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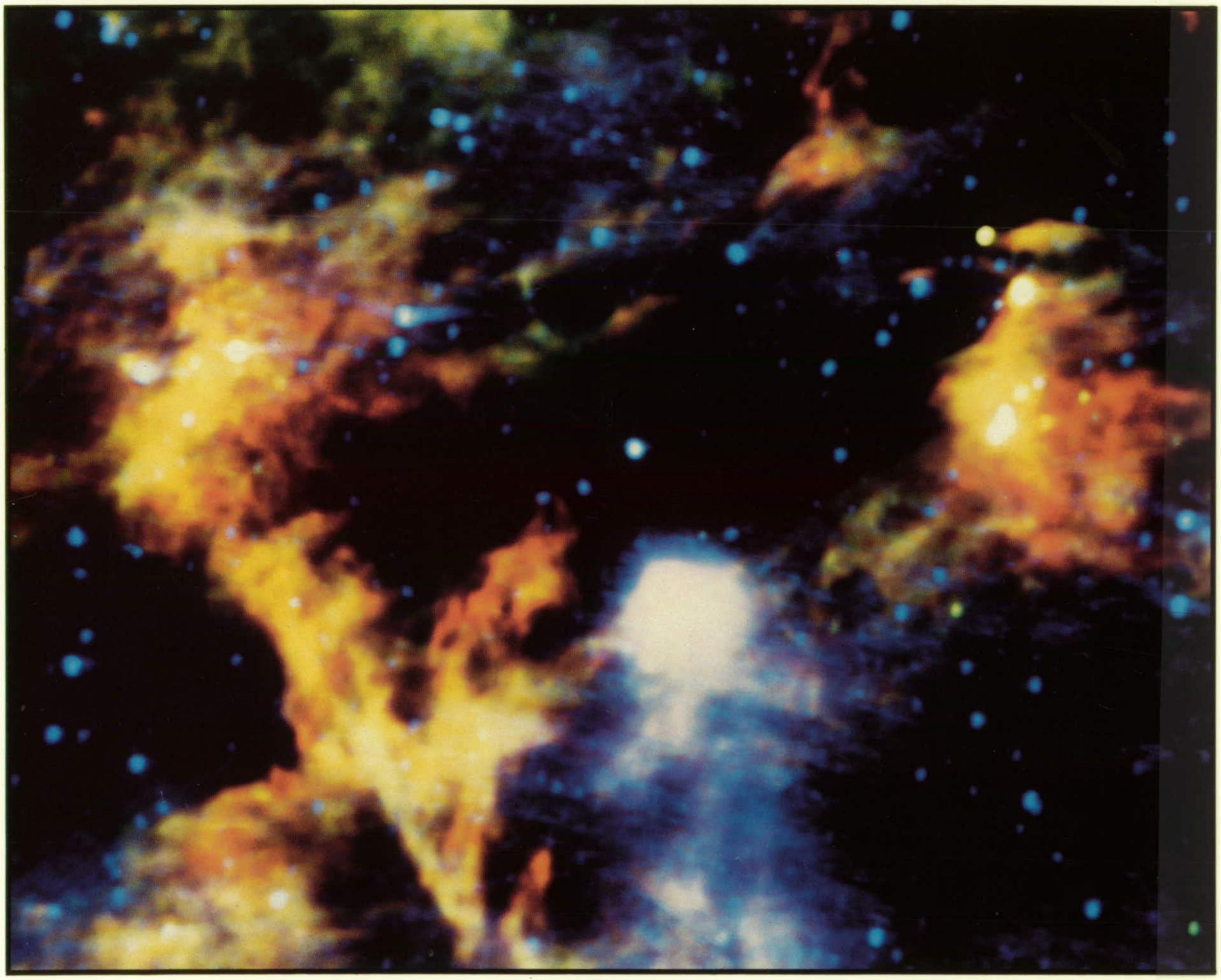
A Scientific Program for Infrared, Submillimeter and Radio Astronomy From Space

A Report by the Management Operations Working Group



June 1989

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An IRAS image of a 9° × 9° region of the Chamaeleon molecular cloud shows stars younger than 10^5 yr forming out of dense molecular gas. The color coding is such that 12 μm emission is blue, 60 μm emission is green, and 100 μm emission is red. Hot stars appear blue, while embedded protostars appear orange or white.

A Scientific Program for Infrared, Submillimeter and Radio Astronomy From Space

A report by the Management Operations Working Group

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EXECUTIVE SUMMARY

Important and fundamental scientific progress can be attained through space observations in the wavelengths longward of 1 μm. The formation of galaxies, stars and planets, the origin of quasars and the nature of active galactic nuclei, the large scale structure of the Universe, and the problem of the missing mass, are among the major scientific issues that can be addressed by these observations. Significant advances in many areas of astrophysics can be made over the next 20 years by implementing the program outlined in this report. The program combines large observatories with smaller projects to create an overall scheme that emphasizes complementarity and synergy, advanced technology, community support and development, and the training of the next generation of scientists. Key aspects of the program (Figures 1 & 2) include:

- *The Space Infrared Telescope Facility (SIRTF)*

SIRTF* will complete NASA's Great Observatory program. It will be a 1-m class orbiting infrared telescope, cryogenically cooled to enable observations in the 2.5—200 μm region. Its sensitivity will be limited only by the natural radiation background of space. Throughout its mission life of at least five years, SIRTF will be operated as an observatory for the astronomical community. It will carry an instrument complement (an infrared array camera, a spectrometer and an imaging photometer) that will capitalize on the latest in detector array technology developed in the United States. SIRTF's unprecedented sensitivity for broad-band imaging and photometry and for moderate-resolution spectroscopy will allow it to attack the wide range of scientific problems discussed in this report, for example, to search for brown dwarfs, extra-solar planets in nearby space, protogalaxies, and IR-luminous galaxies throughout much of the universe.

- *The Stratospheric Observatory For Infrared Astronomy (SOFIA)*

SOFIA will complement SIRTF by providing the ability to study in depth the dynamics of, for example, regions of star and planet formation, interacting galaxies, planetary atmospheres and comets. SOFIA will be an airborne 2.5-m class telescope mounted in a specially modified Boeing 747 aircraft. The project is a joint venture of NASA and BMFT, NASA's counterpart in the Federal Republic of Germany. SOFIA will provide at least 120 flights per year and its long operational life offers a unique opportunity for continuing instrument development and for training the next generation of astronomers. It offers improvements over SIRTF in spectral resolution and far-infrared spatial resolution that are critical for expanding our understanding of the physical mechanisms operating in astronomical sources. The timely development of SOFIA and SIRTF will ensure that long wavelength data will be available to help understand, and in some cases to guide the observations made by the Hubble Space Telescope (HST) and the Advanced X-ray Astrophysics Facility (AXAF).

SIRTF and SOFIA will provide infrared and submillimeter measurements with the necessary sensitivity, angular resolution, and spectral resolution to complete NASA's Great Observatories. SIRTF and SOFIA should be NASA's highest priorities for this wavelength region.

- *A robust program of small missions*

Explorer-class missions will provide unique opportunities for research and will make vital contributions in the development of new space-qualified instruments and the training of future space scientists. An excellent example is the recently approved Submillimeter Wave Astronomy Satellite (SWAS), a Small Explorer mission, which will pioneer the use of submillimeter heterodyne spectroscopy for space-based astronomical observations. Other aspects of the program include: international collaborations on programs such as the ISO mission and the radio OVLBI missions VSOP and RADIOASTRON; data analysis programs for missions such as IRAS and COBE; and theoretical, laboratory, and ground-based observational investigations relevant to the program's overall goals.

- *The creation of the technology base for future major observatories*

The long-term goal for space-based infrared and submillimeter astrophysics after SIRTF is the Large Deployable Reflector (LDR), a 10—20 m telescope for the 30—600 μm region. Building LDR presents fundamental challenges in a number of areas of technology, including detector arrays, large space structures, cryogenics, and manned operations in space. A strong program of technology development is crucial to LDR's success. SWAS, SOFIA, and a Delta-class Explorer or a moderate mission will provide the scientific assessment of the submillimeter regime and are crucial testbeds for the advanced technologies needed for LDR.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

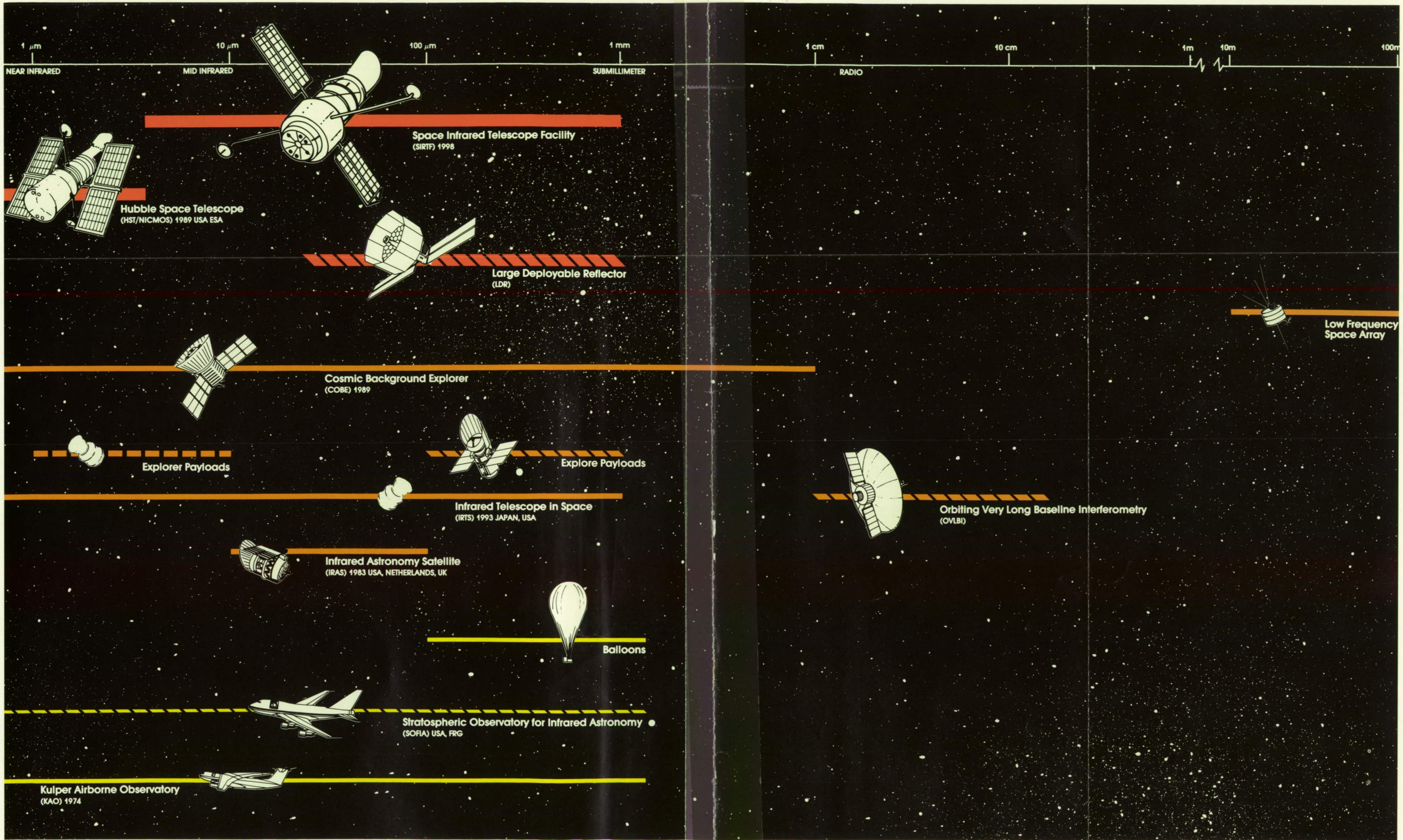

Figure 1. A mixture of large, moderate, and small missions along with programs in laboratory and theoretical astrophysics are needed to carry out the investigations outlined in this report.

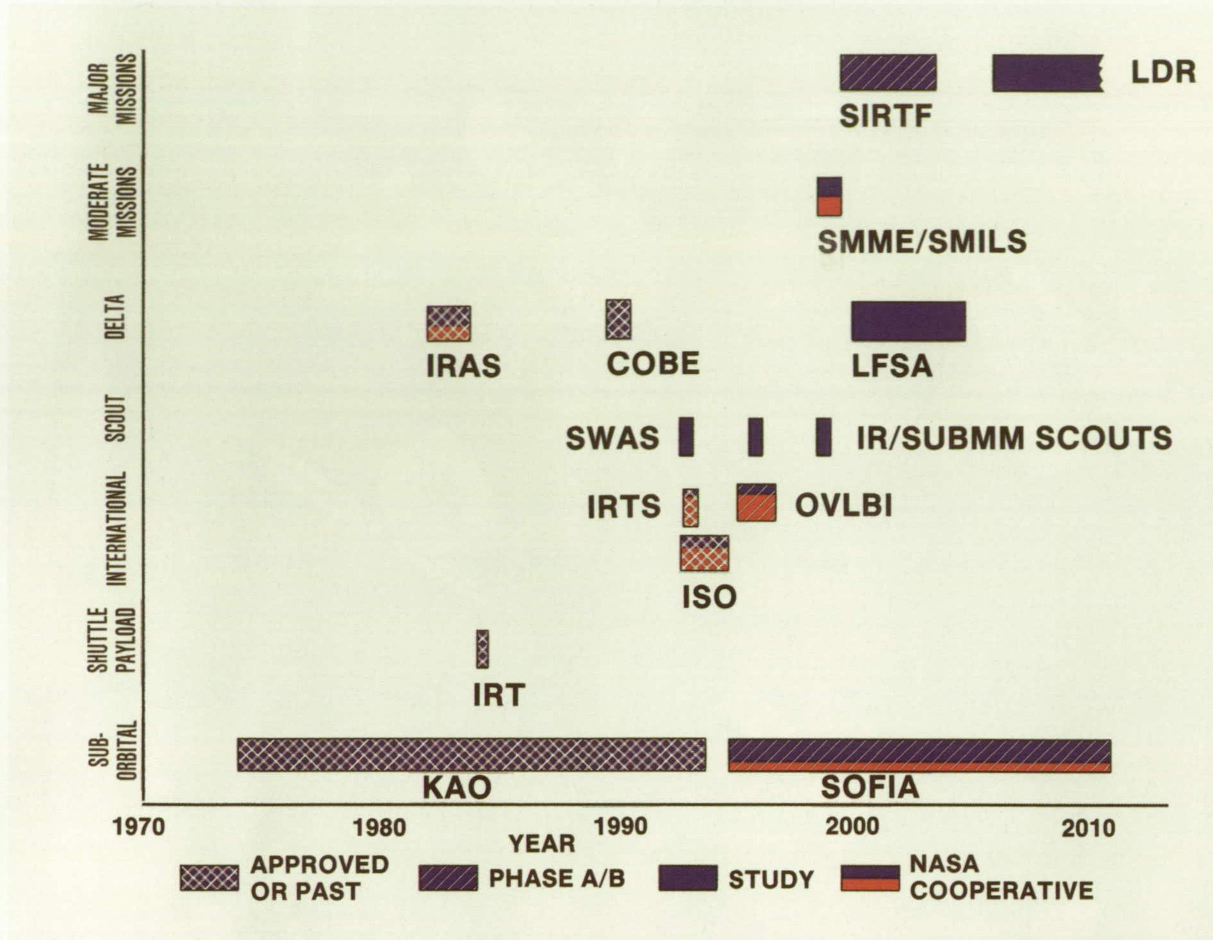

Figure 2. The timeline shows a possible ordering of launch dates for the missions discussed in this report. A list of abbreviations and acronyms appears in the Appendix.

INTRODUCTION

The range of wavelengths covered by NASA's Infrared/Radio Astrophysics Branch is enormous, spanning three decades from the near infrared to the millimeter regime, and extending decades further into the radio. These wavelengths are rich in physical processes that can be used to explore many aspects of the Universe (Figure 3).

