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Charting the Winds that Change the Universe
Far Infrared and Submm Astronomy

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Abstract: The behavior of interstellar gas and dust is responsible for many intriguing mysteries of the Universe, giving the far infrared/submm spectral region a special importance. New missions in the next decade will advance our understanding of the FIR/Submm Universe, but will leave us orders of magnitude behind the capabilities of the surrounding spectral regions by 2010. Closing this gap in capability requires an expanded technology program, definition of a major space telescope at the end of the decade, and development of a precursor mission for a km-baseline interferometer.

1. The Role of the Far IR/Submm

Winds and flows in the interstellar medium convert a potentially static scene into our mysterious and fascinating Universe. A supermassive black hole lurks unseen in the nucleus of a galaxy until interstellar gas collects into a central accretion disk and spirals in, causing an active galactic nucleus (AGN) to blaze up. Galaxy collisions spray stars in intriguing patterns, but the fundamental consequences arise from the ability of the interstellar medium (ISM) to lose angular momentum and collapse to fuel nuclear starbursts. Stellar populations everywhere are established and renewed by the formation of new stars in molecular clouds. The heavy elements that shape stellar evolution and make life possible are transported by interstellar material to the sites of star formation, awaiting incorporation into new stars and planets.

The far infrared and submm are critical for probing the interstellar medium. Regardless of the original emission process, cosmic energy sources glow in the far infrared due to the effectiveness of interstellar dust in absorbing visible and ultraviolet photons and reemitting their energy. For example, the Milky Way and other galaxies show two broad spectral peaks, one produced directly by stars and extremely thoroughly studied in the visible and near infrared and the second comparatively unexplored in the far infrared. Warm, dense interstellar gas cools predominantly through low energy fine structure lines and also emits profusely in rotational transitions of the most abundant molecules; both systems of lines emerge predominantly in the far infrared and submm. These lines are key participants in the process of collapse that regulates formation of stars and AGNs. They also provide detailed insights to the temperature, chemical composition, density, and ionization state of the collapsing clouds.

We explore the scientific potential of new, large aperture telescopes and interferometers in space operating over the ~20 to ~800μm FIR/Submm range.

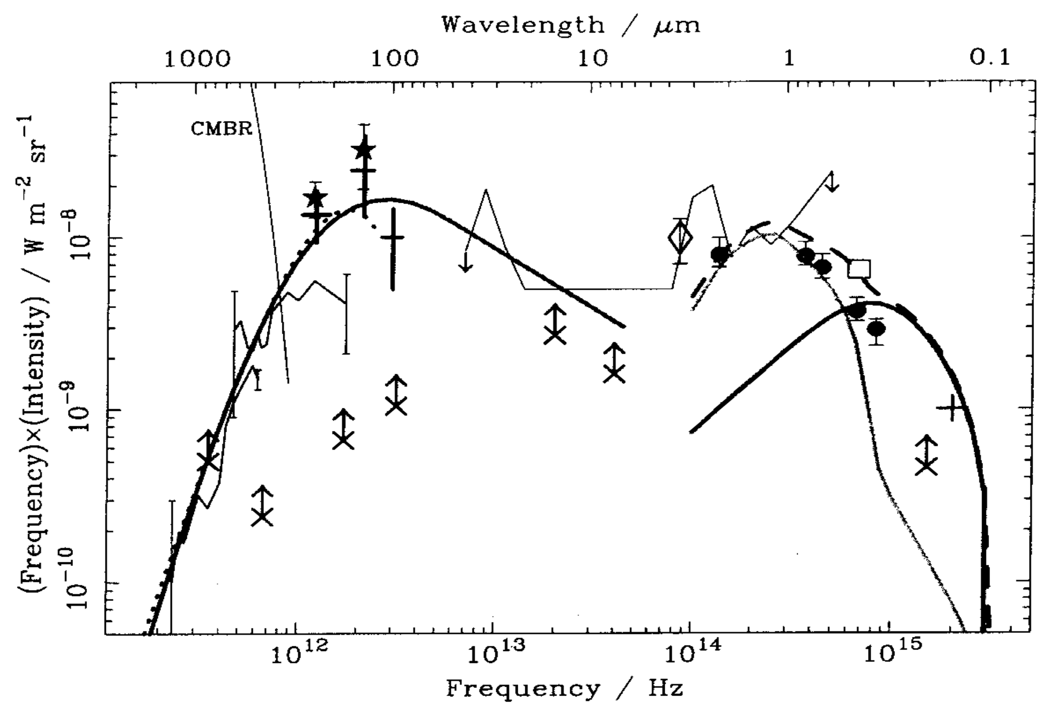
2. The Far Infrared/Submm Universe and the OSS Strategic Plan

2.1 How stars and Galaxies Emerged from the Big Bang

The history of star formation determines the evolution of galaxies and the generation rate for heavy elements. It has been traced by a combination of deep Hubble Space Telescope (HST) imaging with photometry and spectroscopy using the Keck Telescope. However, even at modest redshifts, these techniques only probe the rest frame ultraviolet. Interstellar dust can absorb nearly all the UV in star forming galaxies. In the best-studied starburst galaxies such as M82, a debate raged for more than a decade regarding how to correct even the near infrared emission for the effects of interstellar extinction. Such corrections are poorly determined for galaxies at high redshift. Consequently, there are significant uncertainties in the star forming rate for $z > 1$.

