

THE DECADE OF INFRARED ASTRONOMY

The 1990s should see an 8-m infrared telescope built atop Mauna Kea, a 2.5-m telescope in a 747 jumbo jet that will fly above 99% of the water vapor in Earth's atmosphere and a 1-m cryogenic telescope inserted into a 100 000-km orbit.

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The enormous technological and scientific advances of the 1980s give us an unparalleled opportunity to address fundamental issues in astrophysics through observations at infrared wavelengths. The recommendations of the Astronomy and Astrophysics Survey Committee reflect these opportunities for research in the 1–1000-micron wavelength range. The highest priority recommendations for large new projects in this part of the spectrum are for a Space Infrared Telescope Facility, or SIRTf, and an 8-meter ground-based Infrared Optimized Telescope, or IRO. A Stratospheric Observatory for Infrared Astronomy, or SOFIA, is a highly recommended medium-sized initiative, and there are strong recommendations for several other infrared initiatives.

Two technological breakthroughs of the 1980s have revolutionized our ability to exploit the scientific potential of infrared astronomy: the development of solid-state detector chips sensitive to infrared radiation, and the demonstration of long-duration containment of superfluid liquid helium in space.

The recent development in the US of high-performance infrared arrays promises to make ir telescopes millions of times more capable than their predecessors of a few years ago. Each picture element of a modern ir array can be some 10 to 100 times more sensitive than previous single-pixel detectors. Combined with the increased numbers of pixels, the gain in "speed" can be 10^7 to 10^9 , enabling qualitatively new approaches to instrumentation

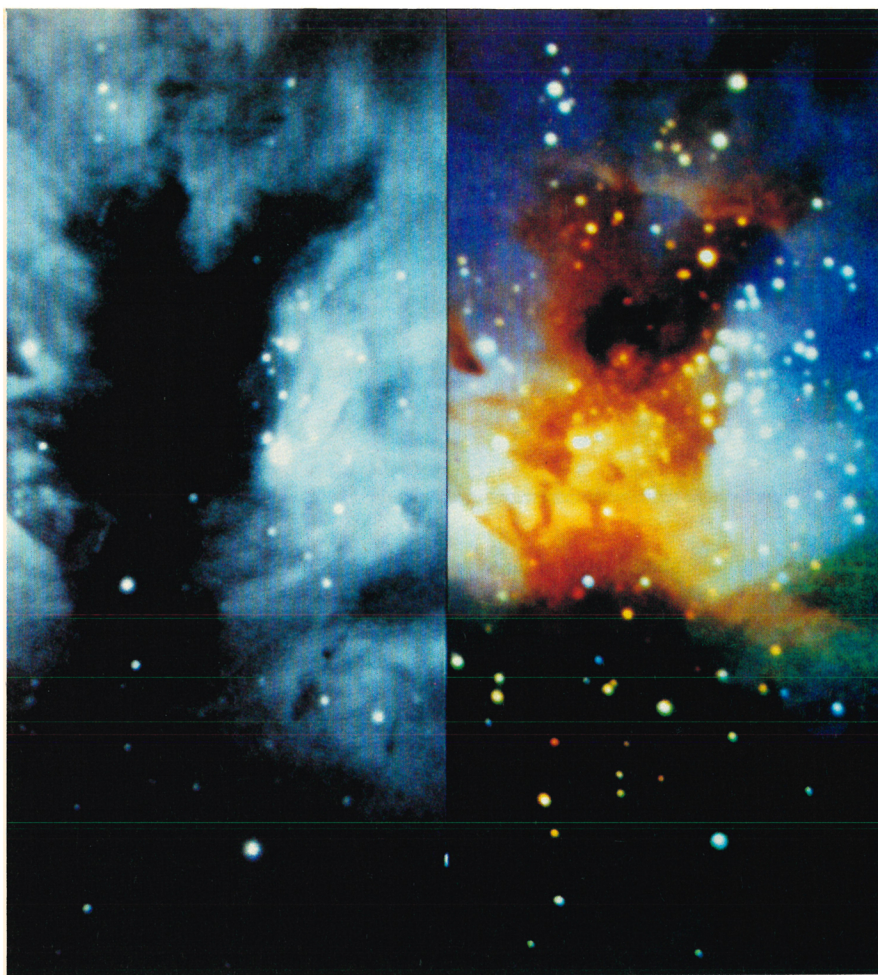
design and entirely new classes of scientific investigation. Although still in their infancy, these arrays have already been used to study a wide range of phenomena, such as the nearby star-forming region NGC 2024 shown in figure 1 and the starburst galaxy NGC 253 in figure 2.