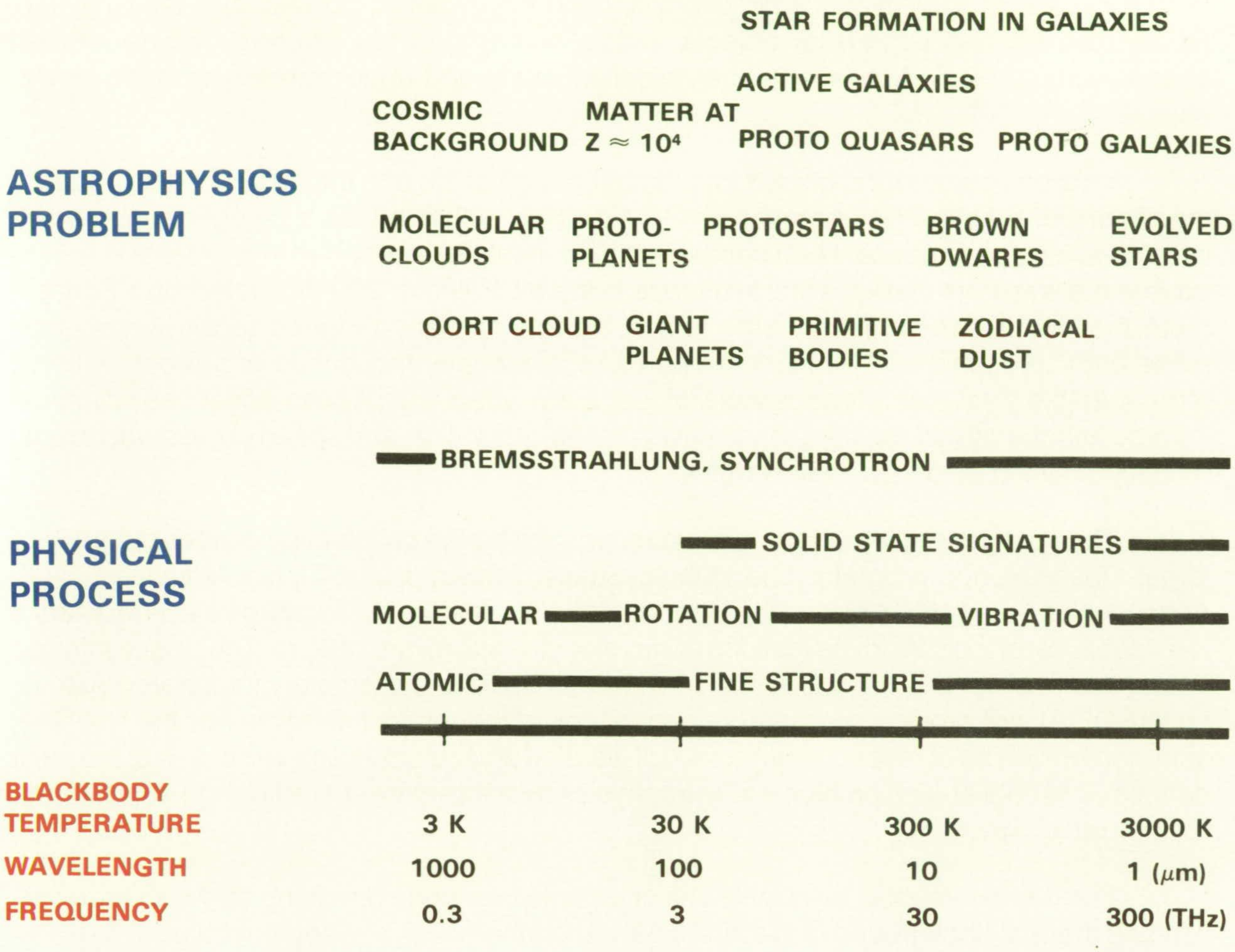

Figure 3. A variety of basic physical and astrophysical principles makes the wavelengths from 1 to 1000 μm critical for investigating important aspects of the Universe. These wavelengths are best studied from space or, in some cases, from airborne telescopes. As discussed in the text, radio wavelengths from 1 cm to >10 m also probe many important aspects of the Universe and some critical observations can only be made from space.

Wavelengths longer than one micron hold the key to the origins of the major structures in the Universe, revealing the formation of solar systems and stars, probing the complex chemistry of the interstellar matter that leads eventually to life itself, uncovering the genesis of normal and active galaxies as well as of quasars, and mapping the overall distribution of matter in the Universe following the Big Bang. Four physical principles account for much of the importance of infrared and submillimeter astrophysics. First, the Hubble expansion inexorably makes the infrared the premier wavelength for the study of the large scale structure of the early Universe; the 3K cosmic microwave background is only one example of this effect. Second, interstellar dust absorbs optical and ultraviolet radiation, then re-radiates the energy at infrared wavelengths. This makes infrared observations essential to uncovering the physical processes that govern the formation of stars and planets in the visually obscured cores of molecular clouds, or that produce the enormous luminosities seen in the dusty centers of active galaxies. Third, major spectral features of many atoms and ions, virtually all molecules and most solids lie in the infrared and submillimeter regime. Thus, this wavelength regime is uniquely suited to studies of cosmic chemistry and the evolution of material in the Universe. Finally, planets and sub-stellar objects radiate primarily in the infrared, making infrared observations particularly critical to the detection, study and understanding of these similar objects.

Infrared astronomy is poised for a breakthrough of the sort that happens only rarely in the history of a field. The improvement in sensitivity achieved by a cryogenically-cooled infrared telescope in space when compared to the best ground-based instruments is analogous to the leap from Galileo's first telescope to the Mt. Palomar 200-inch telescope. Furthermore, the recent development of large-format, high-performance infrared sensitive arrays will make both cryogenic and ambient-temperature telescopes thousands or millions of times more capable than their predecessors of just a few years ago. These advances will thrust infrared astronomy into regimes of sensitivity, spatial resolution, and speed of observation only recently attained at optical wavelengths.

The next generation of infrared telescopes will be the culminating element of NASA's Great Observatories program. The Hubble Space Telescope (HST), the Advanced X-ray Astrophysics Facility (AXAF), and the Gamma Ray Observatory (GRO) will give astronomers a formidable set of tools for investigations at wavelengths shortward of 3 μm. The Space Infrared Telescope Facility (SIRTF), supported by the Stratospheric Observatory for Infrared Astronomy (SOFIA), will provide comparable capabilities at longer wavelengths. For the first time, astronomers will be able to routinely conduct detailed and comprehensive studies of the most complex and challenging problems in astrophysics over the entire spectral range from gamma rays to radio waves.

The improvement in sensitivity of a cryogenic telescope operating above the absorption and thermal background of the terrestrial atmosphere was first demonstrated in 1983 by the Infrared Astronomical Satellite (IRAS), an Explorer-class mission designed to carry out an all sky survey in four broad wavelength bands from 10 to 100 μm. During its 300 day lifetime, this pioneering mission revealed the enormous complexity and variety of the infrared sky (Figure 4). The IRAS discoveries range from dust bands in our solar system, that appear to be debris of asteroid collisions, to structured emission from interstellar grains or "infrared cirrus", believed to be produced in part by large complex hydrocarbon molecules which must be very abundant in the interstellar medium. In addition, IRAS discovered disks of particles surrounding nearby stars which may be planetary systems in formation, numerous "protostars" still shrouded in their cocoons of dust, and IR-luminous galaxies which radiate hundreds of times more energy in the infrared than in the visible. The scientific issues and opportunities raised by the IRAS discoveries will be further discussed in the next section.

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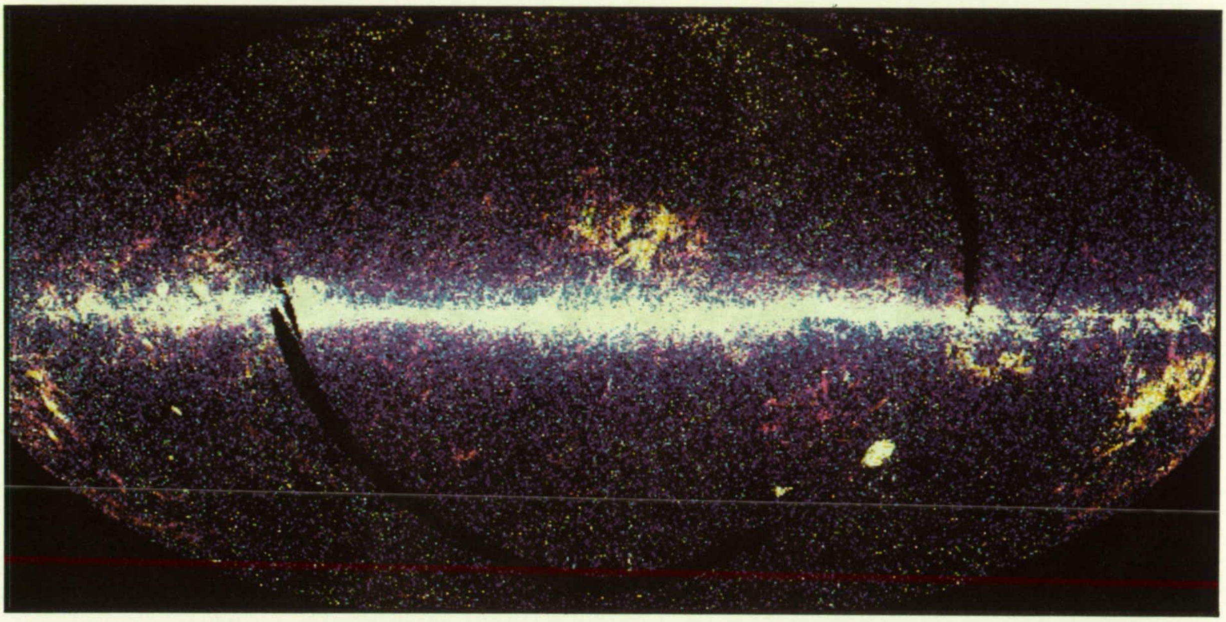

Figure 4. The infrared sky revealed by the Infrared Astronomical Satellite (IRAS) shows approximately 250,000 individual point sources. This view of the entire sky in Galactic coordinates shows the hottest sources (detected at 12 μm) in blue, cooler sources (detected at 60 μm) in green, and the coldest sources (detected at 100 μm) in red. Stars and regions of star formation dominate the Galactic plane, which appears as a horizontal band, while external galaxies dominate the high latitude sky.

In the next few years, two additional missions will complete the *initial assessment* of the infrared spectral regime from space. The Cosmic Background Explorer (COBE), to be launched in 1989, will study the overall emission from the sky on angular scales of a few degrees and larger. This will provide information on the large scale structure of the cosmic background radiation and the earliest phases in the formation of galaxies. In 1993, the European Space Agency will launch the Infrared Space Observatory (ISO) to make follow-up photometric and spectroscopic observations of individual objects found by IRAS.

Since the flight of IRAS, the United States has pioneered a technological revolution in infrared sensors. Sensitive arrays have been developed consisting of tens of thousands of individual infrared detectors in two-dimensional formats as large as 128×128 and 256×256. The Kuiper Airborne Observatory (KAO) serves as an immediately available platform for scientific exploitation of some aspects of this new technology. The new class of arrays will first be used in space in a second-generation Hubble Space Telescope instrument, called the Near Infrared Camera and Multi-Object Spectrograph (NICMOS), which will cover the 1 to 3 μm region. NICMOS is currently being prepared for on-orbit installation in the mid-1990's. However, the full impact of arrays at longer wavelengths will be felt when they are used in conjunction with a cryogenic telescope in space. SIRTF will be a 1 meter-class infrared space telescope and will utilize large-format arrays in high-performance imaging and spectroscopic instruments operating at wavelengths from 2.5 to 200 μm. These arrays will be limited in sensitivity only by the low, natural background of space. Because of its larger aperture and larger, more sensitive arrays, SIRTF can map a given region more rapidly than either IRAS or

ISO by factors that range from one thousand to more that one hundred million! ***It is no exaggeration to state that SIRTF offers a greater gain in the observational state of the art than any astronomical facility envisioned by NASA at any wavelength.***

Nonetheless, the size of SIRTF's aperture is limited due to cost considerations. At very high spectral resolution, instrumental and atmospheric background is less important than telescope aperature in determining the sensitivity for detecting emission lines. The Stratospheric Observatory for Infrared Astronomy (SOFIA) will consist of a much larger airborne telescope (2.5 meter-class) mounted in a specially modified Boeing 747 aircraft. SOFIA and SIRTF are highly complementary, with SOFIA providing the capability for very high spectral resolution, particularly in the submillimeter regime. Together, they will supply the capabilities necessary to carry infrared astronomy into the next century. SOFIA is planned as a joint venture of NASA and BMFT, NASA's counterpart in the Federal Republic of Germany.

SOFIA will serve a dual role within the NASA program: in addition to providing essential, complementary data for SIRTF and the other Great Observatories, SOFIA will be a valuable training ground for the next generation of astronomers and will be a key element in the emerging field of submillimeter astronomy. It will provide NASA with the means to remain at the forefront of long wavelength astrophysics, to develop new instruments and maintain a healthy community of observers, instrument builders, and theoreticians. In addition because of its greater than 20-year lifetime, SOFIA will provide continuity between the IRAS, SIRTF, and LDR eras.

Because many questions in submillimeter and far-infrared astrophysics require ultra-high spatial and/or spectral resolution for their solution, NASA has been studying the feasibility of orbiting a 10 to 20 meter-class ambient temperature (150 K) telescope called the Large Deployable Reflector (LDR), sometime early in the 21st century. LDR will study important far-infrared and submillimeter atomic and molecular spectral lines with velocity resolution better than 1 km s^{-1}. It will have better than 1" spatial resolution between 30 and 100 μm. Maintaining a strong technology development program for LDR should be a critical part of NASA's planning. SOFIA together with small- and intermediate-size precursor space missions—a Submillimeter Explorer or a moderate mission such as the Submillimeter/Infrared Line Survey (SMILS)—are also important for the success of LDR. These missions will carry out pioneering scientific observations and initial far-infrared and submillimeter line surveys, and they will stimulate development and testing of the crucial technologies needed to build LDR.

Although the Earth's atmosphere is transparent at most radio wavelengths, Earth-based very long baseline interferometry (VLBI) has reached the maximum baseline possible — the diameter of the Earth. Higher spatial resolution, together with enhanced dynamic range, can be obtained only by placing radio telescopes in space. The enhancement in spatial resolution afforded by orbiting radio telescopes will result in new insights into a variety of questions, including the nature of the compact central sources which power quasars and active galaxies. An international collaboration on orbiting VLBI (OVLBI) projects such as Japan's VSOP (VLBI Space Observatory Program) and/or the Soviet RADIOASTRON mission would return excellent science for a modest investment by NASA.

At radio wavelengths longer than about 10 m, the Earth's ionosphere blocks celestial signals; beyond about 300 m, the interstellar medium becomes opaque. An Explorer class mission called the Low Frequency Space Array (LFSA) would permit an initial sky survey of this unexplored region.

LONG WAVELENGTH SCIENCE: THE FORMATION OF THE UNIVERSE, GALAXIES, STARS, SOLAR SYSTEMS, AND LIFE

This section addresses a representative set of the fundamental scientific issues that can be answered by observations longward of one micron (Table 1). A continuing theme of long wavelength astronomy is the search for the origins of various astronomical objects, from stars and planets to quasars and the large scale structure of the Universe. To answer these fundamental questions requires different observatories that emphasize various combinations of the broad wavelength coverage, high sensitivity, high spatial resolution or high spectral resolution possible from space.

Table 1. Major Scientific Issues

- The Origin of Stars and Planets
  - The Formation of Stars
  - Protoplanetary Disks
  - Detection of Brown Dwarfs and Extra-Solar Planets
  - Properties of the Solar System
- The Origin and Evolution of Matter and Life
  - The Interstellar Medium and the Formation of Complex Molecules
  - Mass Loss and Nucleosynthesis
  - Solid Matter
  - The Origin of Life
- The Origin and Evolution of Galaxies
  - Protogalaxies
  - Massive Objects in Active Nuclei
  - Ultra-Luminous Galaxies and the Origin of Quasars
  - The Cosmic Distance Scale
- The Evolution of the Universe
  - Background Radiation and Cosmology
  - Distribution of Galaxies in the Local Universe
- Serendipity
- Complementarity with HST, AXAF, and GRO

Formation of Stars

The infrared is the optimum spectral region for the study of the formation of stars out of interstellar gas. The IRAS survey discovered hundreds of stars less than 10^5 yr old embedded in nearby molecular clouds such as Ophiuchus and Chamaeleon (Cover Photo). Many of these objects are thought to be still deriving much of their energy from infalling cloud material and thus can be considered as true protostars. Since physical conditions in the primitive stellar nebulae around these young stars are probably very similar to those that attended the birth of our own solar system four and a half billion years ago, observations of these sources will help identify the conditions that led to the formation of planets as well as the composition of the gas and dust from which they were formed.