These uncertainties could be removed by measuring the far infrared emission emitted by dust heated by young stars in these galaxies. The importance of this approach is underlined by the Cosmic Background Explorer (COBE) discovery of a background in the submm with an energy density comparable to that of the visible light cosmic background (see Figure 2-1). This background has been partially resolved by ISO in the very far infrared and is thought to arise from starburst galaxies at $z = 1$ to 3. A 10-m or larger telescope with detection limits of 0.1mJy or less would probably resolve most of this high redshift background into individual galaxies.

Figure 2-1. Cosmic energy density between 0.1mm and 2mm wavelength. The various upward pointing arrows indicate counts of point sources, while the heavy solid and dashed lines show the results of large beam measurements and models that measure or predict the true absolute sky brightness. This plot and subsequent ones in the report are in vF_v or similar units, so a horizontal line represents constant energy per logarithmic frequency or



Ultradeep optical images (e.g., Hubble Deep Field) reveal many galaxies too faint to contribute significantly to the submm diffuse background. The infrared emission of "normal" starbursts is dominant over infrared cirrus emission between about 15 and 80μm. At $z \geq 4$, it will begin to become possible to measure this emission with the Millimeter Array (MMA). However, for $z < 4$, the MMA only probes the cool dust and infrared cirrus emission that may not be a reliable indicator of the recent star formation. The rate of star formation for $1 < z \leq 4$ can be determined through high sensitivity imaging from 20 to 70μm. As illustrated in Figure 2-2, angular resolution of about 1" (10-m telescope at 50μm) will be adequate; sensitivities of ~10μJy would allow measurements to well below galaxy luminosities of 10^{11} L_{υ}.

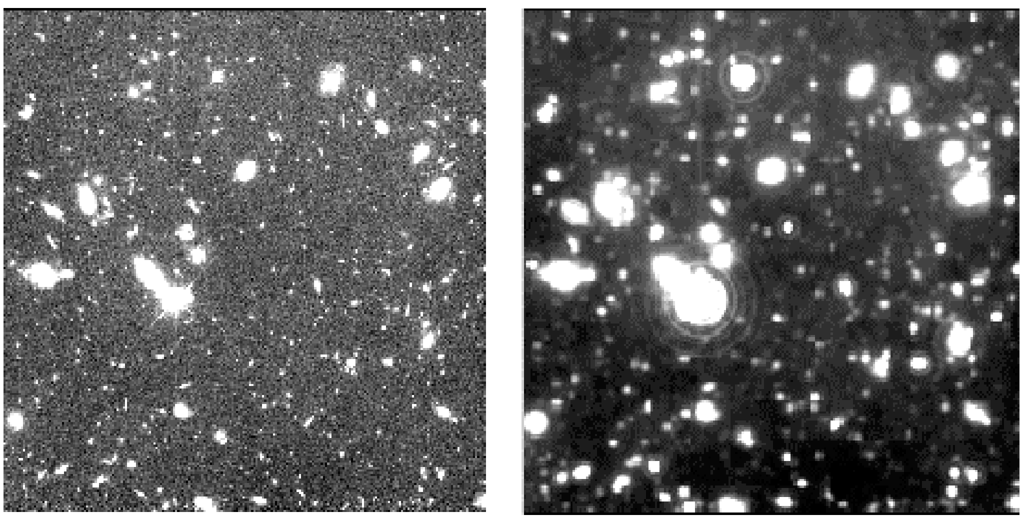


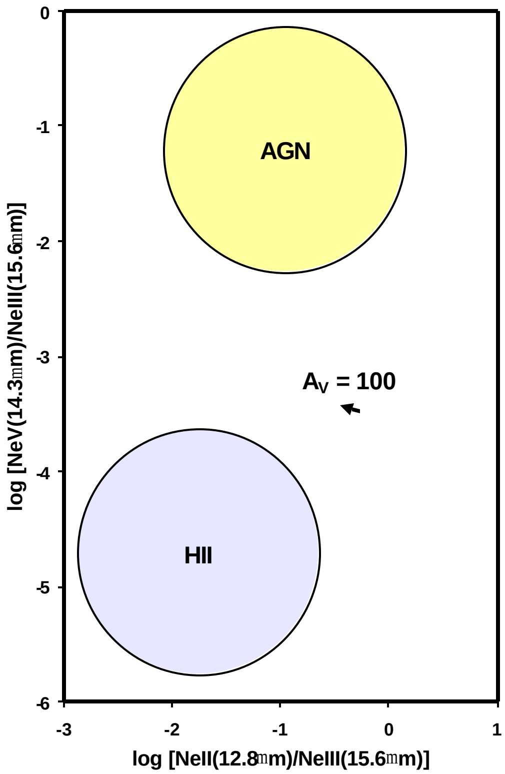
Figure 2-2. A section of the Hubble Deep Field at the original resolution and convolved to a diffraction limit of 1" FWHM. Thanks to J. Bechtold.

2.2 Extreme Environments and Discovery of New Phenomena

2.2.1 Formation of AGNs

It appears that central supermassive black holes are a universal component of galactic bulges. At the current epoch, galaxy mergers produce huge far infrared fluxes through a combination, evidently, of violent starbursts and of AGNs associated with these black holes. Both types of energy source are hidden within cocoons of interstellar dust that are impenetrable in the optical and near infrared. What happens during the much more common mergers that build galaxies in the early Universe? Is the strong cosmic evolution of quasars an indication that their formation is favored at early epochs? Is much of the far infrared luminosity in the early Universe derived from dust embedded AGNs?