The highly successful Infrared Astronomical Satellite, which was one of NASA's Explorer program missions and a joint project of the US, the Netherlands and the United Kingdom, was the first orbital demonstration of a long-lived telescope and instrument package cooled by superfluid liquid helium. The 1983 IRAS all-sky survey revealed the full richness and variety of the infrared sky, laying the foundation for major scientific advances throughout astrophysics. IRAS discovered infrared emission at 25, 60 and 100 microns from disks of particles orbiting nearby mature stars, first by studying the bright star Vega; these disks appear to be closely related to the evolution of planetary systems and may be debris of the planet accumulation process. Further into the Galaxy, IRAS observations of dark molecular clouds provided the first census of the luminous stellar content in these stellar nurseries and identified candidate protostars, which are compact stellar-like objects dominated by accretion of material from the surrounding prenatal dark cloud.

At much greater distances, IRAS discovered ultraluminous galaxies that emit more than 99% of their radiation in the infrared, radiating 1000 or more times the energy output of the Milky Way. These galaxies are more numerous than quasistellar objects of the same luminosity and may represent an early stage of QSO evolution. Because of their relatively high space density and their high luminosity, ultraluminous ir galaxies are potentially powerful tracers of luminous matter out to the edge of the universe.

In the seven years since the IRAS survey, a broad

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Star-formation region imaged in the visible (left) and infrared (right). The left-hand panel is an I-band (centered at 9000 Å) CCD image of the nearby region NGC 2024 showing a very heavily obscured band across the cloud. The right-hand panel is a near-infrared view of the same region, with 1.2-, 1.6- and 2.2-micron images printed in blue, green and red, respectively. The infrared image reveals a complex of young and forming stars at its heart. The near-ir image was created in less than one hour by a camera that uses modern infrared array detectors. A few years ago, such ir images were virtually impossible; mapping this region with a single ir detector and a large telescope would have taken many hundreds of years. The images were obtained using telescopes at the National Optical Astronomy Observatories, in Tucson, Arizona. (CCD image courtesy of Ron Probst; infrared image courtesy of Ian Gatley and Mike Merrill.) **Figure 1**

cross-section of the astronomical community has published more than a thousand scientific papers using IRAS data, testifying to the broad impact of infrared observations on astrophysical investigations.

Fundamental principles

Four physical principles allow infrared observations to play a critical role in addressing questions at the core of modern astrophysical inquiry. Infrared observations enable us to:

▷ **study cool states of matter.** The most common stars are cooler than the Sun and emit much of their energy in the infrared. Near-infrared wavelengths (1–3 microns) are particularly sensitive to the stellar component that dominates the luminous mass in evolved galaxies. Substellar objects and all planets, including Earth, emit most of their radiant energy in the mid infrared (3–30 microns) and far infrared (30–300 microns). Star-forming regions and massive interstellar clouds are cooler still, radiating the bulk of their energy in the far infrared; this makes ir observations essential for understanding the process of star and planetary system formation.