Figure 5 shows the complex structures visible in a region of high mass star formation such as the Orion Molecular Cloud. In the center is an IRAS image of almost the entire Orion constellation. Flanking the IRAS image are near-infrared images of two small regions taken with array cameras on ground-based telescopes. The large number of embedded sources

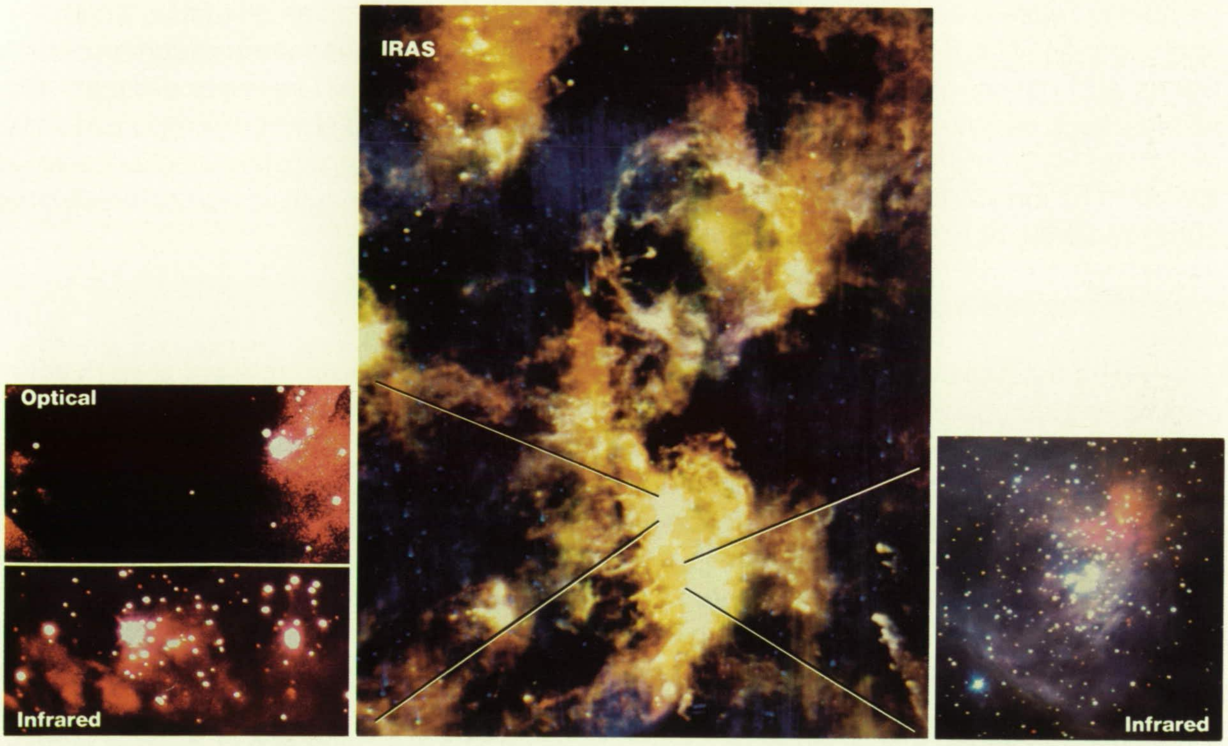

Figure 5. The center image shows an IRAS image of a 30° × 40° region in the Orion Molecular Cloud. The color coding is such that 12 μm emission is blue, 60 μm emission is green, and 100 μm emission is red. The image on the left shows a combined optical (top) and 2 μm image (bottom) of a small part of the larger image near NGC 2024. The inset at the right shows an infrared array camera image of the densely packed star-forming region at the core of the Orion Molecular Cloud.

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found within a few square arcminutes shows how concentrated star formation is within these regions. By contrast with the infrared images, an optical image of the NGC 2024 region (top, left) shows very few stars; most of the young stars are hidden in the visible by intervening interstellar dust. Comparison of the various images reveals the power of observing from space and of the revolutionary new infrared detector arrays.

A suite of spectral lines including H_2 (1-28 μm), CO (2.3 and 4.6 μm), [O I] (63 μm) and [C II] (157 μm), CI (370, 609 μm) and H_2O (1 μm—1 mm) can be used as diagnostic probes of the environment of the central young stars. In particular, submillimeter and far-infrared lines can probe regions of elevated temperature and density (T = 100K and $n > 10^6$ cm^{-3}) inaccessible to other wavelength regions. Maps from SIRTF in various lines will reveal the interactions between infalling material, accretion disks and the bi-polar outflows that mark the earliest stages of star formation. NICMOS, the infrared instrument on HST and, eventually, LDR will emphasize high spatial resolution observations of various spectral features on size scales between 10—100 AU for stars within 150 pc.

On a much larger scale, star formation is known to be the energy source for many energetic infrared luminous galaxies. SIRTF will make images of external galaxies from 5 to 100 μm to uncover the distribution of hidden star-forming regions with respect to spiral arms and giant molecular clouds. SOFIA, Submillimeter Explorer or SMILS, and ultimately LDR will be able to make detailed maps of star-forming regions in galaxies as distant as 10 Mpc in spectral lines of CI, [CII], [OIII], and CO to reveal the influence of phenomena such as density waves and galaxy-galaxy interactions in initiating star formation. Only space-based telescopes, such as SWAS, will be able to measure the chemically and physically important water molecule, H_2O, and molecular oxygen, O_2, which are almost completely blocked even at aircraft or balloon altitudes. SIRTF will determine the integrated strength of many of these lines out to redshifts of z = 3 to investigate evolutionary effects.

Protoplanetary Disks and the Formation of Solar Systems

The most exciting discovery of IRAS was that of circumstellar disks of solid material orbiting around apparently normal stars such as Vega and β Pictoris (Figures 6 & 7). These disks may represent matter left over from the formation of planetary systems. With the exception of the β Pictoris system, follow-up observations of this phenomenon have proven to be very difficult because of the lack of adequate sensitivity at existing infrared telescopes and the extreme faintness of most circumstellar disks at optical wavelengths. Further progress in their study will require infrared observations from SOFIA and SIRTF. Key issues are the frequency of occurrence of the phenomenon as well as the composition and size of the dust grains and their spatial distribution. SIRTF will be able to detect Vega-like systems hundreds of parsecs away and perform moderate-resolution spectroscopy to determine the composition of the emitting material. SIRTF will also be able to determine the incidence of disks of various mass and will be able to detect disks with 100 times less material than Vega's; material comparable to that of the Zodiacal cloud surrounding our own sun. SOFIA, and eventually LDR, will map the dust distribution around brighter disks like β Pictoris with 5—20 AU resolution. These maps may reveal the presence of gaps or significant scale height variations that would indicate of the presence of planets.

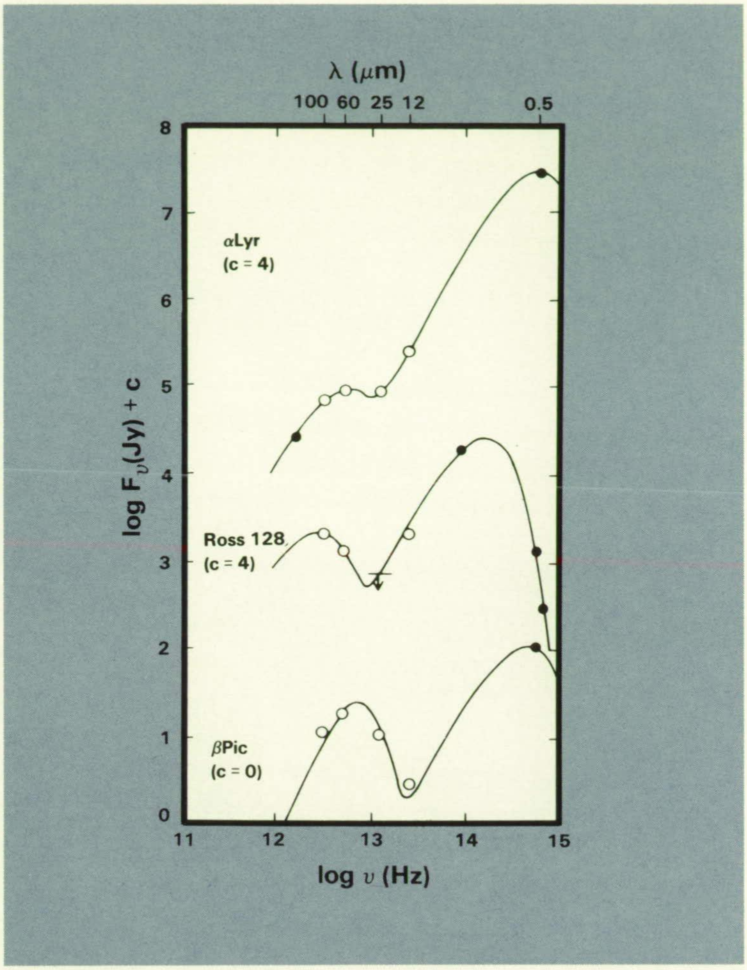

Figure 6.
The spectral energy distributions of a number of apparently normal main sequence stars show strong excesses in the IRAS bands. Approximately 20% of main sequence A-M stars have excesses as strong as that of Vega. SIRTF will be able to detect such systems at a distance of 1 kpc.

Detection of Brown Dwarfs and Extra-Solar Planets

Some astrophysicists claim that only about half of the local gravitational field inferred from stellar velocities can be accounted for by matter presently observed. If low mass stars too small to fuse hydrogen account for this missing mass, about 0.1 $M_\odot$ pc^{-3}, then the number density of brown dwarf stars could be quite high with the closest example only 0.3 pc away. A few brown dwarf candidates have been found around nearby stars using ground-based infrared telescopes, but detailed spectroscopic studies of brown dwarfs and a search for field objects await the enhanced sensitivity possible with space-borne telescopes.

SIRTF will be an extremely powerful facility for searching for brown dwarfs. By surveying several dozen nearby red dwarf stars for brown dwarf companions, SIRTF will complement radial velocity searches which are only sensitive to close binaries. SIRTF will also search for isolated brown dwarfs in the Galactic halo at 6 μm. A substantial fraction (10%) of the stellar objects in a confusion-limited survey at 6 μm will be brown dwarfs if the missing mass is in fact provided by these objects. The infrared instrument on HST will be able to spectroscopically study identified brown dwarfs in the 1—2.5 μm region.

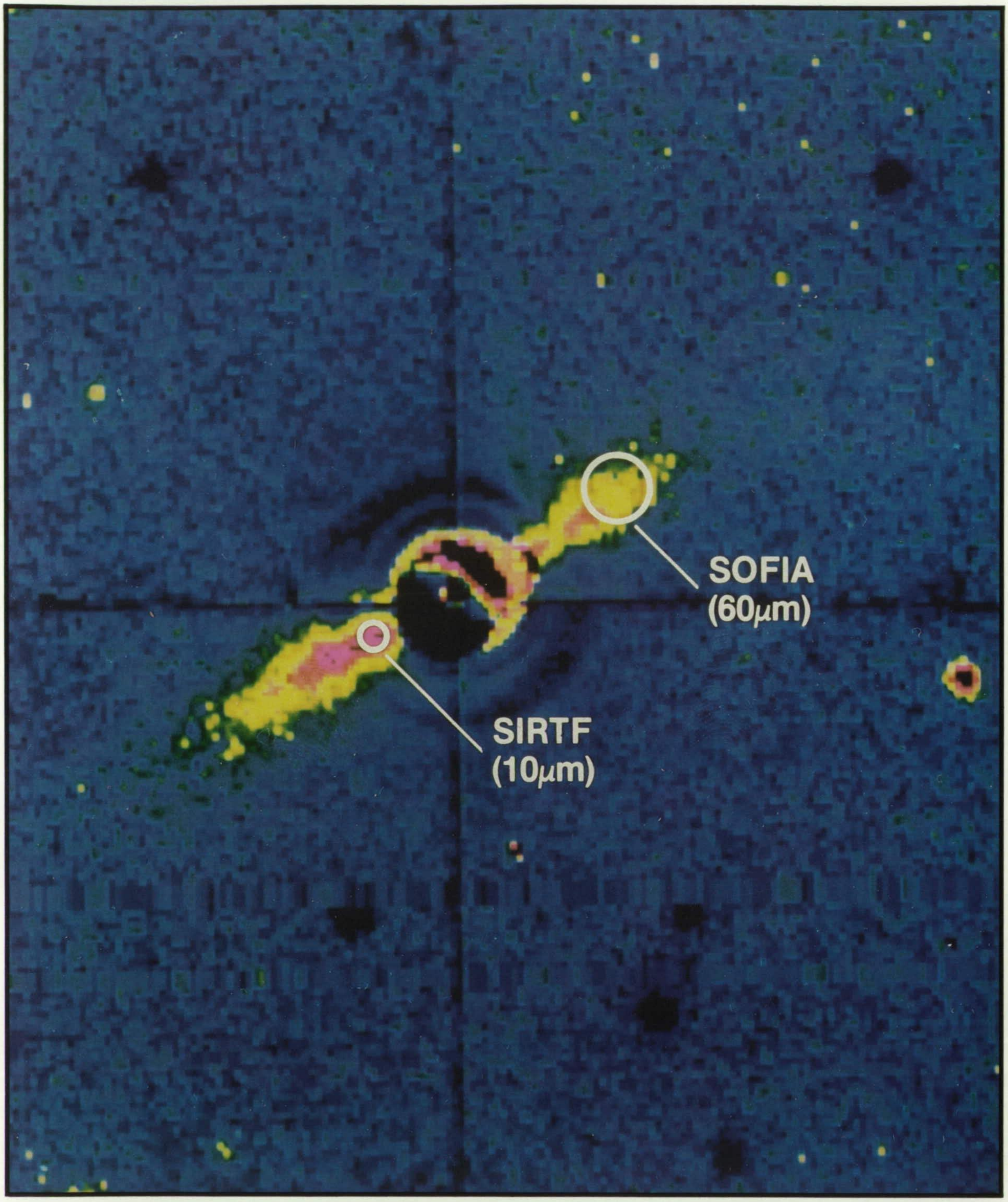

Figure 7. A visual image made with a stellar coronagraph of the star β Pictoris reveals the band of dust giving rise to the infrared excess detected by IRAS. The solid material in orbit around the star may be a precursor to, or signature of, a planetary system. The different sized boxes show the spatial resolution of SIRTF at 10 μm and SOFIA at 60 μm. At infrared wavelengths, the star is much fainter, and the intrinsic thermal emission from the disk will be the dominant source of radiation. The infrared observations, which probe both the structure and composition of the disk, thus can be extended much closer to the star.

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The search for Jupiter-like planets around nearby stars is closely related to the study of brown dwarf stars. Jupiter itself emits 10^{-9} $L_\odot$ with an effective temperature of 100 K. The 20 μm flux from a Jupiter at 5 pc would be about 10 μJy, which is roughly SIRTF's confusion-limited sensitivity. SIRTF would be able to search for giant planets heated to 100 K by a combination of gravitational energy and absorbed star light in a 20 AU orbit around nearby stars, complementing astrometric and spectroscopic studies. LDR would use its spatial resolution to resolve systems as close together as 5 AU. Detecting objects more massive or younger than Jupiter itself is consideraby easier, since objects three times more massive than Jupiter will be almost ten times more luminous, and objects less than 10^6 yr old could be as luminous as 10^{-5} $L_\odot$ and so visible in more distant star-forming regions, out to 100 pc.

Properties of the Solar System

Primitive bodies in the solar system hold important clues to the formation of the solar system. Spectroscopy of comets, asteroids and the atmospheres of the outer planets will help to determine the chemical composition of the primitive solar nebula. The KAO discovered H_2O in comets Halley and Wilson, while space-based, ground-based and KAO observations found evidence in the comets for the small grains composed of minerals and complex hydrocarbons similar to those seen in the interstellar medium. SOFIA will extend the high spectral resolution observations of comets out to ≥ 3 AU, while SIRTF will extend their study to as far as 10 AU from the Sun, measuring gas and dust generation rates. Evidence for compositional gradients can test theories of solar system formation while the presence of complex molecules may hold clues to the origin of life itself.

The infrared can be used to identify the surface composition of solid bodies including asteroids, planetary rings and the cometary debris trails found by IRAS. SIRTF will be able to determine the radii of bodies in the outer solar system with one tenth the diameter of Pluto. Chemical abundances and temperature structure of the atmospheres of Titan and the outer planets can be probed from SIRTF and LDR using various transitions in the infrared and submillimeter. SOFIA will provide the capability for very high spatial resolution observations of planetary atmospheres using stellar occultations.

The Interstellar Medium

Ground-based and airborne observations have yielded valuable information on the chemistry and thermodynamics of the interstellar medium. Observations from space will greatly extend our knowledge. The infrared and submillimeter region is rich in the spectral lines of simple and complex molecules. Figure 8 shows the spectrum of a molecular cloud around a wavelength of one millimeter. The submillimeter region will show a similar complexity of lines; however complete line surveys in the submillimeter must be obtained from space because residual water vapor blocks much of the submillimeter from high spectral resolution observation with even the highest balloon-borne telescopes. A spectral survey made with either a Submillimeter Explorer or a moderate-class mission (SMILS) would provide powerful diagnostics of the abundances of elements and the physical conditions within molecular clouds.