The fine structure lines of NeII (12.8μm), NeIII (15.6μm) and NeV (14.3μm) are the best tool to distinguish unambiguously whether the ISM of a dusty galaxy is ionized by a starburst or an AGN. Figure 2-3, based on work by Voit and Spinoglio and Malkan, is a demonstration. Not only are the line ratios very well separated, but their extinction is reduced by more than a factor of thirty compared with the visible. At the epoch of peak quasar activity, these lines will be redshifted to the 45 to 55μm range. A 10-m far infrared telescope would have both the necessary resolution (compare Figure 2-2) and sensitivity to use this tool to determine the relative roles of star formation and nuclear activity in the early Universe.



Ne V is not excited appreciably by hot stellar spectra, but is produced by the hard UV spectra of AGNs. Hence, the line ratios plotted distinguish the two types of ionizing source unambiguously. The plotted ratios are virtually extinction independent; the short arrow shows the effect of 100 magnitudes of visible extinction.

Figure 2-3. Diagnostic diagram for Mid-IR neon fine structure lines.

2.2.2 Potential to Discover New Phenomena

Technological advances enable astronomical discoveries. Harwit tried to quantify this relation in "Cosmic Discovery," from which we take Figure 2-4. In the 25 years preceding publication of the book, new technology led to important discoveries within 5 years of its development. The exceptional discovery potential in the FIR/Submm region arises because the sensors are still substantially short of fundamental performance limits. As discussed in Section 5.4, modest additional funding can be expected to lead to substantial increases in sensor capabilities, which would compound on the progress possible through larger telescopes and interferometers. Hence, there is a high likelihood that significant and unanticipated advances can be made in our knowledge of the Universe.

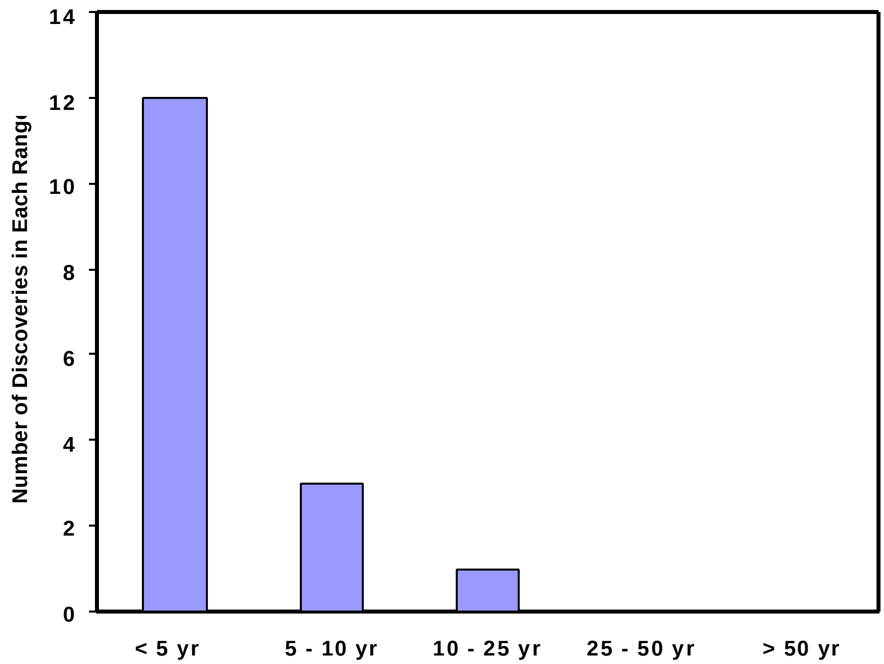


Figure 2-4. Age of Required Technology at Time of Discovery. New technologies produce new discoveries within the first five years of their introduction. From Harwit, Cosmic Discovery.

2.3 Dynamical and Chemical Evolution of Galaxies and Stars

How do the first gas clouds form? What chemical processes occur within them and how do their characteristics change as the first traces of metals are injected into them by stellar processing?

The low lying H_2 lines at 17 and 28.2µm are one of the few conceivable ways to study molecular gas prior to the formation of metals (and to determine if molecules can even form during this epoch). ISO has demonstrated that these lines can be detected in the interstellar medium (see Figure 2-5). In this case, fits to their absolute and relative strengths require a molecular gas temperature of about 100K and a density of about 3000 cm^{-3}. However, these lines are undetectable from the ground until $z > 20$ (particularly since both need to be measured for physical interpretation of temperatures and densities).

Once even traces of metals have formed, the C^+ line at 157µm becomes very bright. Its luminosity in nearby spiral galaxies is typically a few tenths of a per cent of the entire bolometric luminosity of the galaxy. Although this line is partially accessible in the poor atmospheric windows between 300 and 700µm, it will be routinely observed from the ground only at $z \geq 4$, when beyond 800µm. Study of the molecular hydrogen and C^+ emission of gas clouds in the early Universe and as a function of redshift promises to reveal many of the processes occurring in the gas clouds that collapse into the first galaxies. Space-borne observations in the FIR/Submm must be a major component of this study.

