ISOCAM), an intricately designed IR camera/polarimeter, houses two 32 × 32 detector arrays for imaging at wavelengths from 2.5 to 17 µm. The instrument is one of four on board the ISO, which is set to blast off in September 1995.

array; and a 2×16 Ge:Ga (stressed) array. The three instruments include an IR spectrograph, an IR array camera, and a multiband imaging photometer. An 85-cm telescope will collect IR radiation for the instruments, and 1000 liters of liquid helium will cryogenically cool the equipment and arrays over SIRTF's three-year projected lifetime.

For space-based astronomy in the visible and UV, the HST continues to make new discoveries, despite its flawed 2.4-m primary mirror. In July 1993, NASA announced that the HST had resolved the Andromeda galaxy (our galactic next-door neighbor) into two nuclei, and the news has stimulated speculation over whether Andromeda is really two galaxies in collision.

This month, NASA plans to send astronauts from the Space Shuttle Endeavor to pop the hood of the HST for some anxiously awaited repairs (see *Laser Focus World*, April 1993, p. 173).

X-ray vision

At very short wavelengths, the ferocity of the universe begins to emerge. For example, strong x-ray and EUV emissions from active galactic nuclei and quasars suggest that these cauldrons of chaos may be the products of supermassive black holes. Other high-energy stellar sources also dot the sky, such as white dwarfs, x-ray binaries, and cataclysmic variables.

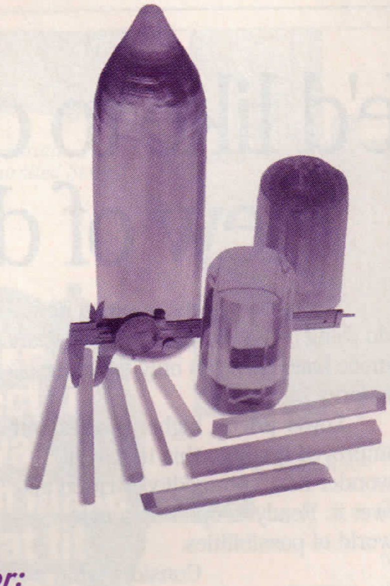
ROSAT has compiled the most complete sky survey of these and other high-energy objects at both x-ray and EUV wavelengths (see Fig. 5); the ROSAT EUV survey is the first of its kind. ROSAT, a joint US and German project, rocketed into space June 1, 1990. On board the spacecraft, two telescopes—a German-built x-ray telescope (XRT) and a British-built wide-field camera (WFC)—focus x-rays and EUV radiation onto image-plane detectors. Detectors for the XRT cover the spectrum from 6–80 Å and include two position-sensitive proportional counters and a high-resolution imager. Two microchannel-plate (MCP) detectors collect radiation from the WFC in the 60- to 200-Å range.

> *At very short wavelengths, the ferocity of the universe begins to emerge.*

Because high-energy photons typically pass straight through matter or get absorbed, ROSAT's telescope designs are unconventional. Both scopes are variations of the Wolter design, which uses nested, grazing-incidence reflectors to focus the radiation.

Two ambitious x-ray observatories are planned for launch toward the end of this decade: NASA's advanced x-ray astrophysics facility (AXAF), which could head skyward in 1998, and the ESA's x-ray multimirror mission (XMM), due to blast off in 1999. Both will carry state-of-the-art instruments for x-ray studies of the universe.

A 1.2-m, high-resolution Wolter-I telescope with six nested mirror shells



will collect radiation for the AXAF's imaging and spectrographic instruments. Imaging will be provided by a CCD and an MCP. The MCP will furnish 0.5-arcsec angular resolution. Also planned is a precision x-ray calorimeter with high quantum efficiency and an energy resolution of 10 eV. The AXAF will scan the sky at wavelengths between 1.24 and 124 Å during its 15-year projected lifetime.

The XMM will analyze the heavens between 1 and 50 Å with an assortment of cameras and spectrographs. An optical monitor will provide simultaneous coverage of the sky at wavelengths from 150 to 1000 nm. A battery of three Wolter-I type telescopes will empower the XMM with tremendous sensitivity at short wavelengths, while a 30-cm Cassegrain will concentrate light for the optical-monitor detector. CCD detectors of various kinds will be used on almost all the instruments of the XMM except the optical monitor, which will use a multichannel plate for the blue end of the spectrum.