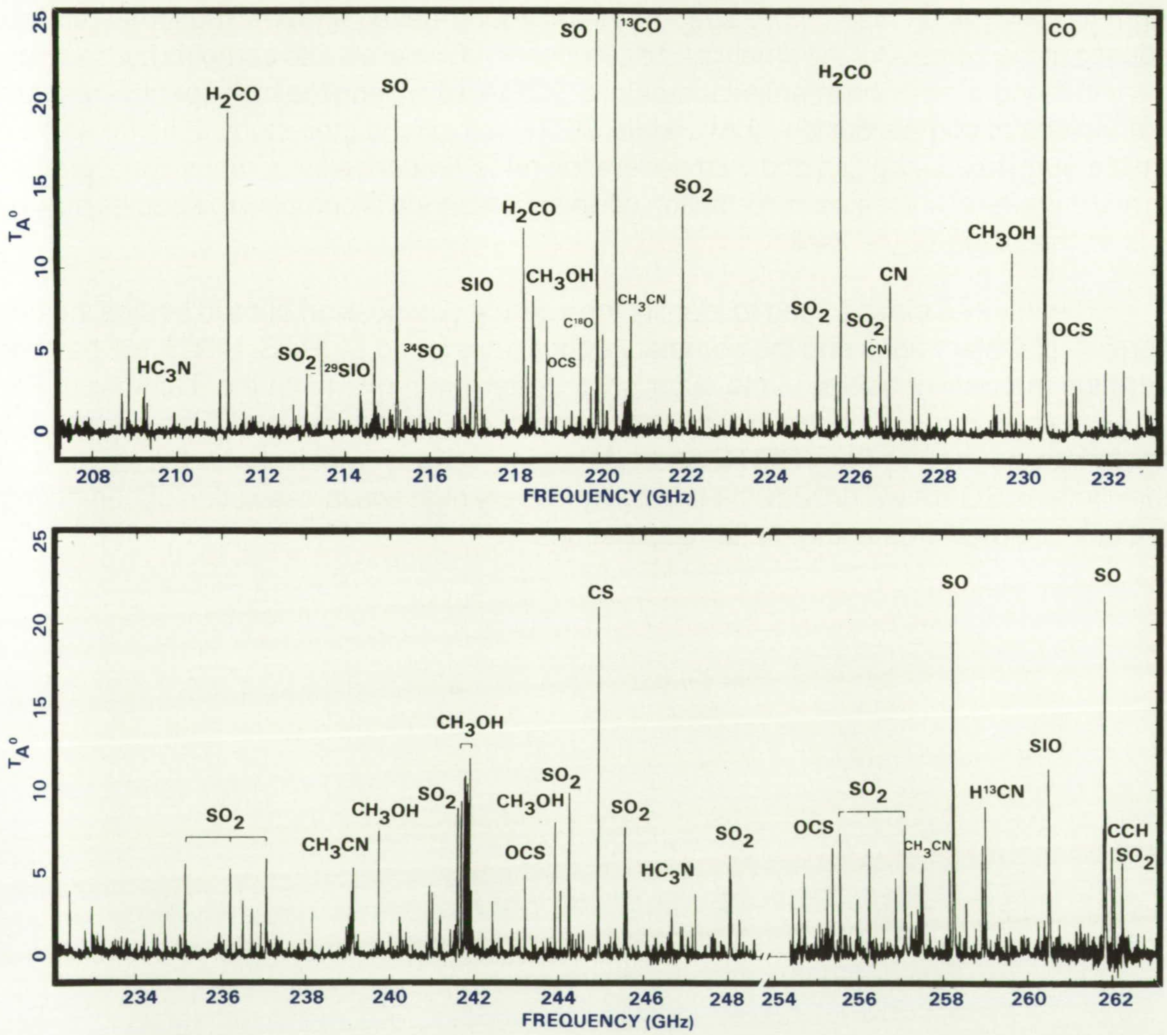


Figure 8. A portion of the millimeter spectrum toward the Orion Molecular Cloud (Figure 5) obtained by ground-based observations shows a wealth of spectral features. A similar spectral survey in the submillimeter portion of the spectrum can only be made from space because atmospheric water vapor blocks much of the spectrum even at high altitudes.

The KAO has already used spectroscopic studies of HII regions to examine chemical evolution in the interstellar medium, finding, for example, evidence for enhanced nucleosynthesis in the 5 kpc ring of molecular material. Observatories like SIRTF, SOFIA and LDR will extend these studies to other galaxies in unique and complementary ways. SIRTF's great sensitivity will enable the study of these lines to cosmological redshifts, while the high spectral and spatial resolution of SOFIA and LDR will enable a more complete understanding of the dynamics of distant galaxies.

The cooling of molecular clouds occurs through a few spectral lines, of which the [CII] 157 μm line may be the most important. Since the formation of stars depends critically on how molecular clouds cool, a detailed study of cloud thermodynamics will advance our understanding of how stars form. On a larger scale, we can use observations of the [CII] line to study kinematics and energy balance in galaxies. For example, as much as 0.1% of the total luminosity of infrared bright galaxies such as M82 and more distant infrared bright galaxies may be emitted in this line (Figure 9). Using the [CII] line, LDR will be able to determine the kinematics in starburst galaxies like M82 out to the redshifts where galaxies are thought to form.

Low frequency radio observations that might be carried out with the Low Frequency Space Array can probe wholly new aspects of the interstellar medium. An all-sky map of the Galactic non-thermal emission will reveal the distribution of low energy cosmic ray electrons and determine the extent of the halo around the Galaxy. The distribution of diffuse ionized hydrogen can be determined from absorption measurements toward a number of Galactic and extra-galactic radio sources, while the electron density in the local interstellar medium can be determined from the foreground emission between the Earth and totally absorbing HII regions.

Mass Loss and Nucleosynthesis

Stars convert hydrogen and helium into heavier elements and return this processed material to the interstellar medium through stellar winds and as supernova ejecta. Both processes can be studied using measurements of continuum infrared emission and optically thin infrared and submillimeter spectral lines. Stars in the red giant phase are responsible for much of the replenishment of the interstellar medium, and may become optically invisible as they shed as much as half of their total mass in a strong stellar wind with outflow rates as large as 10^{-4} $M_{\odot}$ yr^{-1}. These stars provide a unique laboratory for examining the elemental and isotopic content of the nuclear processed material that enriches the interstellar medium with heavy elements. Low and high resolution spectroscopy of the dust and gas content of stellar winds yields important information on elemental and isotopic abundances. The study of late type stars also leads directly to an understanding of the late stages of stellar evolution, including the progress from red giant stars to planetary nebulae.

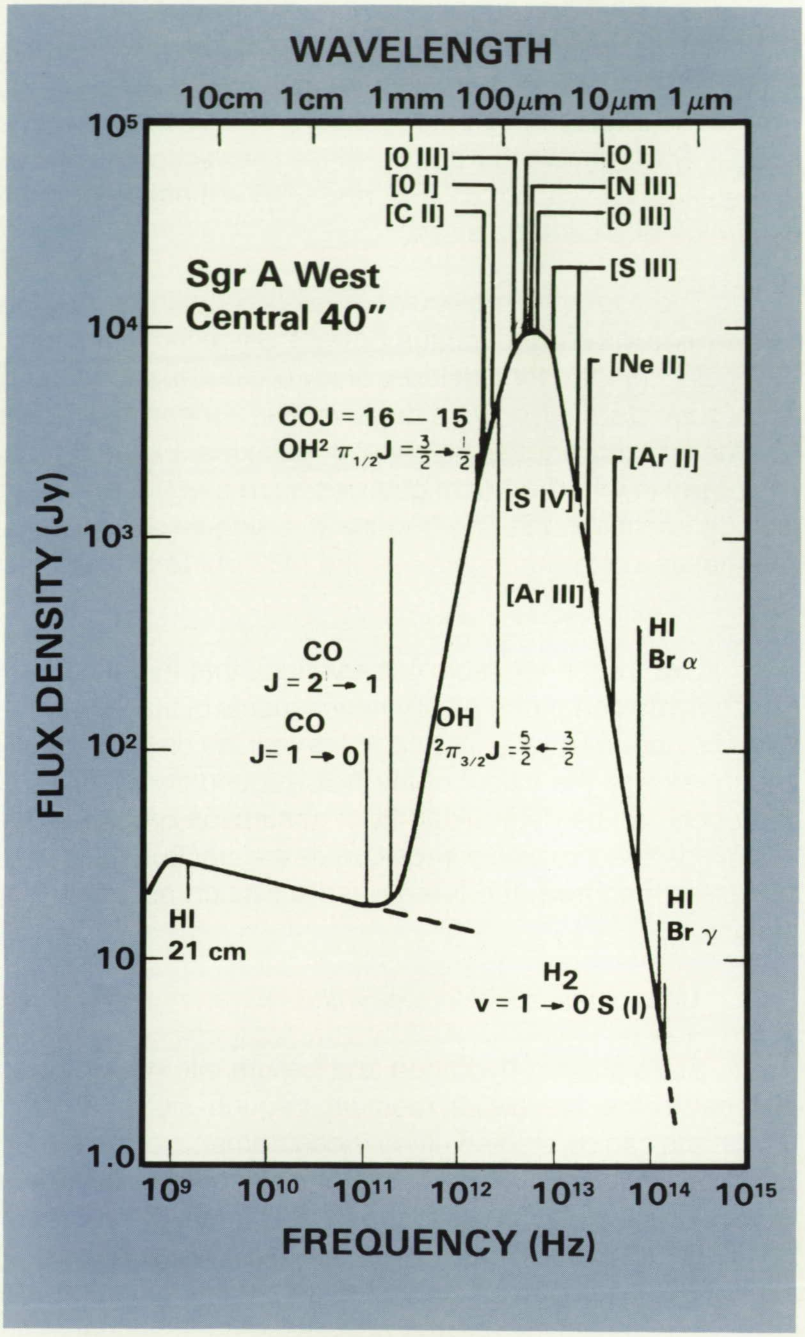


Figure 9.
The submillimeter and far infrared contain many spectral lines that can be used as probes of physical conditions in the centers of galaxies. This composite spectrum of the center of our Galaxy gives an example of what powerful observatories like LDR could study in very distant galaxies.

The KAO has proven the value of infrared observations of supernova remnants by its discovery of optically thin lines of cobalt and other species early in the life of SN 1987A (Figure 10). SIRTF will be able to study Type I supernovae out to a distance of more than 10 Mpc to the same level of detail as the KAO achieved on SN 1987A. Estimates are that 3—4 such supernovae will be born each year within the volume defined by SIRTF's sensitivity.

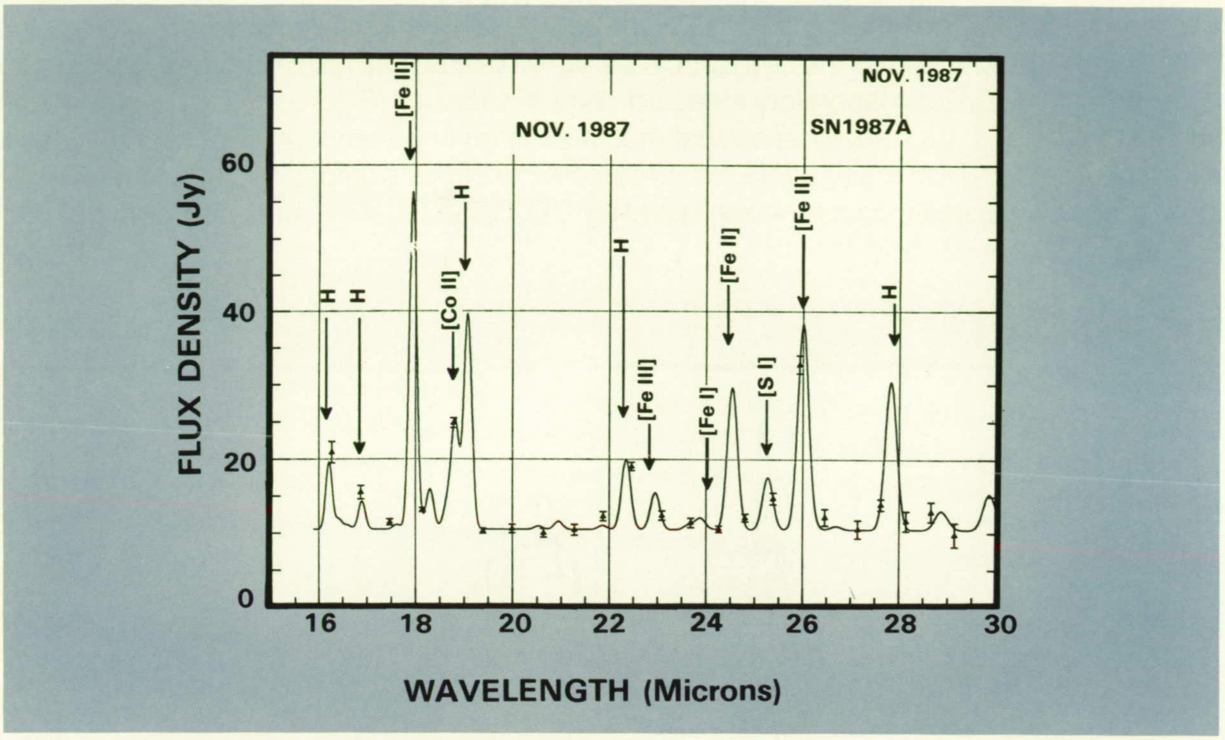


Figure 10. This spectrum of SN 1987A, taken with the KAO, shows a variety of spectral lines which are used to determine elemental abundances and the nature of the energy source, as well as the ionization equilibrium of the expanding shell. SIRTF will have the sensitivity to make similar observations of supernovae out to > 10 Mpc.

Solid Matter

A major fraction of the heavy elements in the interstellar medium are locked up in dust grains. Emission from this dust, which can be heated by a large variety of energy sources, is the origin of most of the infrared radiation detected by our telescopes. Thus it is not suprising that the infrared provides important information about the physical nature of that dust. The study of grain properties has important implications for interstellar chemistry since grain surfaces may provide the sites for a variety of chemical reactions.

Infrared observations from the ground and from IRAS and the KAO have revealed the existence of an entirely new component of the interstellar medium. Small, 10 Å, "grains" are heated by the absorption of single optical or ultraviolet photons to levels far higher than their equilibrium temperature in the interstellar radiation field. At their elevated temperatures, the grains emit more short wavelength (1 μm to 50 μm) radiation than would be expected if the grains were in thermal equilibrium. As much as 50% of the infrared emission from galaxies may come from small grains consisting of complex hydrocarbons such as polycyclic aromatic hydrocarbons (PAHs) that may contain as much as 20% of all interstellar carbon. Determination of the properties of this apparently ubiquitous component of the interstellar medium by SOFIA and SIRTF through large scale mapping, low resolution spectroscopy and polarimetry in the infrared and submillimeter (where PAHs may have vibrational-rotational transitions) is an important aspect of observations in this wavelength region.

Other types of solid material are also seen. Observations from the KAO have revealed for the first time the astronomical emission of features of circumstellar water ice grains at 43 and 62 μm. The spectrum of the Leo Nebula shows emission that matches almost perfectly the spectrum predicted from laboratory measurements of water ice (Figure 11). Observations from the KAO provided the first evidence that methanol is an important component of the ices in molecular clouds. Ultimately, SIRTF will probe the molecular composition and structure of a wide range of interstellar condensates, including: CO, CO_2, CH_4, NH_3, and more complex ices.

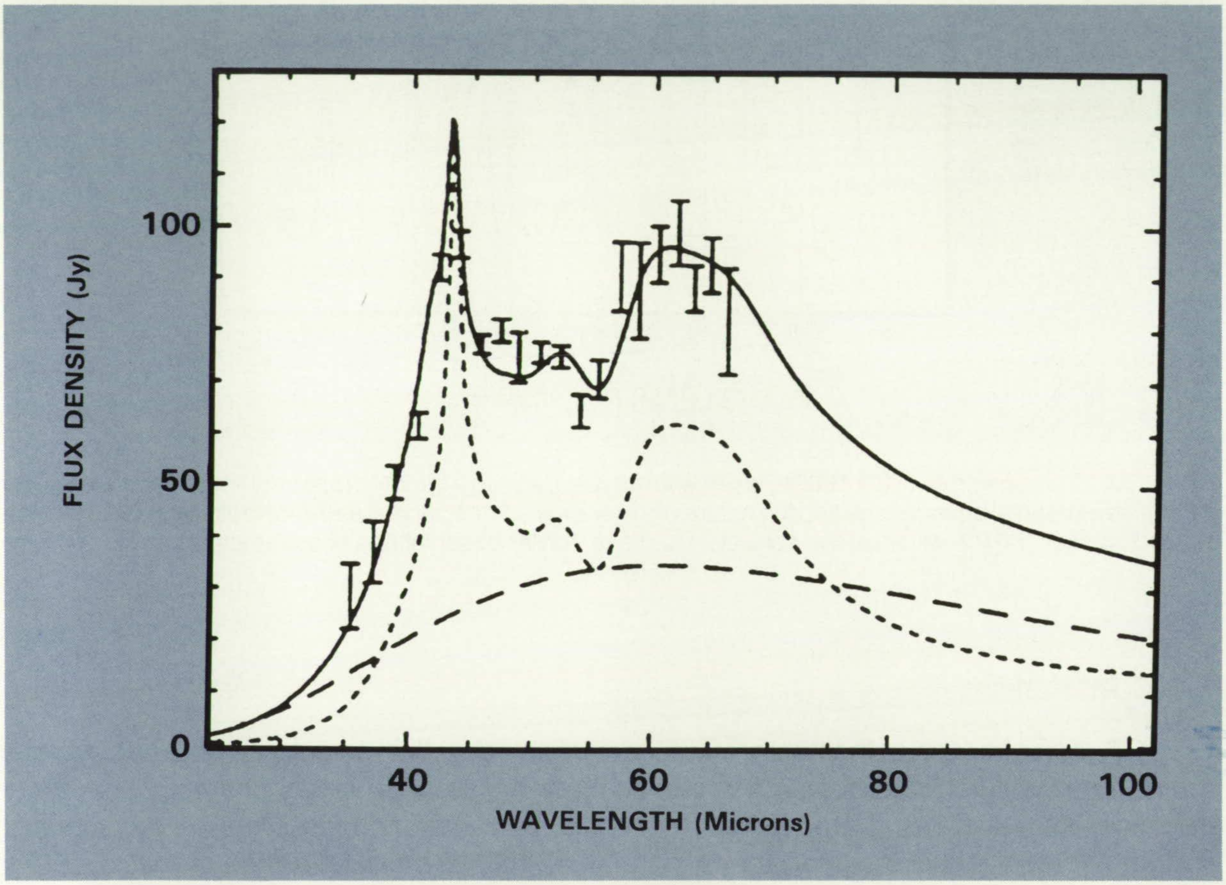


Figure 11. This KAO spectrum of the Leo Nebula reveals the first detection of emission from water ice in an astrophysical source. The peculiar IRAS colors of this source prompted these observations. Plotted with the data are several model calculations. The dashed line is for silicates alone and the dotted line for water ice alone, while the solid line is for silicate grains with water ice mantles.