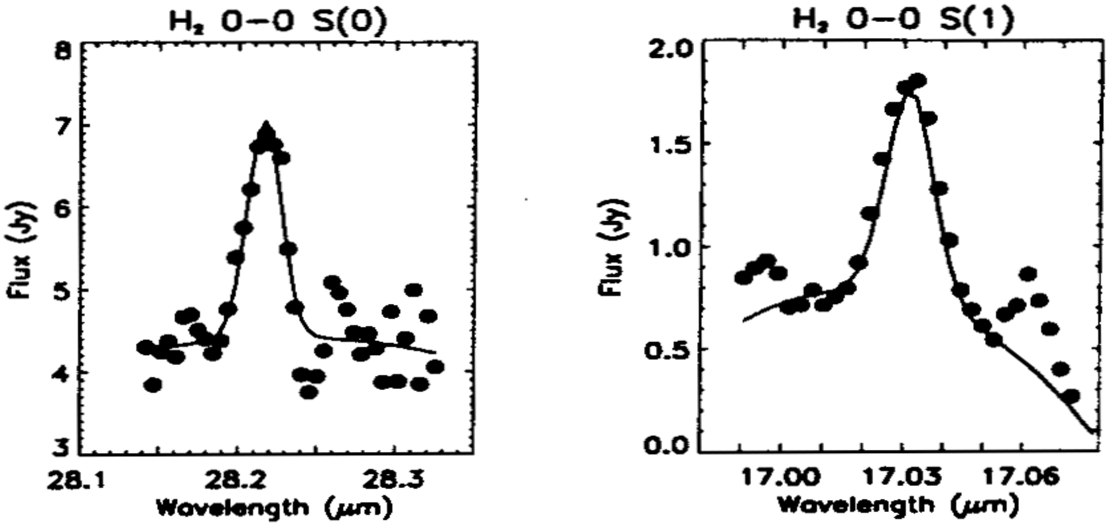


Figure 2-5. Low Lying H_2 emission lines from diffuse interstellar gas at T ~ 100K and n ~ 3000cm^{-3}, from Thi et al.

2.4 Birth and Evolution of Stars and Planetary Systems

Stars are born in cold interstellar cloud cores that are so optically thick they are undetectable even in the mid infrared. In about 100,000 years, a young star emerges, ejecting material along powerful jets and still surrounded by a circumstellar disk; see Figure 2-6. The subsequent evolution is increasingly well studied, but the star formation event has occurred hidden from view. How does the cloud core collapse? How does subfragmentation occur to produce binary stars? What are the conditions within protoplanetary disks? When, where, and how frequently do these disks form planets?

The birth of stars and planets can be probed thoroughly at FIR/Submm wavelengths. A far infrared 10-m telescope provides a resolution of ~1 arcsec at 50μm ($\leq$ 100 AU for the nearest star forming regions), so imaging could probe the density and temperature structure of these ~1000 AU collapsing cores on critical physical scales. The gas in the core is warmed until its primary transitions lie in the FIR/Submm. Spectroscopy in molecular lines such as H_2O and the J>6 high series lines of CO, as well as in FIR atomic lines of OI, C^+, and NII, can probe the physical conditions in the collapse. In addition, 100 AU resolution would reveal the steps toward binary formation. Resolutions of 0.1 to 1 AU (1 to 10 km baseline interferometer at 50μm) are required to probe circumstellar disk structure in the regions of terrestrial planet formation, searching for disk gaps and measuring the sharp thermal and compositional gradients that are predicted as a consequence of planet growth. FIR/Submm spectroscopy at this resolution can determine when and where flows begin that evolve into jets and how the circumstellar disks participate in this process. Far infrared polarimetry is a powerful probe of magnetic field geometries, both for studying core collapse and mapping the fields that must play an important role in accelerating and collimating jets.

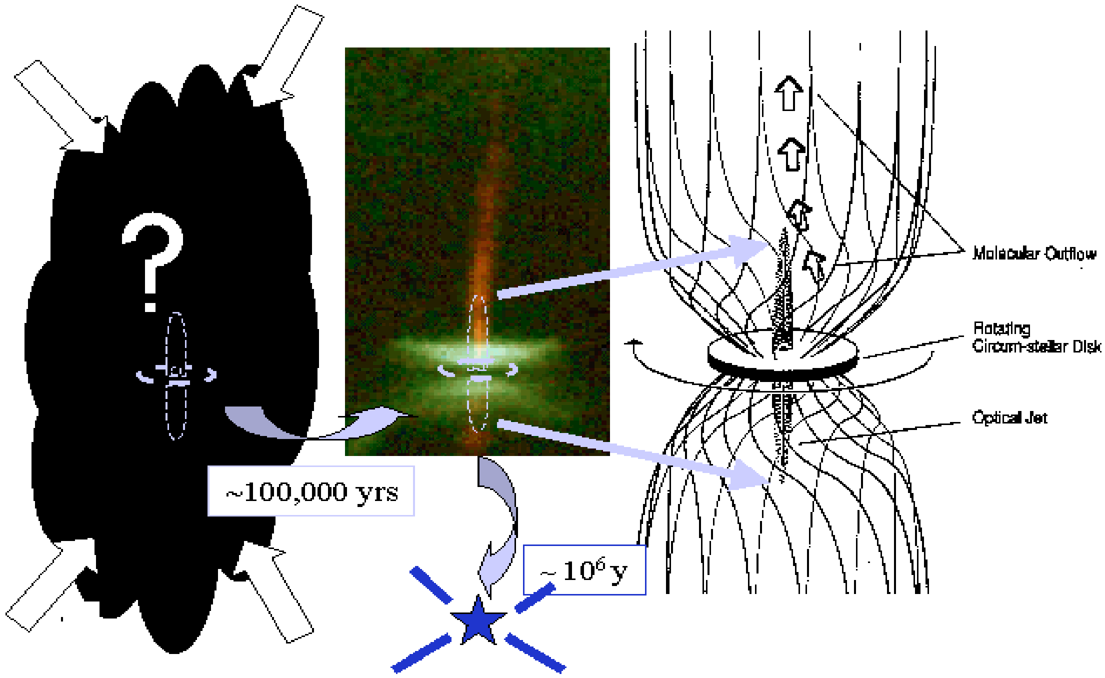


Figure 2-6. A star and its protoplanetary disk emerge from a cold cloud core.