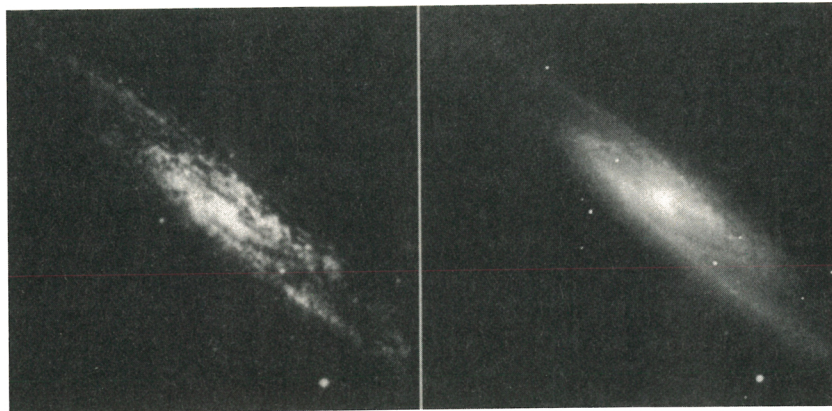
▷ **explore the hidden universe.** Cosmic dust, a ubiquitous and efficient absorber of optical and ultraviolet radiation, becomes increasingly transparent in the infrared, where it re-emits the bulk of its absorbed energy. This is illustrated dramatically in figure 3. Our Galaxy is transparent at mid-ir wavelengths, while optical radiation from the galactic center is attenuated by a factor of about 10^{12} . Star and planetary birth processes occur deep within molecular clouds that are even more opaque.

▷ **access a wealth of spectral features.** Atoms, ions

and virtually all molecules and solids have some spectral features in the infrared. These features carry information on conditions in regions as diverse as atmospheres of planets; cold interiors of dark clouds; circumstellar disks, which contain the raw material of planets; and shocks in supernova remnants; obscured stars and the nuclei of galaxies. The emitting material in these sources ranges from condensed forms of matter, such as ices and silicates, to highly ionized gases, and from that most abundant of simple molecules, molecular hydrogen, to highly complex hydrocarbons. Highlights of the strides made in the past decade to assess this wealth include: the first detection of the H_2O parent molecule in comets; the initial estimates of the masses of Fe, Co and Ni in supernova 1987A; the measurement of the dominant far-ir cooling lines of atomic gas in such diverse objects as ionized regions around young stars and the centers of active galactic nuclei; and the tentative identification of the “unidentified ir emission bands,” found in the mid ir, with emission from polycyclic aromatic hydrocarbon molecules. These large molecules are transiently heated by absorption of a single uv photon, and IRAS observations suggest that transient heating is very widespread and that such macromolecules may represent a major new component of the interstellar medium.

▷ **reach back to the early life of the cosmos.** The expansion of the universe inexorably shifts energy to longer wavelengths. The primeval fireball of high-energy gamma rays produced in the Big Bang now appears as 2.7 K blackbody radiation that peaks near 1000 microns. Most of the energy emitted from stars, galaxies and quasars since the beginning of time now lies in the

Starburst galaxy NGC 253 viewed in the optical (left) and near infrared (right). The color coding of the infrared radiation is as in figure 1. Near-infrared radiation penetrates the internal dust obscuration in this peculiar and interesting galaxy, allowing study of the distribution of stars and interstellar material throughout the galaxy. (Optical image courtesy of Anglo-Australian Telescope Board, photography by David Malin; infrared image courtesy of Gatley and Merrill.) **Figure 2**



infrared. Recent optical observations have established that the initial nucleosynthesis, star formation and galaxy formation occurred at a redshift z greater than about 5—sufficiently high so that infrared observations are required to locate the formation epoch.

Observing techniques

Most of the infrared radiation arriving at Earth is absorbed in the atmosphere long before it can reach the ground. Although water vapor is the principal absorber, carbon dioxide, ozone and methane are also important. Ground-based ir observations are made between the strong molecular absorption bands, through the half-dozen windows in the atmosphere in the 1–30-micron range and 300–1000-micron range.

Observational techniques in the near ir are similar to those used at optical wavelengths, but the instrumentation and detector technology are different. In the mid and far ir, the thermal background radiation produced by an ambient-temperature telescope and the atmosphere are far larger—by 5 or 6 orders of magnitude—than the astronomical signal of interest. Infrared optimization techniques to minimize the local background and extract the astronomical signal have evolved to the point that for many observations, the fundamental photon statistics of the background signal power (in which the uncertainty is simply the square root of the number of collected photons) sets the ultimate limit to the system sensitivity.