The Origin of Life

Observations in the infrared and submillimeter are one of the few ways by which we can begin to understand how life arose in the Universe. Currently, a self-consistent outline is emerging of the pathways leading from the stellar nucleosynthesis of carbon, oxygen, nitrogen, phosphorus, sulfur, and other biologically significant trace elements to their inclusion into planetesimal-sized bodies within the young protosolar nebula. While this outline is self-consistent, it is far from complete, and many of the most critical details remain to be supplied by more observational, experimental and theoretical effort. The biogenic elements have had a long and complex chemical history before becoming part of the solar system. Understanding the nature and evolution of that chemical complexity is crucial to understanding both the early chemical state of our own solar system and the frequency with which similar or related conditions exist elsewhere in the Universe. Interstellar dust plays an important role in the cosmic evolution of the biogenic elements. These grains show a diverse chemical composition, including refractory materials such as silicates, graphite, and amorphous carbon often coated inside molecular clouds by water-rich ices or ices containing much more complex molecules such as alcohols, aldehydes, and ketones. Furthermore, the size distribution of interstellar amorphous carbon grains may extend well into the molecular domain and complex polycyclic aromatic hydrocarbons (i.e., small carbon "grains") may be very abundant, forming the missing link between carbon dust grains and simple gas phase molecules. The infrared-submillimeter portion of the spectrum provides unique information about the biologically interesting molecules and particles in diverse cosmic environments and is to date almost completely unexplored. SIRTF will provide enormously sensitive measurements on the solid component of the interstellar medium and SOFIA, and eventually LDR, will provide the high spectral and spatial resolution submillimeter observations of the molecular component. Interpretation of the measurements will require new laboratory and theoretical studies of the appropriate molecules and solids.

ORIGIN AND EVOLUTION OF GALAXIES

The origin and evolution of galaxies represents one of astronomy's deepest engimas and is closely tied to our understanding of the earliest moments in the Universe after the Big Bang. Profound questions that can be addressed by observations in the infrared include:

- At what point after the Big Bang did galaxies form?
- What is the relationship between galaxies and extremely luminous quasars?
- Do black holes provide the energy source for active galaxies?

Protogalaxies

A protogalaxy evolves from previously uncondensed, primordial hydrogen and helium to form a first generation of massive, hot stars. The time at which this process occurs corresponds to redshifts between $2 < z < 20$, depending on cosmological theories. To understand why the infrared is the proper wavelength to look for and to study protogalaxies, one need only recall that the Hubble expansion of the Universe inexorably redshifts the emission of distant objects; a redshift of only 0.5 makes H alpha an infrared spectral feature while a redshift of 7 moves hydrogen Lyman alpha to wavelengths longer than 1 μm.

Currently, no reliable predictions of the properties of protogalaxies can be made. If the protogalaxy phase is short, these objects will be bright but rare: if the protogalaxy phase is long, protogalaxies will merge into the faint, high redshift tail of normal galaxies. The advent of infrared arrays on ground-based telescopes has suggested what we might find in deep surveys (Figure 12). A blue object discovered in a very deep 2.2 μm search, combined with deep optical images has proven to be a galaxy at a redshift of 3.5, which is emitting most of its energy in Lyman alpha. This source may be the first protogalaxy. Deep surveys from SIRTF and from the infrared instrument on the HST will be critical for understanding the origin of galaxies and the evolution of the early Universe.

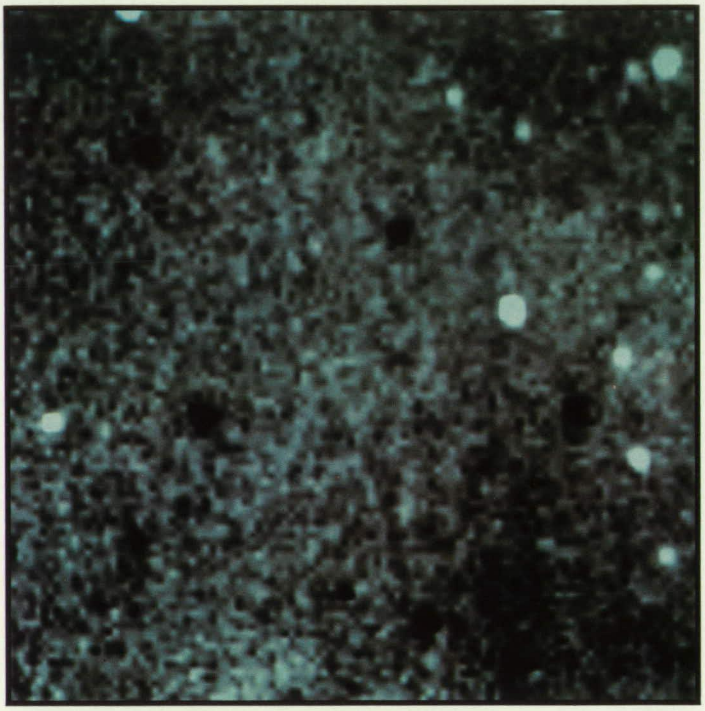


Figure 12.
A 14.5 square arcmin field imaged at 2.2 μm as part of a search for primeval galaxies. Two fields are observed in a beam-switched mode, thus objects appearing bright are located in one field and objects appearing dark are in the other field. The limiting magnitude is K (2.2 μm) = 23 mag/arcsec^2 (1 sigma). Further study is required to determine which objects may be primeval galaxies. The imaging was obtained using a 128×128 HgCdTe test array from the NIC-MOS program. The Pixel size is 1.8 arcsec square.

The infrared may be the only window on galaxy formation regardless of the redshift at the epoch of formation. Regions of active star formation invariably form large quantities of dust on time scales that are essentially instantaneous with respect to the Hubble expansion time. The opacity of this dust to visible and UV light is high so that most of the energy radiated by stars is thus absorbed by dust and re-emitted at 50 $\mu m < \lambda < 100$ μm in the rest frame. Thus if protogalaxies are similar to the starburst galaxies observed by IRAS, then the background from these protogalaxies will be redshifted to submillimeter wavelengths. The background emission may already have been observed as the excess brightness in the cosmic background radiation observed in a recent sounding rocket experiment, or may await detection by COBE or SIRTF in the excellent natural window that occurs near λ = 300 μm. In either case, detection and study of the radiation due to galaxy formation will provide a unique probe of the large scale structure of the universe at $3 < z < 20$, an epoch about which we know almost nothing. The anisotropy of this radiation, on all spatial scales, will provide a critical test for the theories of the evolution of structure in the universe.

ORIGINAL PAGE
COLOR PHOTOGRAPH

Massive Objects in Active Nuclei

The nature of central objects inhabiting the cores of luminous galaxies and quasars has profound implications for all physics. A major question in the evolution of galaxies is whether *all* galaxies harbor a central massive object that occasionally bursts into prominence. The center of our own Galaxy (Figure 13) may be the location of the nearest massive black hole and can be studied in the infrared through the optically opaque screen of intervening interstellar dust. Already the infrared has been used to study the distribution and motion of gas and dust in the Galactic center. High sensitivity spectroscopy in lines of HeI (2.06 μm), CO (2.3 and 4.6 μm) and [NeII] (12.8 μm) hints strongly at the presence of a compact object a million times more massive than the Sun. SOFIA will allow more sensitive observations at higher spatial resolution in these and other lines to determine whether there is a black hole at the center of the Galaxy.

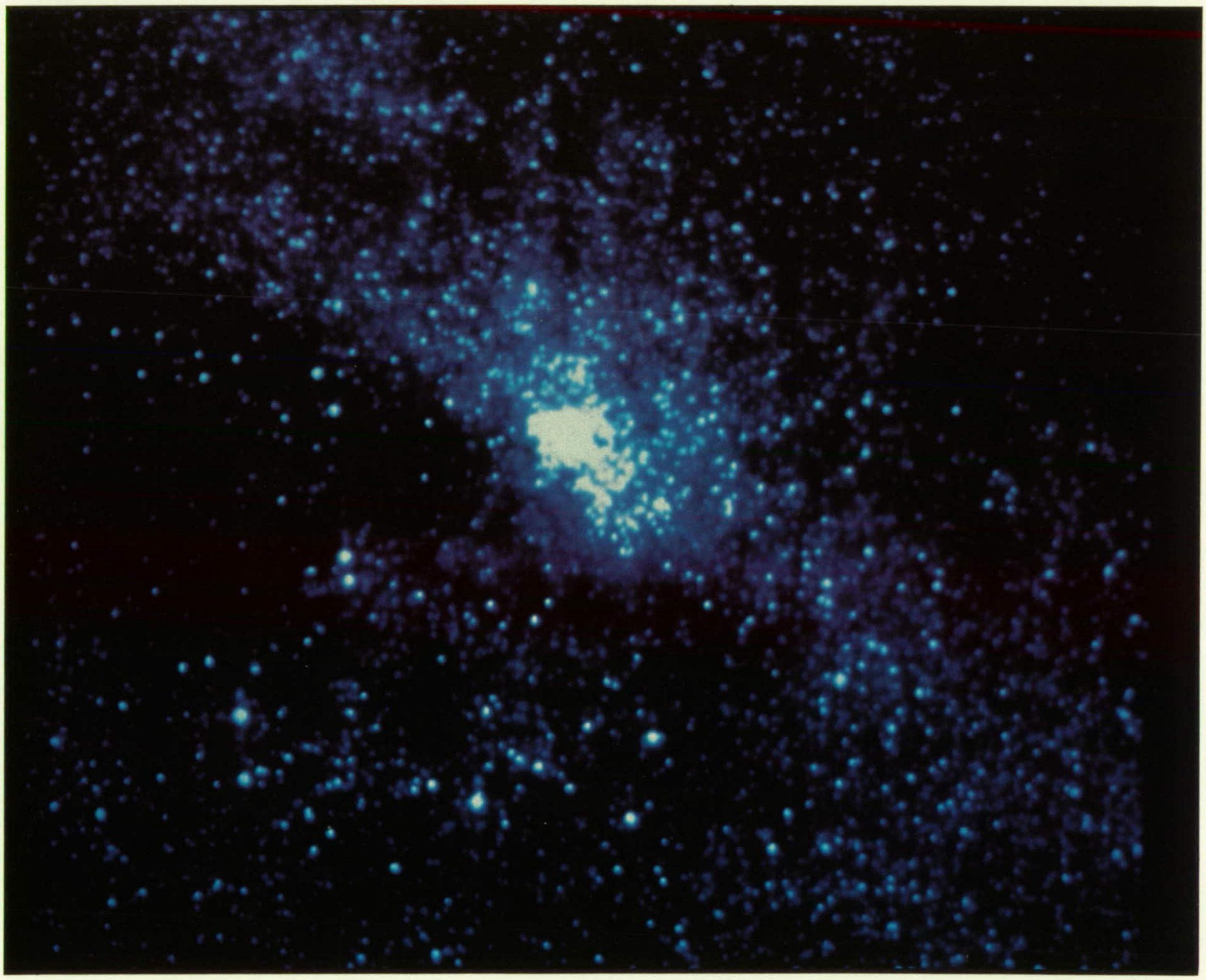


Figure 13. A 2.2 μm image taken with a ground-based telescope shows a 30' × 40' region around the center of the Galaxy. This region may contain the closest massive black hole.

ORIGINAL PAGE
COLOR PHOTOGRAPH

Active galaxies are thought to contain central black holes a hundred times more massive than the one at the center of our Galaxy. The dynamics of stars and gas in the visually obscured cores of active galaxies can be investigated using a variety of spectral tracers across the infrared and submillimeter in objects such as M82, NGC 1068 and NGC 6240. SIRTF will be a sensitive probe of the luminosity distribution in distant galaxies. High spectral and spatial resolution from SOFIA and eventually from LDR will be critical in separating emission in the active nucleus from the surrounding galaxy. For quasars dominated by power-law emission, the far infrared will give clues to the mechanisms operating in radio loud and radio quiet quasars; the turnover in the emission from radio quiet objects occurs around 150 μm.

Physical scales as small as a few AU in the cores of nearby active galaxies can be studied with Orbiting Very Long Baseline Interferometry (OVBLI). Fundamental problems that can be addressed on this scale include the acceleration of superluminal material (Figure 14) and the existence of brightness temperatures in excess of the 10^{12}K Compton limit.

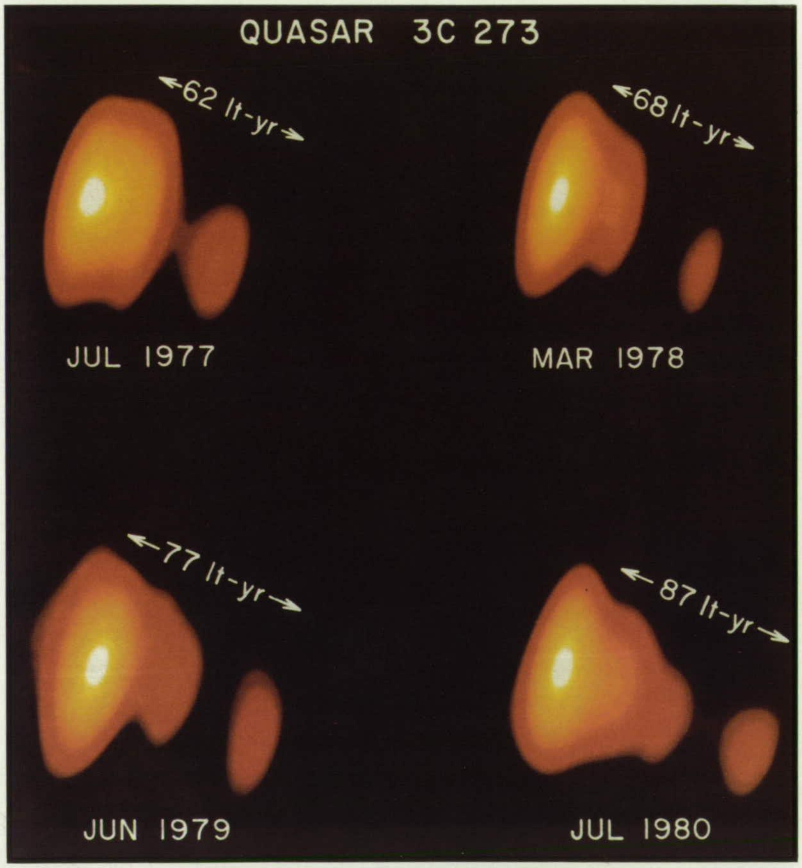


Figure 14.
Very long baseline interferometry has identified jets of material, emitted from the cores of active galaxies, that appear to move at speeds far in excess of the speed of light because of geometrical effects due to special relativity. The study of the acceleration of this material holds important clues about the nature of the central source, possibly a massive black hole.

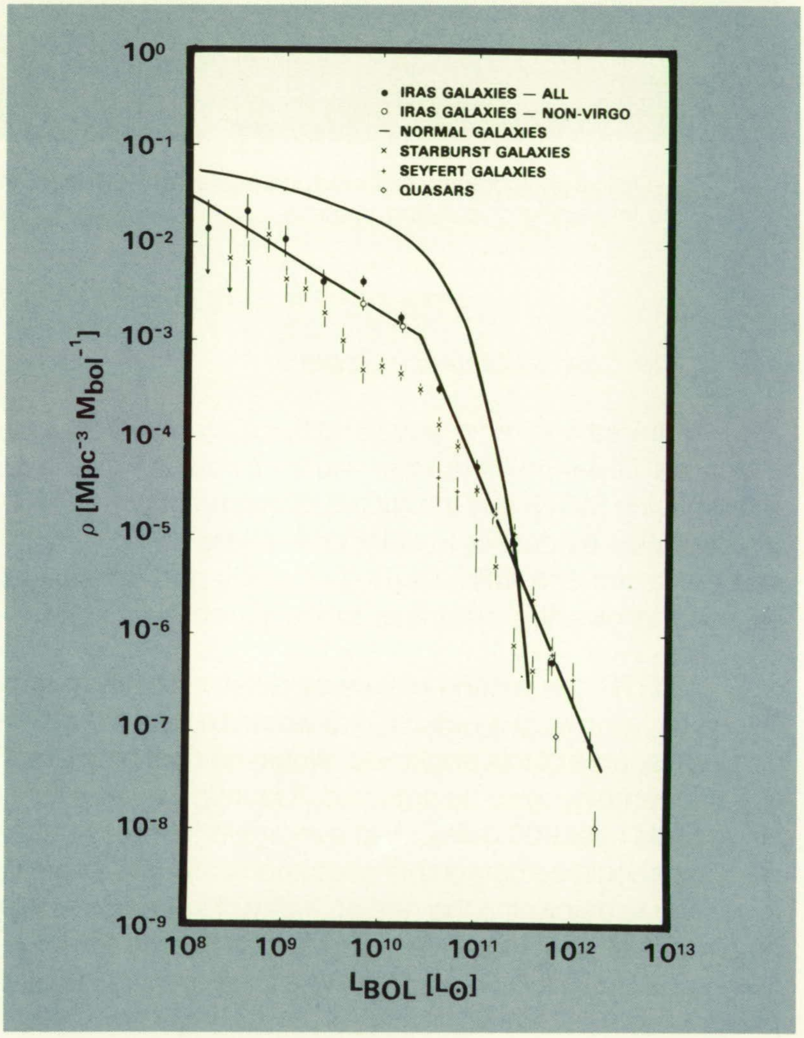
The presence of "fossil" shells of low frequency radio emission around presently quiet radio galaxies and quasars will give an indication of the frequency and lifetime of the active galaxy phenomenon. Since the lifetime of the energetic electrons capable of emitting at MHz frequencies is a significant fraction of the age of the Universe, such observations by a Low Frequency Space Array would be a sensitive test for earlier epochs of activity.