The spectrum predicted for a collapsing cloud core is shown in Figure 2-7. The OI lines have narrow components from the infalling envelope and broad ones from outflow shocks. They are the main coolant of the gas in the intermediate regions of the cloud. Bright H_2O lines between 25 and 180μm are the dominant coolant in the inner cloud, where a broad component is expected from the accretion shock and a narrow one from the disk. The CO lines from 170 to 520μm are the main coolant for the outer cloud; warmer CO from within the cloud can also be studied because of velocity shifts due to the collapse. This suite of lines therefore would allow us to probe the process of star formation thoroughly.

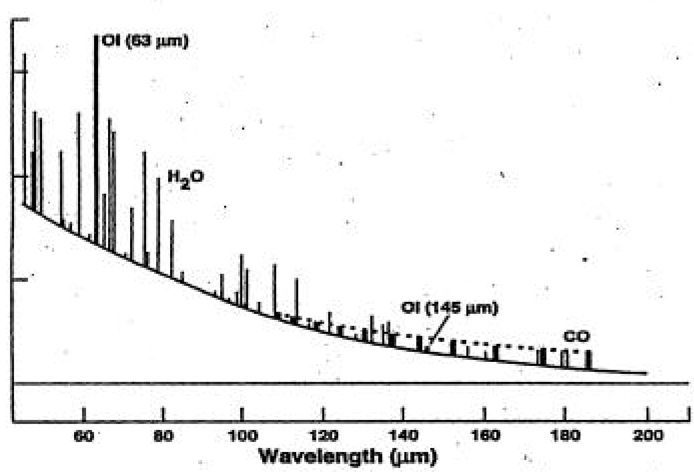


Figure 2-7. Predicted far infrared spectrum of a collapsing cold cloud core, from Ceccarelli, Hollenbach, and Tielens. The spectrum is dominated by OI and complexes of CO and H_2O.

2.5 Nature and Formation of the Solar System

What were the conditions in the early solar nebular, as the protoplanetary disk formed and planets and small bodies accreted out of it? All the bodies in the inner solar system have been so heavily processed that they no longer reflect clearly the conditions at their formation. The discovery of many small bodies outside the orbit of Neptune, or crossing that orbit, gives access to objects where accretion proceeded slowly and its products should be primitive and still reflect conditions in the early solar nebula. For brevity, we refer to all these objects as Kuiper Belt Objects (KBOs).

KBOs are being discovered rapidly, from deep CCD images that catch their reflected light. It has become clear that there is a large population, including objects of large size, rivaling the largest asteroids. The distribution of discovered KBOs is shown in Figure 2-8. Because of selection effects, the system probably extends much farther than indicated in the figure.

Surprisingly, the KBOs and related objects appear to have a broad variety of surface characteristics as shown in Figure 2-9. To interpret the clues they provide for formation of the solar system requires that we understand how this variety of surface chemistry has come about. Two very important parameters are: 1.) the albedoes of the surfaces (important to help identify the substances that cover them); and 2.) surface

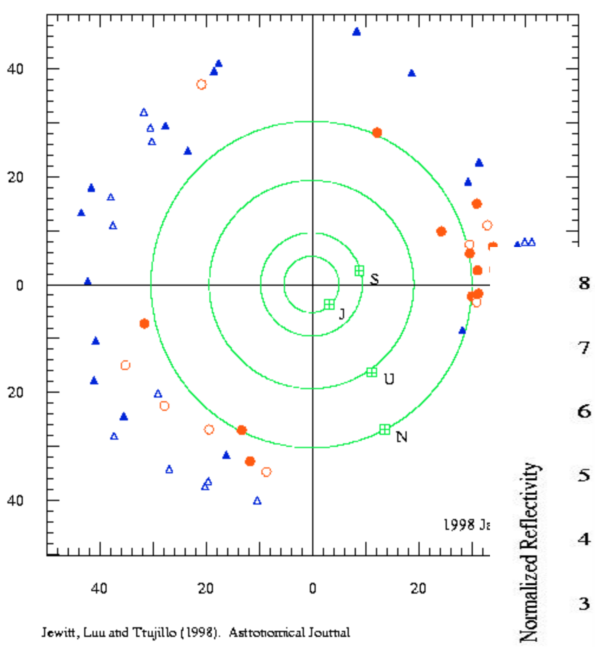


Figure 2-8. Distribution of KBOs. J, S, U, and N mark the orbits of Jupiter, Saturn, Uranus, and Neptune. Different colors and symbols refer to different