These missions offer just a taste of the

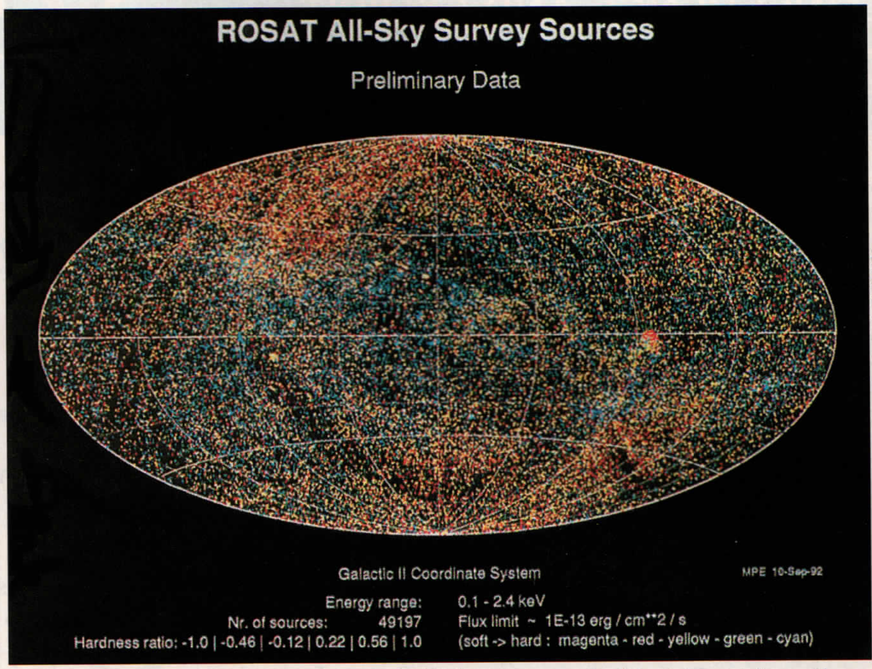


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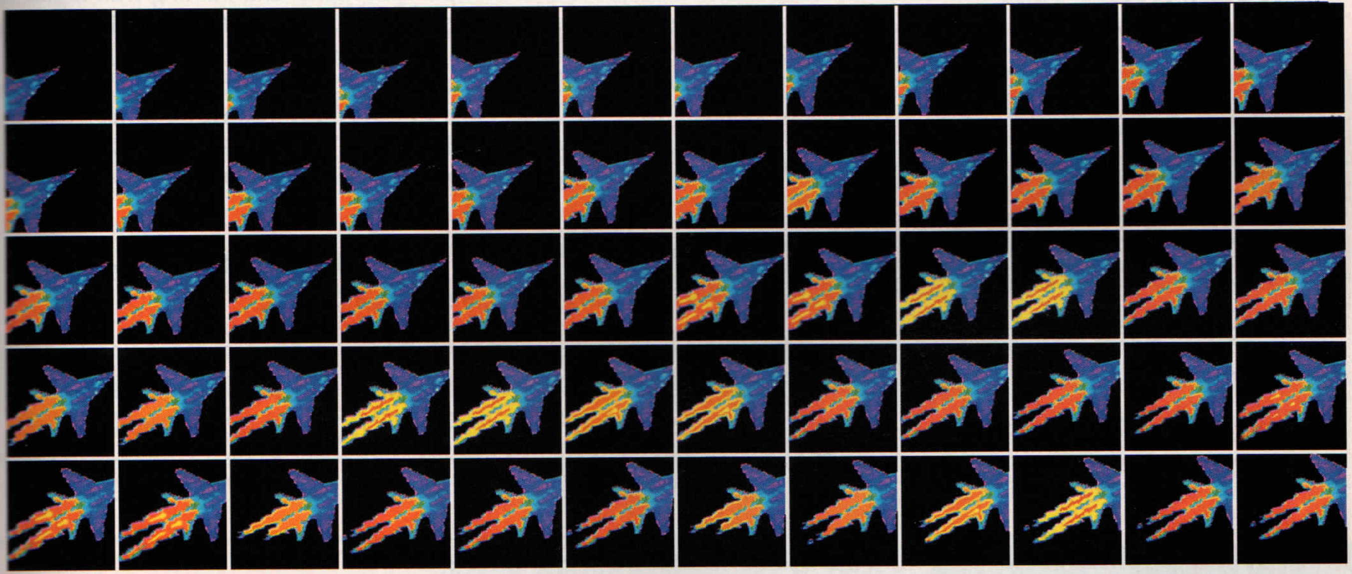
FIGURE 5. Some 50,000 x-ray sources appear in this first-ever portrait of the universe taken with an imaging x-ray telescope. Data gathered by ROSAT were used to compile this galactic map of sources in the 0.1–2.4-keV energy range.



many breathtaking advancements that continue to inspire astronomers. When Galileo first peered through his crude 2-in. refractor, what he saw changed forever our view of the universe and ourselves. And as astronomy ventures forth into a new era of discovery, the view from earth just keeps on getting better. ☐

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