Infrared array technology in the near and mid ir is evolving very rapidly, and substantial development, evaluation and application work are still needed. High-quantum-efficiency, low-noise, low-dark-current arrays, such as shown in figure 4, are becoming available in formats up to 256×256 pixels in the 1–5-micron wavelength range, and formats of 1024×1024 pixels may be feasible within five years. Arrays of comparable quality for the 5–30-micron range in formats of 256×256 pixels are also within reach.

Experiments during the past decade have shown that corrections to the wavefront distortion caused by the atmosphere can restore the angular resolution of a large infrared telescope to nearly the diffraction limit. The development of the IRO, an ir-optimized 8-m telescope equipped with modest adaptive optics, will allow imaging through the 1–30-micron atmospheric windows with unprecedented spatial resolution.

Earth's atmosphere is essentially opaque in the far ir, and so observations over much of this spectral range and at the many other infrared wavelengths obscured from the ground can be made only from stratospheric or higher altitudes. NASA has developed a unique airborne astronomy program, led by the Kuiper Airborne Observatory, a

0.9-m telescope in a C-141 aircraft. The airborne program has been very successful for over a decade and a half, demonstrating its flexibility and utility. It has made critical observations ranging from stellar occultations at optical wavelengths to collapsing clouds at 300 microns; unfortunately, it is now becoming scientifically limited because it can study only a small fraction of the known infrared sources. *SOFIA*, which will replace the Kuiper Airborne Observatory, is key to the continued development of airborne infrared astronomy.

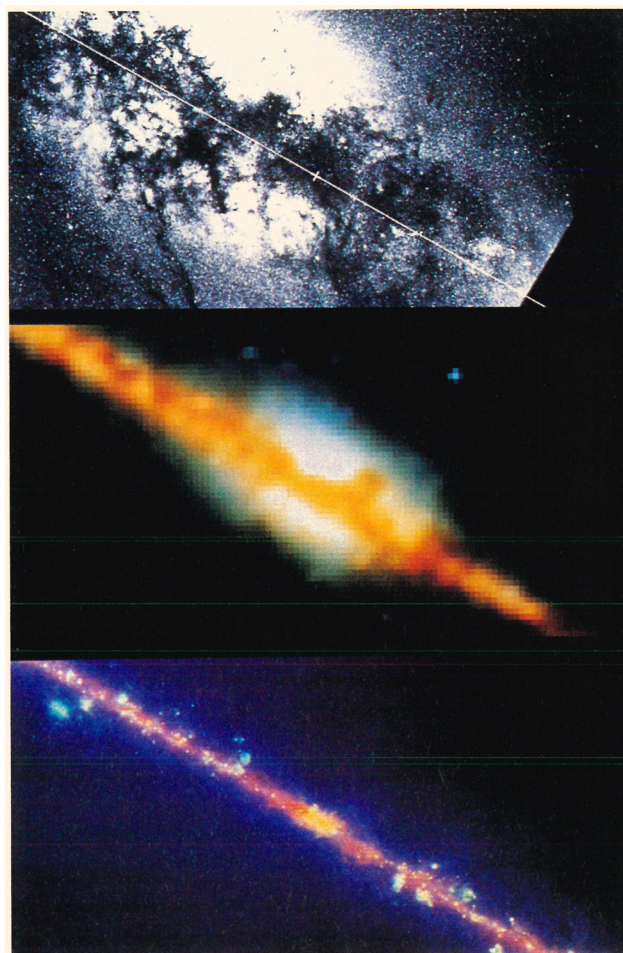
The natural mid- and far-ir background in space, due primarily to emission from interplanetary and interstellar dust grains, is about a million times fainter than that of an ambient-temperature telescope. A cryogenically cooled space telescope exploits this enormous reduction in background, obtaining a sensitivity increase of a factor of 1000. *IRAS*, and more recently the Cosmic Background Explorer, opened the era of ir space astronomy by demonstrating the fundamental cryogenic technology and providing a glimpse of the rich variety of the ir sky. In 1993 the European Space Agency is planning to launch an *IRAS* follow-on mission called the Infrared Space Observatory. The proposed *SIRTF*, a larger, much more capable ir space observatory, will combine the sensitivity of a cryogenic space telescope with the power of modern ir detector arrays to achieve extraordinary gains in capability—a millionfold or more over the current state of the art in the infrared, and a thousandfold over the Infrared Space Observatory.