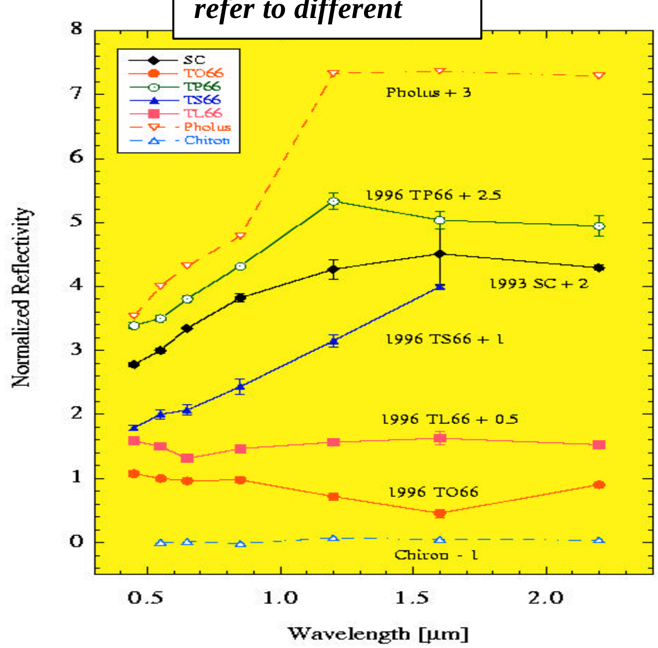


Figure 2-9. Wavelength dependent reflectivity of KBOs and related objects. There is a wide variety of behavior

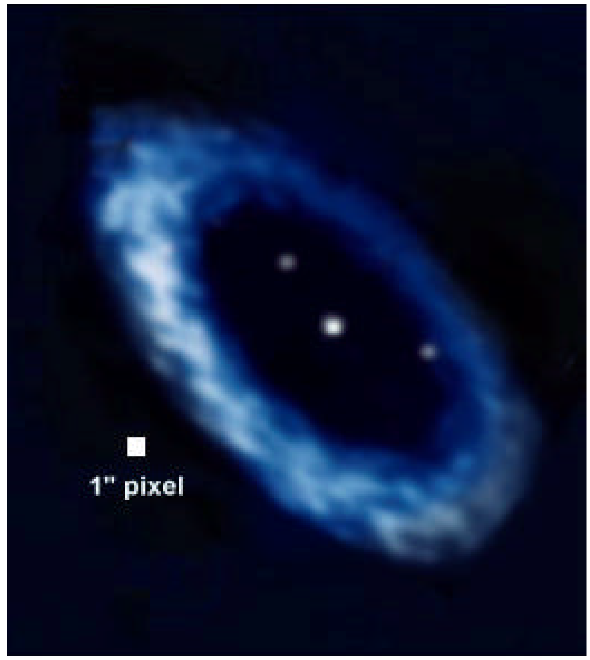
temperatures (both to help understand what chemical reactions can occur and to determine the escape rates for different molecules). Both of these parameters can be determined in the far infrared, through measurements of the thermal emission. It is for this reason that the 1998 National Academy of Sciences study on “Exploring the Trans-Neptunian Solar System” placed a very high priority both on large, far infrared telescopes and on development of high performance far infrared detector arrays.

2.6 Comet and Asteroid Impacts and the Origin of Life

The Kuiper Belt is thought to be the source of short period comets and hence has a central role in the comet impacts that brought water to the earth and made life possible here. However, most traces of this process have been erased by time. How can we understand the conditions that regulated the early formation and evolution of the KB and its release of comets toward the inner solar system?

The Infrared Astronomy Satellite (IRAS) discovered debris disks around Vega, β Pic, and other stars, with evidence for inner voids that might have resulted from planet formation. The Kuiper Belt is therefore similar in many ways to these systems and should be interpreted as the debris disk of the solar system. Taking an example, β Pic is thought to be only about 20 million years old. Transient and variable absorptions by the CaII H&K lines in its spectrum have been interpreted as the infall of small bodies from the debris system. This system contains fine grains that heat sufficiently to be detected in the mid infrared and scatter enough light to be seen at shorter wavelengths. Because it should be drawn into the star quickly, this fine dust may be produced in recent collisions between planetesimals. Thus, this system and others like it demonstrate the potential of examining the early, violent evolution of debris disks and the infall of comets.

Debris disks are bright in the far infrared, where they can be imaged to identify bright zones due to recent planetesimal collisions, as well as voids. The radial zones sampled will vary with wavelength, from a few AU near 20μm to hundreds of AU in the submm. Figure 2-10 illustrates the potential advances with a large FIR telescope. Spatially resolved spectroscopy with such a telescope could probe the mineralogy of the debris disks in the 20 - 35μm region where the Infrared Space observatory (ISO) has found a number of features diagnostic of crystalline and amorphous silicates, and can locate ice through its 63μm emission feature. Giant planets similar to Jupiter and Saturn could be detected to compare their placement with the debris disk structure. Similar views of very young planetary systems forming in the nearest molecular clouds could be achieved with an interferometer baseline of about 200 meters.



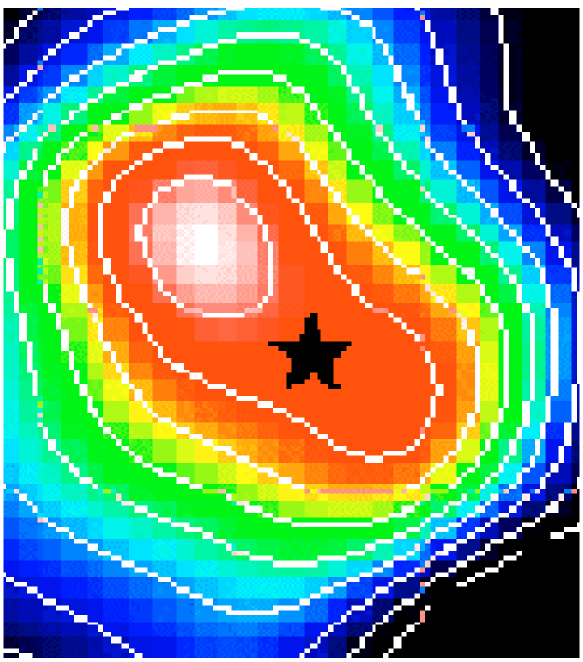


Figure 2-10. The Vega Planetary System. To the left is the best available image of the debris system, obtained at 850mm with SCUBA bolometer array (the black star is the position of Vega itself). To the right is an artist's concept of how the system might look to a 10-m telescope operating at 50mm. In addition to the debris ring, two giant planets (~ Jupiter mass) are indicated to suggest the possibility of probing their relationship to the structure of the debris system.