ORIGINAL PAGE
COLOR PHOTOGRAPH

Ultra-Luminous Galaxies and the Origin of Quasars

One of the most surprising results of the IRAS mission was the discovery that a small, but significant fraction of galaxies is highly luminous (a few times $10^{12}\ L_\odot$) and these galaxies emit more than 95% of their power in the infrared. The space density of these infrared luminous galaxies exceeds that of quasars in the same luminosity range (Figure 15). These galaxies are rich in molecular material and almost invariably show signs of a collision or merger with another galaxy (Figure 16). It has been hypothesized that the collision disrupts the normal orbits of material, forcing matter onto a central black hole to form a quasar still enshrouded in dust. Over time, the veil of dust either evaporates or is blown away, revealing an ultraviolet bright quasar. Much more observational data will be needed before this scenario is more than just speculation. For example, SOFIA will observe spectral lines from nearby infrared luminous galaxies like Arp 220 to understand their internal dynamics and to determine whether they contain massive black holes. SIRTF can study the entire class of infrared luminous galaxies back to the epoch of galaxy formation to determine whether infrared luminous galaxies are more numerous than the brightest quasars, $10^{12} - 10^{13}\ L_\odot$, and whether the space density of infrared bright galaxies increases with redshift, as expected from evolutionary models.

Figure 15.
The number density of high luminosity ($10^{12}\ L_\odot$), infrared bright galaxies exceeds that of quasars of the same luminosity. SIRTF will determine whether this effect holds true at redshifts as great as z = 2 and whether these colliding galaxies are the progenitors of quasars.



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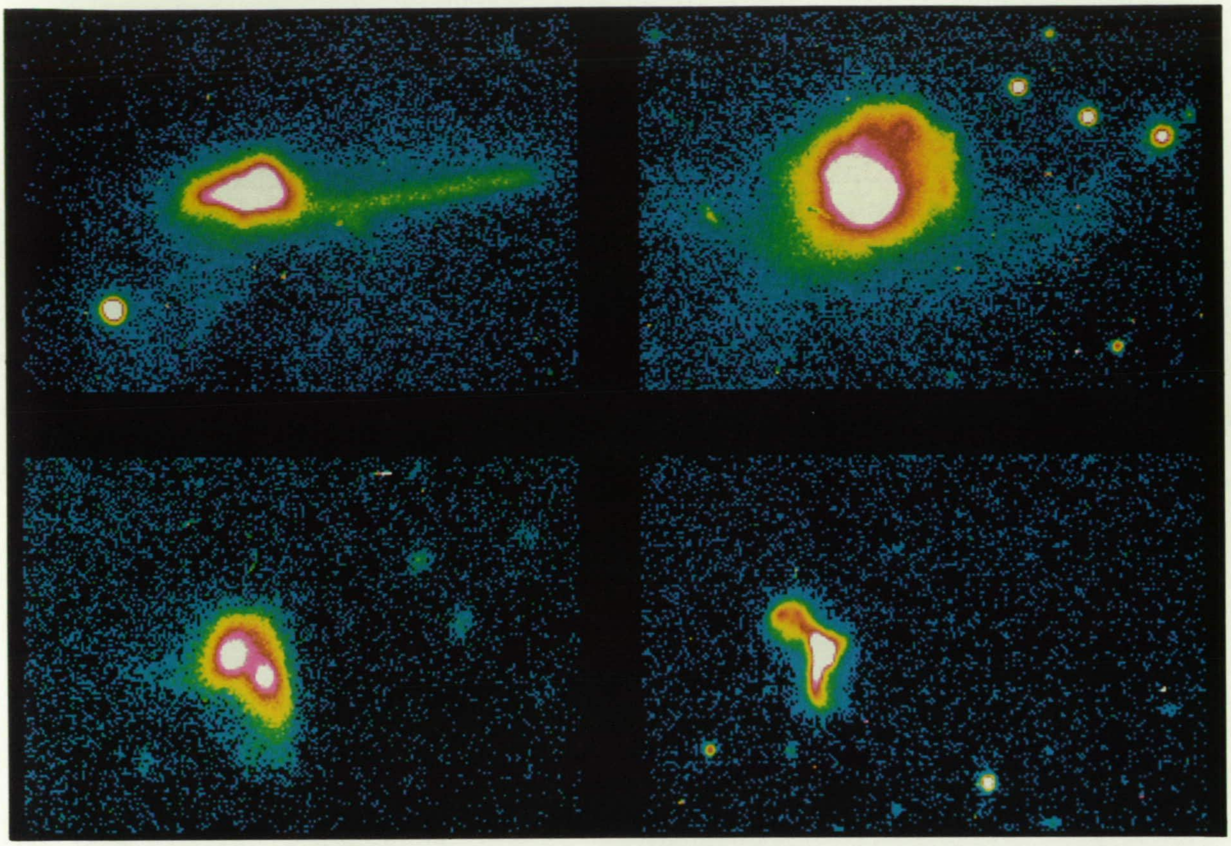


Figure 16. Optical photographs of infrared bright galaxies show that almost all of the objects more luminous than 10^{12} $L_{\odot}$ are interacting or colliding systems.

The Cosmic Distance Scale

Infrared and radio wavelengths offer a number of techniques to measure fundamental distances. Distance moduli derived from near infrared observations of Cepheids in the Virgo cluster using SIRTF and the NICMOS instrument on HST will not suffer from uncertainties due to absorption by dust or to color corrections to the period-luminosity relation. Infrared measurements are also well suited to determining the angular sizes of supernovae which can then be used to give the distances to the parent galaxies.

SIRTF can extend distances determined from supernovae to very high redshifts. A Type I supernova at a redshift of 3 would have a 2.5 μm flux density of 0.24 μJy. Although a constant source of this brightness would be confused in a 1" beam, a high amplitude variable like a supernova could be detected. Assuming a value for q_0 = 0.5, the 5' field of view of SIRTF will include over 900 galaxies of average brightness out 2z = 3, therefore many supernovae per year should be detectable photometrically in a single field of view. Such a data set would allow one to determine the rate of decay of supernovae light curves vs. redshift: high redshift supernova should decay more slowly than nearby supernovae. Near IR colors should provide fairly good redshift estimates for Type I supernovae, since their spectra are quite distinct from power laws.

Orbiting VLBI will permit the direct, trigonometric determination of distances to nearby galaxies using proper motions of H_2O masers in star forming regions. The calibration of basic extragalactic distance indicators such as Cepheid variables can then be improved for use at still greater distances.

Finally, both SIRTF and LDR will be able to measure the deviation of the cosmic background radiation from a Planck law due to the effects of an intervening cluster of galaxies, the Sunyaev-Zeldovich effect. In conjunction with AXAF data, these observations will determine Ho to within 20% and provide an estimate of q_o, in a manner independent of other luminosity based indicators.

EVOLUTION OF THE UNIVERSE

Many aspects of the evolution of the Universe on the largest scales can be studied in the infrared and submillimeter. The spectral shape and isotropy of the cosmic background radiation contain many clues to the question of how the Universe evolved to its present condition after the cosmic microwave background was decoupled from the matter at $z = 1000$.

Background Radiation and Cosmology

A summary of the presently understood infrared and millimeter cosmic backgrounds is given in Figure 17. The best known and most studied component is the 2.7 K remnant of the primeval explosion. It is nearly isotropic and has a blackbody spectrum at wavelengths longer than 1000 μm. Any observation of a deviation from the ideal spectrum or perfect isotropy will provide crucial information for cosmology. Local backgrounds such as emission and scattering from galactic and zodiacal dust are of intrinsic interest, but also mask background radiation from more distant or older sources. Windows in the known backgrounds exist at submillimeter wavelengths and near 4 μm where opportunities exist to observe additional backgrounds of cosmological interest. Phenomena which may contribute to the background in the submillimeter window include Compton scattering distortion of the 2.7 K radiation, redshifted dust emission from infrared galaxies, and redshifted radiation from population III stars, which has been thermalized by dust. A recent sounding rocket experiment has given evidence for a submillimeter excess which may arise from one or more of these phenomena. It may be possible to observe the redshifted remnant of starlight from the earliest generation of stars in the 4 μm window. Among the questions to be answered by observations of the cosmic background are:

- What has influenced the cosmic background since its formation in the Big Bang?
- Can we see the expected effects of turbulence and inhomogeneity in the early universe which would cause anisotropy?
- Can we detect energy release from black holes, antimatter, gravity waves, etc., through their effects on the cosmic background radiation spectrum?
- When did galaxies form, and how bright were they?
- What is the total electromagnetic energy density in the universe?

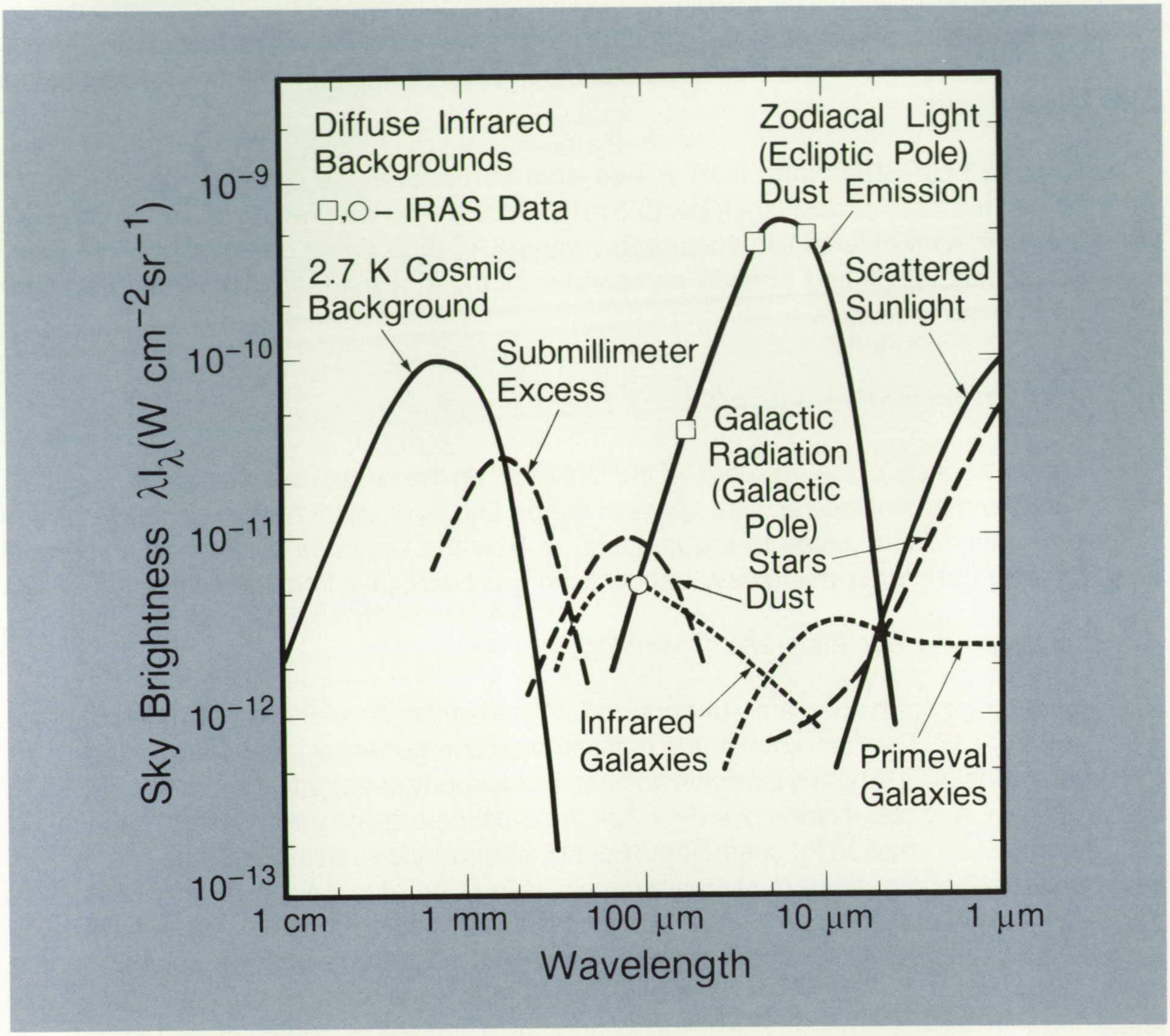


Figure 17. The spectrum of the background radiation will be measured by COBE. In addition to the 2.7 K cosmic background in the submillimeter range, there may be other submillimeter backgrounds due to redshifted emission from dust created and heated by an early epoch of star formation. Redshifted starlight from primeval galaxies may appear in the 4 μm range.

COBE will produce detailed spectral information on angular scales from 1° to 7° as well as on large scale anisotropy of the 2. 7 K background with full sky coverage. Medium and small scale anisotropy of the 2.7 K background can be determined from ground-based and balloon platforms at wavelengths longward of 1 mm. Small scale background observations are also important and possible at wavelengths shortward of 2 mm. Thermal emission from the atmosphere prevents ground-based or balloon-borne observations of the cosmic background at the most important wavelengths and major opportunities exist for future space missions. International cooperations, SIRTF, and, eventually, LDR will provide unprecedented sensitivity for the study of submillimeter backgrounds at important angular scales, smaller than those obtained by COBE.

Distribution of Galaxies in the Local Universe

The IRAS catalog revealed for the first time a dipole anisotropy in the number density of galaxies. The fact that the direction of the galaxy count dipole agrees with that of the dipole anisotropy in the Cosmic Background Radiation suggests that IRAS has found the mass concentration responsible for accelerating the Galaxy relative to the more distant standard of rest. SIRTF will conduct unbiased surveys out to z = 0.5 in selected areas that will measure a sample of galaxies as large as the IRAS survey, but with a typical distance 10 times greater. Combined position and velocity information can then be used to map the distribution of matter out to cosmologically interesting distances and will provide insights as to the nature of the missing mass. If the missing mass inferred to exist in the halos of galaxies and in clusters of galaxies is in the form of cool, low luminosity stars, then SIRTF or the infrared instrument on HST may be able to detect emission from such objects.

SERENDIPITY

A measure of the power of an astronomical facility is not just how well it can study known astrophysical phenomena, but to what extent it can be expected to uncover new phenomena. IRAS detected many stars and star forming regions, but it also surprised us with a large number of ultra-luminous galaxies, protoplanetary disks, and solar system dust bands.

SIRTF's great sensitivity and large format detector arrays will make it capable of surveying small regions of space far deeper than IRAS. Present plans are to make two surveys of limited regions at four wavelengths between 3 and 60 μm. Approximately 1 sq. deg would be surveyed to a few tens of μJy and a few arcminutes would be covered to a few μJy. These surveys will be capable of finding brown dwarf stars radiating 10^{-5} $L_\odot$ at distances of 1 kpc, normal galaxies out to a redshift of 3—5, and ultraluminous objects emitting 10^{13} $L_\odot$ can be detected at either 3 or 60 μm out to a redshift in the range of 7—50.

Surveying the sky in a new spectral window is also likely to reveal new astrophysical phenomena. The submillimeter wavelength band is largely unexplored so that a Submillimeter Explorer making a systematic line survey is certain to find spectral features of unsuspected species. The lowest frequencies of the electromagnetic spectrum are blocked from reception by the Earth's ionosphere. Exploration of the spectral region from 1—20 MHz should find thousands of new sources and perhaps reveal the presence of coherent emission processes in galactic or extra-galactic objects.

COMPLEMENTARITY WITH HST, AXAF, AND GRO

The science topics discussed above concentrate on problems for which long-wavelength observations are essential. However, almost all astrophysical problems demand observations throughout a wide range of wavelengths for a more complete understanding of the physical processes involved. The requirement for coordinated, multi-wavelength observations lends urgency to the need for a significant time overlap between the other Great Observatories and SIRTF and SOFIA.

Using AXAF and SIRTF, detailed studies of infrared-luminous galaxies and proto-quasars such as Arp 220 will probe the ultimate energy sources in these objects. The objects are so heavily dust enshrouded that viewing the region in the optical or the near infrared is essentially impossible. However, the interstellar dust becomes transparent in the long wavelength regime and at energies above 2 keV where SIRTF and AXAF, respectively, can provide diagnostics through IR spectroscopy and X-ray imaging. Understanding quasars and active galaxies, some of which are highly time-variable and have redshifts as high as 3, will require submillimeter to gamma rays.

Using SIRTF and the NICMOS instrument on HST, combined near-infrared and longer wavelength measurements of embedded young stars will lead to a better understanding of the first 10,000 years of stellar birth and solar system formation. Coordinated HST, AXAF, SOFIA and SIRTF observations of young T Tauri Stars will study stellar disks and probe the physical conditions close to the surface of young stars. Triggers of star formation can be investigated through the combination of HST and SIRTF observations of star formation regions in other galaxies.

Through the comparison of submillimeter and gamma-ray measurements of the interstellar medium made using SOFIA and GRO, the overall distribution of matter in our Galaxy can be investigated. The Hubble constant can be determined using SIRTF and AXAF to make combined infrared and X-ray measurements of the Sunyaev-Zeldovich effect in clusters of galaxies.