Initiatives for the 1990s

The Space Infrared Telescope Facility, the fourth of NASA's Great Observatories, is a 1-m-class telescope cooled by liquid helium and mounted on a free-flying spacecraft that will be launched into a circular orbit of 100 000-km altitude by a Titan IV–Centaur rocket.¹ (See figure 5.) *SIRTF* will be equipped with instruments that use modern infrared arrays to provide diffraction-limited imaging from 2 to 200 microns, photometry to at least 700 microns and low- and moderate-resolution spectroscopy over most of the 2.5–200-micron range.

SIRTF will operate as a national facility, with more than 85% of its observing time available to the community. Its five-year lifetime will permit follow-up studies of the many new scientific questions that its own discoveries will raise. An archival research program will insure that the *SIRTF* data remains accessible to the scientific community long after the data acquisition ends. The sensitivity of a cryogenically cooled space observatory, coupled with the power inherent in large-format infrared arrays, make *SIRTF* a unique tool for solving key astrophysical problems ranging from the solar system at our doorstep to whatever

Galactic plane as it appears in the optical (top), near infrared (middle) and mid and far infrared (bottom). The view is toward the Galactic center. The near infrared view is from the COBE satellite and uses the same color coding as figure 1. The mid- and far-infrared view is from the IRAS satellite and shows 12-, 60- and 100-micron radiation as blue, green and red, respectively. Interstellar dust obscures the Galactic plane at optical wavelengths, while near-ir radiation penetrates the dust to expose the stellar content of our Galaxy, showing the concentration of stars toward the plane and in a strong stellar bulge around the center. At the longer ir wavelengths, one sees the well-defined plane and a very compact, bright center, as defined by the emission from star-formation regions and regions of ionized hydrogen. **Figure 3**



is beyond the horizon of our current understanding of the universe.

SIRTF has been under extensive study by NASA, the astronomical community and industry for nearly a decade. If development starts in FY 1994, **SIRTF** can be launched around the year 2000, allowing a significant period of time for coordinated observations with two of NASA's other Great Observatories, the Hubble Space Telescope and the Advanced X-Ray Astronomy Facility.

The Infrared Optimized Telescope, an 8-m ground-based telescope optimized for infrared observations, is to be built atop Mauna Kea, Hawaii, which is generally recognized as the best ir site in the world.² The telescope's thermal emission will add only minimally to that from the atmosphere. Modest adaptive optics will enable the IRO to achieve near-diffraction-limited imaging performance of 0.1 arcsec at 2.2 microns and to exceed the sensitivity of a conventional 8-m telescope by more than an order of magnitude while achieving the sharpest practical imaging.

The IRO's high spatial resolution will enable it to make detailed images of complex regions of star formation and the nuclei of galaxies. Its large collecting area will gather the huge numbers of photons needed for high-resolution spectroscopy.

SOFIA. The Stratospheric Observatory for Infrared Astronomy is a 2.5-m telescope system mounted in a modified Boeing 747 aircraft.³ Flying more than 100 eight-hour missions per year at an altitude of 41 000 feet, which is above 99% of the water vapor in the Earth's atmosphere, **SOFIA** will provide the astronomical community with routine observations at most of the infrared wavelengths that are inaccessible from the ground. **SOFIA**'s tenfold increase in collecting area over the Kuiper Airborne Observatory will allow routine study of the sources in the IRAS Point Source Catalog and will give the highest spatial resolution at ir wavelengths obscured from the ground. **SOFIA** will provide an excellent platform for the development of advanced instrumentation and for the education and training of the next generation of experimenters.