2.7 Other Contributions to the Strategic Plan

The capabilities that could carry out the programs above would also enable many other investigations relevant to the strategic plan. With adequate tools, FIR/Submm astronomy can provide new insights to many areas of current investigation in other spectral regions, where the FIR/Submm currently appears to be irrelevant because of instrumental limitations. Some examples, keyed to the strategic plan sections above are:

- **How Galaxies and Stars Emerged from the Big Bang**
  - Document the star formation sites and intensity in galaxy mergers as a function of cosmological epoch, probing the role of mergers in the building of large galaxies and in other aspects of galaxy evolution
  - Locate forming galaxy bulges and spheroids, resolving out the foreground emission by young galaxy disks ($z \leq 3$?) and searching for luminous emission by heated dust in relatively compact proto-bulges at $z \sim 3$ to 10(?)
- Look between the $z = 0$ to 10 foreground galaxies to search for emission by dust heated in the first episode of star formation in the very early Universe
- **Extreme Environments and Discovery of New Phenomena**
  - Map the magnetic field geometry at .04 parsec resolution (or better) around the supermassive black hole and its circumnuclear disk in the Galactic Center
  - Probe the processes that accelerate and confine jets, both in young stellar objects, and in AGNs
  - Study the distribution of matter around nearby AGNs by imaging them in the Submm; probe the radiative transfer in circumnuclear disks by imaging from the mid through far infrared
- **Dynamical and Chemical Evolution of Galaxies and Stars**
  - Examine the injection of metals into the ISM by studying the chemistry and dust formation in outflows from AGB stars, in planetary nebulae, and in the shocks between supernovae remnants and the surrounding ISM
  - Determine the evolution of cosmic dust with increasing accumulation of metals in galaxies, both locally and at cosmological distances
  - Explore conditions in photodissociation regions (PDRs) through study of fine structure and molecular lines, emission by dust. Study PDR properties over interesting cosmic timescales. Use the [CII] 157μm line from PDRs (which accounts for ~ 0.5% of the luminosity of a galaxy disk) to track the massive star forming rate with redshift
  - Examine the conditions in the interstellar medium leading to massive star formation in nearby galaxies. Explore the full range of conditions from bulge to outer disk, including a broad range of metallicity and a significant range in the strength of star formation triggering mechanisms
- **Nature and Formation of the Solar System**
  - Study atmospheric chemistry in giant planets with spatially and temporally resolved spectroscopy in the major far infrared molecular transitions
- **Comet and Asteroid Impacts and the Origin of Life**
  - Measure properties and evolution of comets in the outer solar system

In combination with the programs described in detail in Sections 2.1 to 2.6, the FIR/Submm can make a broad variety of contributions to the goals of the Strategic Plan.

3. Suborbital Telescopes for the FIR/Submm

A strong, ongoing program of ground-based submillimeter astronomy is an important precursor for a major space mission, because it will advance the scientific goals of the submillimeter region and sharpen the questions that can only be explored from space. It will also provide important venues for technology demonstration and optimization, particularly for heterodyne receivers and direct detectors, in anticipation of the eventual operation of these devices in space. Finally, the rapid turn around and hands-on access characteristic of ground-based facilities makes them ideal for the education and training of students and young scientists who will be among the creators and users of future space missions.

During the past 15 years a number of 10-15 meter aperture submm telescopes have been completed on high, dry mountain sites (the Caltech Submm Observatory (CSO) and James Clerk Maxwell Telescope (JCMT) on Mauna Kea and the Heinrich Hertz Submm Telescope (HHSMT) on Mount Graham). These instruments can operate at ~ 850μm nearly all the time and in semi-transparent atmospheric windows as short as 350μm under exceptionally dry conditions. Their scientific roles are centered on continuum imaging in the submm atmospheric windows at a new level of sensitivity and angular resolution (λ/D ~ 9” for an 8-m telescope at 350μm), and on spectroscopy, particularly in the 800μm to > 1mm range where the atmosphere is relatively clear under dry conditions. They have fostered the development of new and powerful instrument concepts (e.g., the bolometer imager SCUBA for the JCMT: see Figure 2-2) and provide access to the submm for many scientists and students. There is a proposal for such a telescope to take advantage of the exceptionally dry atmosphere at the South Pole. In general, placing a major telescope at a site much better than the current ones would make the conditions required for observation up to 350μm the norm. There would be significant, potentially enabling, gains for the steady, predictable, and long term observing required to conduct major scientific programs and to support accurate calibration essential for many objectives. These advantages would justify development of a telescope significantly larger in aperture than those now in use.