In addition to these and other instances where the Great Observatories will work in concert to solve specific problems, SIRTF, with its great sensitivity, will discover objects such as protogalaxies, brown dwarfs or serendipitous sources that will demand observations at visible and X-ray wavelengths for their complete characterization. The sensitivity of the Great Observatories is so great that in many cases detailed follow up studies can only be done with another Great Observatory.

CRITERIA FOR A BALANCED PROGRAM

Before describing individual missions it is appropriate to discuss the criteria that characterize a balanced program. We have placed each mission into a broader context by asking about the science, technology and sociology of the program and addressing the following issues:

- What are the crucial scientific questions to be answered by observations from a particular facility and how will results from NASA's observatories lead or complement progress in various branches of astrophysics?

- What is the scope and state of technical readiness of a particular mission in the areas of detectors, the telescope, and cryogenics?

- How does each project help provide for a healthy astronomical community? Is the mission a large one of fundamental importance to all astronomy; does it nurture young scientists or lead to innovative new technologies important for future instruments?

- Is the existing infrastructure, consisting of laboratory measurement of key physical constants, developoment of basic theory, data reduction from previous missions and exploratory observations, adequate to support the major goals of this program?

SCIENCE

The discussion of long wavelength science provides the overall themes of the program: the formation of planets, stars, galaxies, the elements, and ultimately the structure of the entire Universe. The combination of missions discussed here will give astronomers powerful tools to study these fundamental questions. Taken together, these observatories provide complementary data on a variety of spatial and spectral scales over a broad range of wavelengths that will answer fundamental questions in astronomy.

Since the pressure on NASA's scientific budget is extreme, each project must be carefully scrutinized so that the scientific questions addressed are the most urgent. While this dictum applies most strongly to the largest programs like the Great Observatories which require a decade or more to execute, care must be exercised to ensure that NASA will be able to implement innovative new ideas on a more rapid timescale. Thus, the recommended program includes large flagship missions as well as moderate and small missions. A balanced program must also support a community of scientists making critical laboratory measurements and deriving basic theoretical principles that enable the interpretation of new observations.

TECHNOLOGY

NASA has advanced the state of the art in various aspects of infrared, submillimeter and radio technology and has also benefited from large Department of Defense investments in detectors. Since different wavelength bands are in different states of readiness, the technological state of the art is a relevant parameter in ordering different missions. The role of modest projects, including instruments on ground-based and airborne telescopes, as well as small and large Explorers, cannot be overemphasized in bringing different technologies to an appropriate state of readiness for inclusion in larger missions less tolerant of development risk.

Detectors

The heart of any observatory is its complement of detectors and receivers. Continued research and development that capitalizes on developments in industry and university laboratories is critical to making the most of the space environment. NASA has carefully nurtured detector development activities for SIRTF and the infrared instrument on HST. Background-limited arrays as large as 128×128 or even 256×256 in the 2.5—30 μm region are currently within reach and large, more radiation-resistant arrays in the 30—200 μm region can be available prior to the start of SIRTF development. It is extremely important to continue the development and testing of such arrays in order to maximize both the scientific return from SIRTF and the understanding of their properties and use.

A program has been started to develop the mixers and local oscillators necessary for submillimeter astronomy, leading eventually to LDR. In this context it is crucial that laboratory devices be incorporated in instruments that can be used on ground-based or airborne telescopes, or on small space missions, as appropriate. Such instruments return valuable scientific results relevant to planning larger space missions, motivate scientists in the long gaps between major missions and uncover problems at a phase of development when the cost of fixing them is low.

Telescopes

It is an astronomical cliche that "there is no substitute for aperture", meaning that astronomers always want the largest possible telescope to maximize both sensitivity and spatial resolution. It is also well known that the cost of an observatory increases as some high power of the size of its telescope. Thus, NASA has to plan carefully to ensure that telescopes large enough to satisfy the scientific requirements can be built while keeping total mission costs within reasonable bounds. In the near term, this goal can be accomplished by complementing SIRTF, the 1 meter-class, cryogenically-cooled infrared Great Observatory, with SOFIA, a 2.5 meter-class, cool, airborne observatory.

IRAS verified the feasiblity of cryogenic telescopes in space so that there is a great deal of confidence in the technological readiness of SIRTF. The requirement for infrared/submillimeter telescopes much larger than 2 meters has pushed NASA to begin development of precision, lightweight panels and support structures. NASA's Precision Segmented Reflector program is a good example of a long term development program tied directly to future needs. There is a need to utilize this technology in a near-term precursor to LDR.

Cryogenics

Almost all instruments envisioned in this report require cooling to temperatures between 0.1 and 80 K. Development of active coolers for space applications is an important area of technology, currently supported at a modest level by the Office of Aeronautics and Space Technolgy (OAST). Support for continued progress in active cooler technology must be increased in order to provide the capability that will be required for a long lived submillimeter facility like LDR.

COMMUNITY SUPPORT AND DEVELOPMENT

There is a grave risk that a program devoid of opportunities for young scientists at various stages in their careers will lack the senior people required to carry out the major missions as they arise. Flagship missions like SIRTF and LDR demand the best, most experienced scientists and engineers to work on their design and construction and ultimately to interpret the data returned by them. To attract and keep such people NASA must continually offer challenging projects. Small Explorer missions such as SWAS fit well into this category. But in the infrared/submillimeter disciplines, the airborne astronomy program is unmatched in providing "hands-on" experience to a large number of young scientists. This is because sub-orbital experiments are modest in scale and proceed rapidly enough from conception to conclusion to train the graduate and postdoctoral students who will become the next generation of space scientists. The most important mission from this standpoint is SOFIA with at least 120 flights per year involving more than two dozen experimental groups developing state of the art instrumentation. SOFIA, like its predecessor the KAO, will be without peer in providing young scientists with an exciting environment that closely simulates the rigors of space research.

It is also important to note that the enormous amount of high quality data promised by the future NASA missions provides both an opportunity and a challenge to the astronomical community. The infrared, submillimeter, and radio program addresses scientific questions in all areas of astrophysics, and it is important for NASA to make efforts to ensure the needed presence of skilled space scientists to make use of these data. Combined with the aging of the current generation of scientists, a potential crisis is developing unless NASA makes efforts to encourage new people to enter the field. Two promising proposals are long-term NASA post-doctoral fellowships and long-duration PI grants.

Although this recommended a program covers a variety of timescales and provides for astronomers at all levels in their careers, there are major concerns in this area. If the time between space missions drags out much longer, established scientists will leave the field and graduate and postdoctoral students will never enter it. *The space astronomy program will not survive such a hemorrhaging of talent.*

INFRASTRUCTURE

The planned NASA missions, particularly the Great Observatories will provide a greatly increased flow of data to the astronomical community. To fully exploit this wealth of information, NASA needs to continue its support of the necessary infrastructure. These areas include important laboratory measurements, theoretical studies, and data analysis for previous missions. This support has been essential to the conversion of data into meaningful scientific results.

NASA's laboratory astrophysics program has provided measurements of key physical parameters needed to interpret the observations. The conditions and species studied under this program are often very different from those normally studied in the laboratory, and NASA has been the chief source of support of this work. But the enormous increase expected in the flow of data due to SIRTF, SOFIA, SWAS, etc., requires an attendant increase in the laboratory astrophysics program. Theoretical studies have also been essential to the understanding of observational data. It is important for NASA to continue its broad-based support for data analysis. The continuing flow of scientific results from previous missions has amply demonstrated the value of archival data analysis and proved the merit of the Astrophysics Data Program.

Within each wavelength area the aim is to progress from simple missions such as balloons, rockets and airborne telescopes that pioneer the field, to small and moderate Explorers that survey the sky and qualify new technologies, culminating in a major space mission capable of answering the basic questions in the field. In this section, we describe a program which accomplishes the scientific goals discussed in the previous sections. The individual projects are described briefly herein; considerably more detail can be found in the literature describing each mission. We assume a basic familiarity with the missions and in this section attempt to put each mission in the context of an overall program that emphasizes complementarity and synergy. Figure 2 shows the proposed timeline for the various missions in the program.

THE HIGHEST PRIORITY MISSIONS: SIRTF and SOFIA

The combination of SIRTF's 1-m cryogenic telescope with SOFIA's 2.5-m uncooled telescope will provide the astronomical community with an observational capability that is well matched to the rest of NASA's Great Observatory program. SIRTF and SOFIA will individually provide outstanding scientific return, as well as complement each other and the other NASA Great Observatories. Since no single facility can offer all of the capabilities, the construction of SIRTF and SOFIA in the 1990s will provide an unrivaled combination of sensitivity and spatial/spectral resolution that will unravel many of the basic questions outlined in this report. SOFIA can begin operations in the mid 1990s, about the same time as AXAF, and will ensure a multi-spectral overlap with the Great Observatories operating at other wavelengths, until SIRTF is launched in the late 1990s. As a sub-orbital facility, SOFIA has other programmatic advantages that are discussed below. *SIRTF and SOFIA should be the highest priority missions of the Infrared/Radio Astrophysics Branch of NASA.*

Space Infrared Telescope Facility

The SIRTF mission, with a 1 m-class infrared telescope, cooled to take full advantage of the very low natural background of space, will crown NASA's program in infrared astronomy and take its place among the other Great Observatories as the definitive instrument in this wavelength range. SIRTF is proposed for a new start in 1992/3 leading to a launch in 1998, and will be the culmination of two decades of pioneering US efforts in infrared astronomy, from ground-based, airborne and space instruments up through IRAS. SIRTF's mirror, baffles, detector, and optical system will be cooled by superfluid helium to a temperature of 2 K. The infrared Great Observatory is designed to have a mission lifetime of at least five years. The science instrument complement consists of an infrared array camera for wide field, diffraction-limited imaging from 2 to 20 μm, an infrared spectrometer with resolving power from 100 to >2000 for wavelengths of 3 to 200 μm, and a multiband imaging photometer for background-limited imaging and photometry from 2 to 700 μm, and for broadband photometry from 200 to 700 μm. SIRTF will capitalize on the revolution now taking place in the development of large-format, low-noise detector arrays. The SIRTF cameras have the ability to map selected regions of the sky 100 to 10,000 times faster than previous missions and with much greater detail than ever before. Searches for brown dwarfs and protogalaxies are examples of scientific goals which are simply unreachable without this enhanced capability. Low noise detectors will also give the SIRTF spectrometer a thousandfold increase in sensitivity. This sensitivity will allow SIRTF to determine, for example, redshifts in infrared luminous galaxies at redshifts of 2—3 and to detect features like Brackett-alpha in primeval galaxies.

Improved spatial resolution is essential for the detection of extra-solar planets and planetary debris; the study of active galactic nuclei and the detection of protogalaxies; and wavelength coverage out to 700 micrometers which will be used to study distant solar system objects, cold molecular clouds, infrared cirrus, active galaxies, and quasars. The technique of super-resolution can be used on the brighter sources to enhance the spatial resolution to match that of a telescope twice as large in primary diameter.

Stratospheric Observatory For Infrared Astronomy

SOFIA offers improvements over SIRTF in spectral resolution and in far infrared spatial resolution that are essential to understand the physical mechanisms operating in astronomical sources. This is because the need for cryogenic cooling limits SIRTF's primary mirror to moderate size. For broadband photometry in the infrared, aperture size is less important than achieving the low background performance. However, at high spectral resolution, the sensitivity for detection of emission lines depends critically on aperture size. SOFIA's heterodyne spectrometers will resolve <1 km s^{-1} velocity differences that are critical to understanding how, for example, stars like our sun form out of interstellar clouds.

SOFIA will be an airborne 2.5-m class uncooled telescope mounted in a specially modified Boeing 747 aircraft. The project is a joint venture of NASA and BMFT, NASA's counterpart in the Federal Republic of Germany. SOFIA will be the modern replacement of the KAO, which has been a highly productive NASA suborbital program. The KAO has demonstrated that it is possible to make a wide range of infrared and submillimeter observations using an airborne telescope flying above most of the atmospheric absorption. SOFIA serves as the next logical step in the airborne program, providing nearly a tenfold increase in sensitivity and areal information over the KAO. The increase in sensitivity is critical since, for example, it will allow SOFIA to take spectra of a thousand IRAS galaxies, determining morphology, chemical abundances, physical conditions, and internal dynamics.

SOFIA builds on the great success of airborne astronomy which has provided first class science in many astronomical areas including the evolution of the supernova SN 1987A, the first detection of water in a comet, the discovery of the rings of Uranus, and the key observations of interstallar features leading to the identification of complex hydrocarbons as a previously unrecognized, but abundant, component of the interstellar medium. In all these areas of research, the increased aperture of SOFIA will enable new types of observations, and permit the measurement for the first time of many quantities in external galaxies. The mobility of an airborne observatory provides a unique capability which has been demonstrated many times with observations of such events as SN 1987A, solar eclipses, planetary occultations, and comets. SOFIA's increased sensitivity will permit the measurement of many more such events.

SOFIA will provide at least 120 flights per year utilizing instruments developed by the university community that can be changed on every flight if desired. Payloads can be tailored for coordinated observations with other Great Observatories. The latest technologies in detector arrays, heterodyne receivers and eventually arrays of heterodyne receivers, can be continuously incorporated into new instruments. This capability is particularly important in the submillimeter where SOFIA represents a critical step building to LDR. SOFIA will bring out the best scientific skills and technological leadership in the design of its submillimeter instrumentation. It will be a valuable training ground for students and young scientists. During the ISO mission, the center of gravity in infrared astronomy will inevitably shift towards Europe. It will enable US astronomers to remain highly competitive while ISO is flying and SIRTF is being built, by providing a unique capability for critical high spatial/spectral resolution observations.

LDR AND SUBMILLIMETER ASTRONOMY

The idea of a 10—20 m telescope operating from 30—600 μm is an exciting one whose time is fast approaching; the technology to make the Large Deployable Reflector (LDR) is close at hand. The scientific return from such a mission would be profound and would range from searches for Jupiter-like planets around nearby stars and maps of the primitive solar nebulae around nearby protostars to resolving individual Giant Molecular Clouds in distant galaxies and detecting the 157 μm line of [CII] in primeval galaxies.

LDR will build on the scientific return from the cryogenic telescopes, IRAS, ISO, and SIRTF, by adding the high spectral and spatial resolution capabilities that these missions lack. LDR would surpass SOFIA by virtue of LDR's enormous aperture and because of the total lack of atmospheric absorption which blocks many specific spectral lines from airborne telescopes. Despite SOFIA and large telescopes atop high mountain sites, the full power of submillimeter astronomy will only be realized when LDR begins to operate.

NASA should continue to follow the coherent plan which has been laid out to progress to the ultimate development and operation of LDR. This plan provides for parallel development of the critical technologies, such as precision segmented reflectors, erection and control of large space structures, mechanical and hybrid cooling techniques, and the evolution of heterodyne receiver arrays throughout the submillimeter. In addition, the timely development of SOFIA, SWAS, and a Submillimeter Explorer or a moderate mission (SMME/SMILS) will provide the necessary scientific structure as well as the demonstration of the technologies required to support LDR.

SMALLER MISSIONS

The Cosmic Background Explorer

The Cosmic Background Explorer (COBE) will provide the definitive data on the spectral properties of the cosmic background radiation. COBE will also measure the spatial isotropy of the background radiation on an angular scale of a few degrees. Of equal importance is that COBE will perform a calibrated survey of the entire sky in the 1—300 μm region with low spatial and spectral resolution to search for a diffuse infrared background associated with the formation of the earliest galaxies. After a trying two-year period of work necessitated by the transition from a Shuttle to a Delta launch, COBE is scheduled for launch in 1989. NASA must ensure that adequate resources are made available to the COBE science team and, eventually to the general astronomical community to reduce and understand fully the COBE data. NASA is to be commended for its support of data reduction for the successful IRAS mission. A similar commitment will be important in the years after COBE.

The Infrared Instrument on Hubble Space Telescope

The review panel examining all the proposed second generation instruments for the Hubble Space Telescope recommended that a near infrared instrument have the highest priority because of the important science possible with its combination of great sensitivity with high spectral and spatial resolution. NASA recently selected the Near Infrared Camera and Multi-Object Spectrograph (NICMOS) to provide an infrared capability for HST. The rapid advances in array technology permit the use of 128×128 and possible 256×256 element HgCdTe arrays that come close to reaching the scattered zodiacal background limit shortward of 2 μm. Sensitivity gains of a factor of 100 or more over ground based 8-10 m telescopes and spatial resolution as good as 0.1" over complex fields are possible with HST. While NICMOS falls within the purview of the UV/Visible Astrophysics Branch of NASA which has overall responsibility for HST science, the Infrared/Radio Astrophysics Branch enthusiastically supports the rapid deployment of the near-infrared instrument on HST.

Submillimeter Explorer/Moderate Mission (SMILS)

The overall program plan that has worked well in other wavelength regions starts with opening up a field with ground-based or airborne facilities, proceeds to a modest space experiment and culminates in a major observatory. If this path is followed in the submillimeter, then SOFIA would be complemented by a Submillimeter space mission surveying the wavelength region in a way that leads logically to LDR. This mission concept is to make a complete spectral survey in the 100 μm to 1 mm range of a variety of astrophysical objects. It received a very high rating during the most recent Explorer study solicitation. Concept definition studies are now underway and should be given a high priority within NASA's planning.