SOFIA is a joint project with Germany, which is participating in the program and providing about 20% of the funding. NASA and the German Science Ministry have completed preliminary design studies for **SOFIA**. A development start in FY 1993 would allow observations to begin in 1998.

Other infrared initiatives. In addition to recommending the national observatories described above, the Astronomy and Astrophysics Survey Committee report identifies several other infrared initiatives for development in the coming decade.

One of the Explorer missions cited in the AASC report is the Submillimeter Mission. This mission will use a 2.5-m ambient-temperature telescope with a complement of liquid-helium-cooled instruments, to obtain complete submillimeter spectra for a large number of galactic and extragalactic sources from 100 to 700 microns. The Submillimeter Mission will provide our first spectroscopic view of a large fraction of the sky in the submillimeter portion of the electromagnetic spectrum.

The mission's spectral atlas of molecules, atoms and ions will provide the critical data needed to understand the chemistry, dynamics and heating and cooling processes that occur in interstellar gas and dust. Submillimeter spectra of nearby galaxies will provide the basis for comparative studies of star formation, interstellar chemistry and energy balance processes.

The AASC report identifies several small initiatives as meritorious. One of these is a near-ir all-sky survey at a level of sensitivity 50 000 times greater than that achieved by the 1969 Two Micron Sky Survey. This initiative is a prime example of a small project with a large long-term payoff. A pair of 1-m-class ground-based telescopes—one for each hemisphere—equipped with modern near-ir array detectors, can survey the entire sky at three wavelengths between 1 and 2.2 microns in less than two years, detecting an estimated 100 million sources. The survey will explore the large-scale structure of the local universe by mapping the distribution of galaxies to a distance of 4×10^8 light-years; investigate the structure of our galaxy; inventory the stellar content of regions of galactic star formation;

and stimulate the major observatories of the 1990s to do follow-up observations of selected survey sources.

Science prospects

Of the many key investigations that the ir initiatives for the 1990s will make possible, we will discuss only two here: the formation of galaxies and the formation of stars and planetary systems.

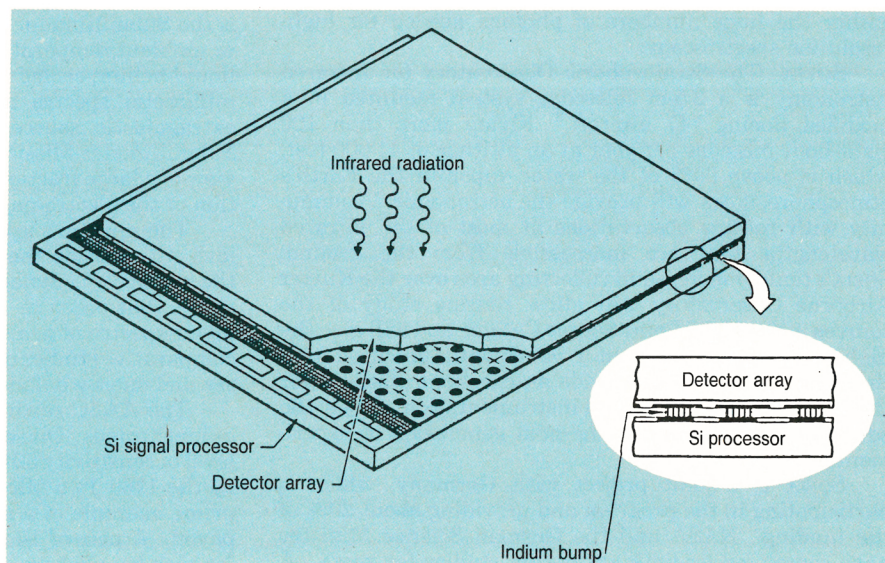
Formation of galaxies. How did the initially homogeneous Big Bang evolve into the observed galaxies and accompanying large-scale structure? To address this question empirically, we must first observe the epoch of galaxy formation and then trace the development of galaxies and the large-scale structure in their distribution as a function of redshift (time). We must understand if and how individual galaxies have been involved in the processes that explain these large structures. On a local scale, we must fit the details of our own Galaxy into this overview.

The most promising regions in the entire electromagnetic spectrum for detecting radiation from the formation of primordial galaxies are two windows in the infrared where the infrared sky is particularly free of foreground emission. One of these falls at 3–4 microns, between the scattered and re-radiated emission from interplanetary dust grains, and the other is at 200–500 microns, between

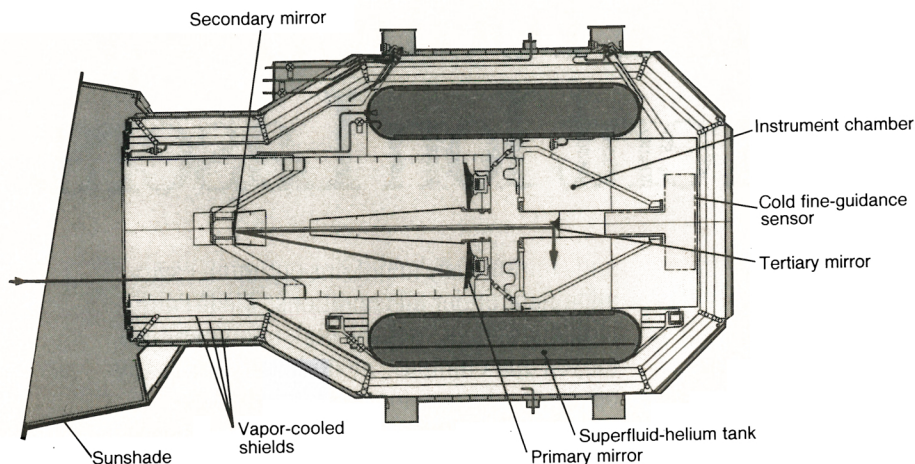
the thermal emission from galactic dust and the cosmic microwave background.

As a first step, measuring extragalactic infrared backgrounds can set limits on the epoch and nature of galaxy formation. The Cosmic Background Explorer mission will provide an accurate measure of the background, and if the contribution from nearby objects can be accurately subtracted, we can detect or set stringent limits on the radiation arising from initial galaxy formation.

The actual detection of individual forming galaxies is within the grasp of the ir initiatives for the 1990s. Star formation in local galaxies is invariably accompanied by dust absorption at uv and optical wavelengths and re-emission in the mid and far ir. If this is the case for the first generation of galaxies, the emission will appear in the far ir. However, the abundance of heavy elements may be so small that an effective dust screen cannot form. In that case, the uv emission will escape from the forming galaxy and appear redshifted into the window in the emission between 3 and 4 microns. In either case, once a galaxy reaches the still very young age of 10–30 million years after its first stars are formed, much of its luminosity is produced by cool red giant stars that emit a broad spectrum of radiation peaked at 1.6 microns, which will escape. Again the dominant emission will be observed in the infrared. SIRTf's extreme sensitivity and broad



IR detector hybrid arrays, consisting of detector and signal-processor sections. The detector absorbs incident photons, liberating charge carriers, which are collected in the silicon signal-processor section and read out through a built-in multiplexer. The detector's picture elements (pixels) are individually connected to the signal processor by means of a flexible indium "bump" bond. **Figure 4**



Space Infrared Telescope
Facility scheme. A cylindrical tank of liquid helium surrounds the Earth-orbiting telescope and instruments, cooling them to about 2 K. The fixed solar panels power the SIRTF observatory and shield the outer shell of its cryogen system from solar radiation; an aperture shade shields the telescope system from the Sun and Earth. **Figure 5**

capabilities will allow it to analyze any of these scenarios. The IRO can obtain detailed images and spectra of young galaxies in the early universe to determine their morphology, redshift, composition and ionization state.