Orbiting Platforms for Radio Astronomy

As discussed earlier there are two aspects of radio astronomy that require operation from space. First, the addition of one, or more, orbiting antennae to the ground-based VLBA would double or triple the spatial resolution of that network. There is a great deal of exciting science that such an enhanced array could carry out. The availability of ground-based radio telescopes means that VLBI is a mature field that can proceed rapidly to a space mission on a sound scientific and technical basis. Limited experiments using a TDRSS communication satellite have already demonstrated the technical feasibility of Orbiting VLBI.

Second, there is an exciting opportunity to open a new spectral window at very low frequencies with a low cost space array. The technology to fly such a mission is straight forward—simple dipole antennae and radio frequency components suffice—and the scientific return is exciting. The major difficulty is in lauching such antennae to a high enough orbit to get above the ionosphere. A science working group should be established to work out the details of a low cost mission that could, perhaps, piggyback on the launch of another satellite.

Small Explorers

NASA's Small Explorer program offers a valuable, new capability to launch payloads weighing a few hundred pounds, requiring less than 100 watts of power and needing only modest orbital requirements. While full-fledged cryogenic telescopes for the thermal infrared do not fit well within the constraint envelope of present small Explorer launch vehicles, instruments in the submillimeter or near infrared, such as SWAS, can use this platform to perform important science on a rapid timescale. This will become even more valuable as future versions of the launch vehicle offer increased capability performance.

The Infrared/Radio Astrophysics Branch should actively pursue Small Explorer missions. One Small Explorer mission for the infrared-submillimeter every three to five years can be scientifically justified and would have the second, essential role of space qualifying both new technologies as well as training new generations of instrument builders.

INTERNATIONAL COOPERATION

Despite the great advances in capability represented by SIRTF, ISO has the considerable advantage of an earlier launch date so that a modest level of collaboration between NASA and ESA on ISO will be beneficial to US astronomers. ISO will point the way to many challenging problems that can only be addressed by SIRTF. Obviously, access to space infrared data is crucial to the health of US astronomy in the 15-year gap between IRAS and SIRTF. NASA recently offered to provide a second ground station for the reception of ISO data while it is out of sight of its primary ground station. In return, the US would receive 10-15% of the observing time.

NASA should consider the importance of international collaboration in submillimeter astronomy because there is worldwide interest in these wavelengths. A project to build an 8-m telescope called FIRST is one of ESA's "cornerstone" missions; and the French Space Agency is actively pursuing a smaller 4-m submillimeter telescope project. NASA must first ensure good communication between US and European scientists about the science goals and technological needs of future submillimeter missions and then try to develop a balanced program in concert with the relevant space agencies.

Two international collaborations are possible in the area of the cosmic background. First, the Japanese will be flying a small, cryogenic telescope called the Infrared Telescope in Space (IRTS) for two to three weeks in 1993. They have invited two groups of US astronomers to participate in the construction of two instruments. The facility and the instruments are low cost, on the scale of what a university laboratory can build, and are an outgrowth of a successful Japanese sounding rocket program. IRTS will study Galactic and extra-galactic radiation on the scale of a 0.1°. It will provide unique scientific data and is an excellent opportunity for US astronomers to participate in a space mission at little cost to NASA. Part of the agreement with the Japanese includes access to IRTS data by the broad US community within two years of the end of the mission. In addition, discussions are underway about sharing the data from the US COBE and the Soviet Relict I and II missions. Additional cooperation may be possible on a Soviet mission to orbit a cryogenic submillimeter telescope called Aelita, a demonstration version of which is due to be launched in 1994.

It is in the interest of US science for NASA to participate in an international OVLBI mission as soon as possible. Because the US has a great deal to contribute, including the ground-based VLBA network and to NASA's tracking system, the cost to NASA would be minimal and the scientific return considerable. Partnership in such an international venture such as Japan's VSOP and/or the Soviet RADIOASTRON should be considered a high priority by NASA.

SUPPORTING RESEARCH ACTIVITIES

Balloons

NASA's balloon program in the infrared and submillimeter is a vibrant one that involves instrumental and observing projects of high scientific caliber that take place on a timescale rapid enough so that graduate and postdoctoral students can be full participants during their short tenures. Approximately 10 experiments are presently supported in a program that studies a range of problems from the presence of O_2 in molecular clouds and the distribution of cool dust in the Galactic plane using submillimenter observations, to measurements of the spectral and spatial peculiarities of the cosmic background radiation. Many of these projects pointed the way for the design and interpretation of COBE data and are now poised to verify and follow up on surprising results expected from COBE. Some of the techniques incorporated into the design of the SWAS mission were pioneered in the balloon program.

A crucial aspect of the balloon program is its ability to train new instrument builders under conditions that approach the rigor of space experiments. Balloon payloads are limited in weight and power and must survive major gravitational loads. Producing state of the art instrumentation under such conditions is a major challenge that too infrequently faces our students.

Ground-Based Observations

The ability to make some astronomical infrared observations using ground-based telescopes has been critical to the development of NASA's program in infrared and submillimeter in the past and will continue to be so in the future. While support for ground-based astronomy is necessarily of secondary importance within NASA, there are areas where such support is essential to achieving NASA's goals.

NASA has in the past supported ground-based programs on purely scientifc grounds; the pioneering Two Micron Sky Survey is one example. NASA should support such activities in the future if they are critical to the success of NASA missions. A new 2 μm sky survey using state of the art detector arrays would be four to five orders of magnitude more sensitive than the original 2 μm survey and would greatly enhance the science returned from the HST infrared instrument and SIRTF.

The use of detectors and receivers on ground-based telescopes is often the first, critical step in their development and verification. For example, the HgCdTe detector arrays selected for NICMOS on the Hubble Space Telescope were first operated and had their performance verified using ground-based telescopes. The submillimeter receivers and local oscillators for LDR will first be used on telescopes atop Mauna Kea.

Finally, it should be pointed out that ground-based telescopes offer inexpensive, widely available research tools for introducing new students at the undergraduate and graduate level to the excitement of observational astrophysics. While NASA's airborne facilities and space data are crucial in the training of students and post-doctoral scientists, wide access to technologically advanced instruments working on first-rate scientific projects that are integral to NASA goals are needed to attract young students to space astronomy in the first place.

Data Analysis

The creation of an entire branch devoted to Mission Operations and Data Analysis demonstrates NASA's commitment to a data reduction program commensurate in scope with the mission returning the data. The establishment of the Infrared Processing and Analysis Center (IPAC) to generate new products from the IRAS mission and to support the guest investigator community is an excellent example of NASA's willingness to extract all of the important science from a successful mission. This model should be carried out in the future for missions such as SIRTF and LDR.

Laboratory Astrophysics

NASA supports various laboratory efforts to study physical processes relevant to its missions. Transforming observations into useful astrophysical data depends on knowing transition frequencies, oscillator strengths and reaction rates of exotic species not normally studied in industrial or university laboratories. Consequently, there are cases where information critical to NASA's missions can only be obtained with NASA support. One good example is the laboratory measurement of spectra of analogs of interstellar hydrocarbons and ices which have proven to be essential to the interpretation of recent KAO spectra (Figure 18). NASA must critically assess which programs are most relevant to its needs and then strongly support those investigations.

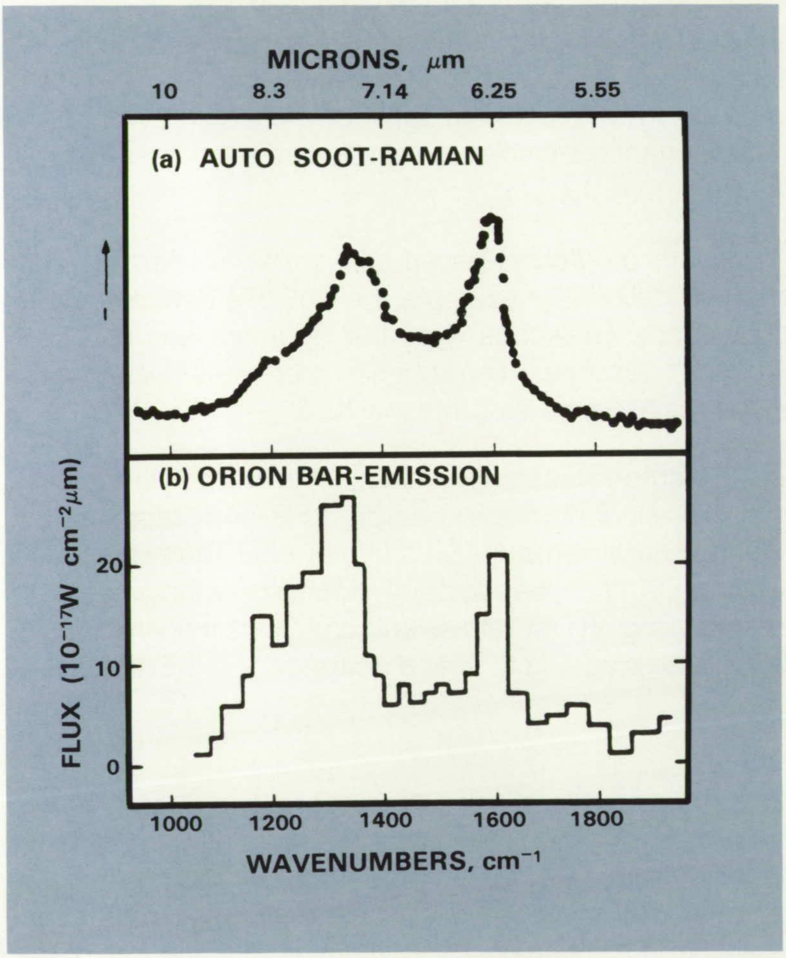
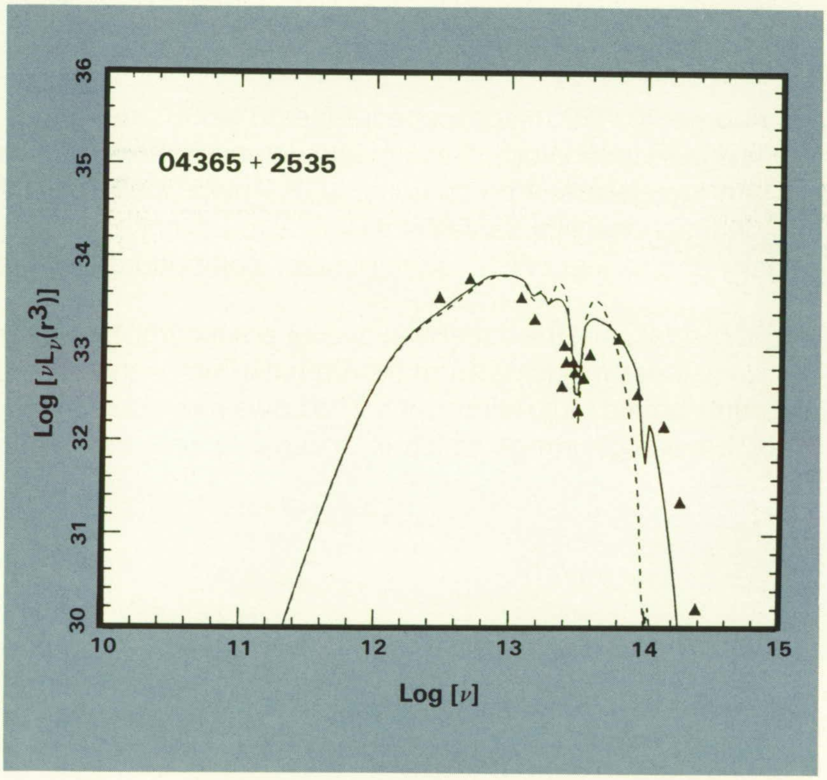


Figure 18.
The top spectrum shows a laboratory measurement of the vibrational spectrum of automobile exhaust (soot) which contains many of the complex hydrocarbons (PAHs) thought to exist in the interstellar medium. The lower figure shows a KAO spectrum of a bright region in the Orion Nebula.

Theoretical Studies

NASA should continue to fund theoretical investigations relevant to its ongoing or future missions. These studies, carried out jointly by theoretical physicists and observational astronomers, have been highly successful in the interpretation of space observations in the context of sophisticated theoretical models. An excellent example is the work on star formation which has advanced our understanding of how low mass stars form out of the collapse of small, dense cores of rotating molecular gas (Figure 19). This theoretical work has been carefully tied to results from IRAS and ground-based telescopes. Investigations of this type help synthesize telescope observations and laboratory measurements into a coherent whole that in turn leads to the posing of new problems requiring new observations. Support of theoretical programs is a key component of a balanced program in long-wavelength astrophysics. NASA should pursue those theoretical activities which relate *directly* to the science returned by its missions. The requirements for a theoretical investigation should be either to lay the fundamental ground work for future missions, or to place the results of data analysis from current or past missions into a broader theoretical framework.

Figure 19. Ground-based and IRAS observations of a nearby protostar are compared to theoretical calculations. The good agreement between theory and observation suggests that these objects are deriving more than half of their energy from the infall of material onto a circumstellar disk.



CONCLUSIONS

The wavelengths longward of 1 μm offer tremendously exciting science opportunities. NASA can make fundamental advances in all areas of astrophysics over the next 20 years by implementing a program that combines large observatories with smaller projects to ensure a steady flow of data and an infusion of new ideas and people. Key aspects of the program include:

- SIRTF will provide the spectacular climax of the Great Observatory program and will derive much of its great potential from using the latest in detector array technology developed in the United States.

- SOFIA is crucial to a vital program in submillimeter and far-infrared astronomy. SIRTF and SOFIA will gather complementary data on a variety of key questions and together provide capabilities that complement HST, AXAF, and GRO in terms of sensitivity, spatial and spectral resolution.

- The Infrared/Radio Astrophysics Branch should pursue a vigorous program of smaller missions ranging from balloons to Small Explorers. These missions will return important scientific results and demonstrate critical new technologies.

- A large 10—20 m telescope for the 30—600 μm band is becoming technically feasible. The LDR technology program should be accelerated, particularly in the area of receivers and cryogenics. A precursor to LDR which would explore the submillimeter with a complete spectral line survey is essential to advance our understanding of the submillimeter sky and to test critical submillimeter components in space.

- Participation in the Japanese and/or Soviet orbiting VLBI radio astronomy projects is vital since these missions will make dramatic improvements in spatial resolution compared with earth-bound radio telescopes. The Low Frequency Space Array will pioneer exploration of a wavelength range which is accessible only from space.

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Appendix
Glossary of Abbreviations and Acronyms

AXAF	Advanced X-Ray Astrophysics Facility	Great Observatory for X-ray observations; to be launched in 1996
BMFT	Bundesministerium Fuer Forschung Und Technologie	NASA's Counterpart in the Federal Republic of Germany
COBE	Cosmic Background Explorer	Cryogenic telescope in space, for radio to near-IR measurements to diffuse backgrounds; to be launched in 1989
ESA	European Space Agency	
GRO	Gamma Ray Observatory	Great Observatory for gamma-ray observations; to be launched in 1990
HST	Hubble Space Telescope	Great Observatory for observations from ultraviolet to near-IR; to be launched in 1990
IPAC	Infrared Processing and Analysis Center	Data processing center for analysis of data from IRAS mission
IRAS	Infrared Astronomical Satellite	0.6 m cryogenic telescope, launched in 1983 as an Explorer
IRTS	Infrared Telescope in Space	15 cm cryogenic telescope; to be launched by Japan in 1993
ISO	Infrared Space Observatory	0.6 m cryogenic telescope; to be launched by ESA in 1993
KAO	Kuiper Airborne Observatory	0.9 m ambient temperature telescope in C-141 aircraft
LDR	Large Deployable Reflector	10-20 m telescope in space
LFSA	Low Frequency Space Array	Survey facility for radio frequencies <10 MHz
NICMOS	Near Infrared Camera and Multi-Object Spectrometer	1-3 μm instrument for Hubble Space Telescope; to be installed in 1995
OVLBI	Orbiting Very Long Baseline Interferometry	Radio astronomy technique using ground and space telescopes
RADIOASTRON		Soviet radio telescope for OVLBI astronomy
SIRTF	Space Infrared Telescope Facility	1 m cryogenic telescope in space; Great Observatory for infrared observations
SMILS	Submillimeter/Infrared Line Survey	4 m telescope to explore submillimeter spectrum

SMME	Submillimeter Explorer	Proposed 2.5 m telescope to explore submillimeter spectrum
SOFIA	Stratospheric Observatory For Infrared Astronomy	2.5 m ambient temperature telescope in Boeing 747 aircraft
SWAS	Submillimeter Wave Astronomy Satellite	Small Explorer mission using heterodyne spectroscopy for submillimeter observations; to be launched in 1993
TDRSS	Tracking and Data Relay Satellite System	NASA communications satellite system in geostationary orbit
VLBA	Very Long Baseline Array	Ground-based array of radio telescopes, scheduled for completion in late 1992
VLBI	Very Long Baseline Interferometry	Radio astronomy technique using widely separated telescopes
VSOP	VLBI Space Observatory Program	Japanese radio telescope for OVLBI

Credits

Figure 4. Infrared Processing Analysis Center.

Figure 5. Center: Infrared Processing and Analysis Center.
Left, top: Courtesy of I. Gatley et al., NOAO.
Left, bottom: Courtesy of M. McCaughrean, Goddard Space Flight Center.
Right: Courtesy of I. McLean., United Kingdom Infrared Telescope.

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Figure 13. Courtesy of I. Gatley et al., NOAO.

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