In some nearby ultraluminous infrared galaxies, bursts of star formation generate nearly all of the observed luminosity, while other such galaxies appear to harbor dust-enshrouded quasars. SIRTF's imaging surveys will trace the evolution of quasars and ultraluminous infrared objects to redshifts well in excess of 5. Low-resolution infrared spectra of emission from dust and gas can identify characteristic features and determine the redshift, and hence the luminosity, while higher resolution spectra can distinguish between starburst and quasistellar object emission. These studies will determine how both the absolute and the relative number of starburst galaxies and dust-enshrouded quasars vary with epoch and how the cosmic evolution of this population compares with that of the optically and radio selected quasars to which they may be related. They will also locate the extreme epoch of observability—the formation epoch.

Our own Galactic nucleus may provide valuable clues to the phenomena occurring in distant galactic nuclei. One interpretation of data from ground-based and airborne observations is that a black hole of moderate mass resides at the center of our Galaxy. Although its mass is far less than that of the black holes postulated for the centers of quasistellar objects, it can be studied at enormously greater spatial resolution. Far-infrared polarimetry spectroscopy from SOFIA will map the magnetic field distribution and gas dynamics in the 8–40 light-year ring of gas and dust that surrounds the center of the Galaxy and may identify a magnetic accretion disk from which material spirals into the Galactic center. The IRO will measure the three-dimensional motion of hundreds of stars within the central parsec of our Galaxy through a combination of proper motion and spectroscopy to an accuracy of 10 km/sec, and so provide a critical test for the presence of a black hole.

Formation of stars and planetary systems. Many essential questions concerning the formation of stars and planets remain unanswered. In the current view, the process begins with the collapse of the core of a dense molecular cloud, forming a protostar and a surrounding accretion disk. The protostar grows by the direct infall of material onto its surface and by accretion from the inner boundary of the disk; the gas and dust that remains in the disk provides the raw material from which planets may later form. The infall phase continues until outflow from

the forming protostar drives away infalling material. The initiatives of the 1990s will be able to identify and study individual forming stars and substellar objects, measure their luminosity and relate star formation rates to the properties of the parent cloud.

SOFIA-based studies of emission from the shocks at the interfaces between the infalling material, the accretion disk, the outflowing material and the ambient molecular cloud will show how these flows evolve and interact. Observations show that the outflows are frequently collimated, by an as yet unidentified process, into a bipolar jet-like flow. IRO imaging will resolve the jets and outflows that are as close as 10 AU to a protostar in the nearby Tarus cloud, thereby probing the collimating agent.

As the accretion phase ends, the dust in the (now) protoplanetary disk settles to the midplane, coagulates and forms planetesimals, which may ultimately accumulate into planets. The IRO will allow us to image nearby protostellar and protoplanetary disks and to detect gaps that may signal the formation of planetary systems.

Finally, only planets, satellites, asteroids and comets are left, although the occasional collisions of these larger bodies produce disks of planetary debris. IRAS's discovery that more than 20% of mature main-sequence stars near the Sun possess orbiting solid material remains the best evidence for the occurrence of planetary systems around other stars. In the next decade, SIRTF will be able to detect and study Vega-like disks around tens of thousands of stars out to distances of tens of thousands of light-years. SIRTF, SOFIA and IRO will be able to obtain detailed images of nearby disks—searching for interior voids that may signal the presence of planets. And low-resolution spectra of the debris will provide critical checks for the composition, replenishment and origin of the material.

References

1. For a more detailed overview of SIRTF, see M. W. Werner, P. G. Eisenhardt, *Astrophys. Lett. and Comm.* **27**, 89 (1988), and the articles on SIRTF that follow, or contact M. W. Werner, MS 171-267, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109.
2. For more information on 8-m telescope designs and advanced technology telescopes, see *SPIE Proc.* **1236** (1990), or contact P. Osmer, NOAO, P. O. Box 26732, Tucson, AZ 85726.
3. For a more detailed overview of SOFIA, see E. F. Erickson, J. A. Davidson, G. Thorley, L. J. Caroff, technical memo 103840, NASA, Washington, DC (1991), or contact E. F. Erickson, MS 245-6, NASA Ames Research Center, Moffett Field, CA 94035. ■