The power of these 10-m class groundbased telescopes can be expanded by using them in interferometers. In addition to increasing the angular resolution in proportion to the interferometer baseline, the areas of a number of 10-m class antennae can be combined to increase the overall sensitivity. The Submillimeter Array (SMA) is a collaboration between the Smithsonian Astrophysical Observatory and the Academia Sinica of Taiwan, consisting of eight 6-meter telescopes on Mauna Kea, arranged for full coverage of the UV plane and with a maximum baseline of 508 meters. It will provide resolution up to ~ 0.2” at its shortest wavelength of operation near 350μm. The Millimeter Array (MMA) is under definition. It is envisioned as fifty 12-m telescopes distributed over baselines of 15 meters to 10 km. It would be placed at 5060 meters elevation at Llano de Chajnantor, Chile, where the atmospheric transmission should be better than for any existing submm telescopes except for ones in the Antarctic. Because of the large baselines and total antenna area, the MMA as envisioned would become the leading groundbased facility for the submm both for sensitivity and angular resolution.

Airborne and balloon telescopes can play similar roles to groundbased submm telescopes in regions where the atmosphere is opaque from the ground. The Stratospheric Observatory for Infrared Astronomy (SOFIA) provides the astronomical community routine access to the entire far-infrared and submillimeter spectrum discussed in this report. Its strengths include its relatively high angular resolution, provided by a 2.5-m primary mirror, and the opportunity to operate equipment in a shirt-sleeve environment that encourages rapid deployment of new techniques. The observatory provides a well understood and calibrated platform for PI driven instrumentation. Facility instruments aboard SOFIA broaden the scientific involvement of the community using the latest technologies developed under PI instrument programs. Because SOFIA will provide many research groups with frequent and reliable observing opportunities, it will be an excellent tool for developing the far-infrared and submillimeter scientific expertise and technologies for next generation missions.

The Long Duration Balloon (LDB) and ultimately the Ultra-Long Duration Balloon (ULDB) programs offer the best opportunity to fly large (> 100 cubic meters) and massive (2,000-3,000 lbs.) payloads in a near-space environment. The atmosphere above an altitude of 100,000 feet (30.5 km) is more than 98 percent transmissive over the FIR/Submm range, providing a significant improvement for spectroscopy over airplane altitudes, as well as minimizing backgrounds and background fluctuations for photometry. Until recently, the scientific productivity of the balloon program has been limited by the short observing times per flight. Under these conditions, it is difficult to conduct successful, well-calibrated and repeated measurement series. The advent of 10 to 30-day flights under the LDB program and the prospect of 50 to 100-day flights under the ULDB program allow much better scientific use of the advantages of very high altitude flight. These programs provide the best available access to near-space conditions for modest cost experiments. The benefit to NASA of the LDB/ULDB programs, as measured by the scientific return per dollar, is also enhanced because the development time of a balloon payload is short compared to a large space mission, and there can be frequent flight opportunities. Like the airborne program, the balloon program is an exceptional vehicle for training future experimentalists.

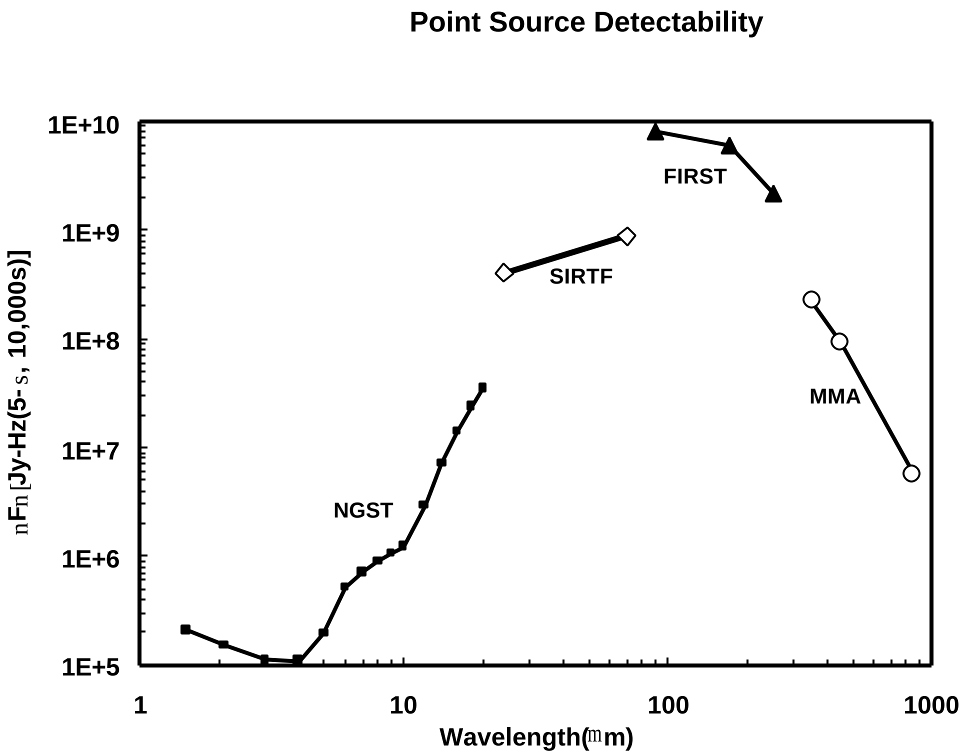
4. The Year 2010

By 2010, groundbased facilities plus the Space Infrared Telescope Facility (SIRTF), SOFIA, and the Far Infrared and Submillimeter Telescope (FIRST) will have advanced our exploration of the long wavelength sky dramatically. Yet, in the majority of the far infrared and submm range our knowledge will still be relatively primitive. Comparisons are difficult to make rigorously. Still, the position of the FIR/Submm in 2010 will in many ways be comparable with that of optical astronomy in about 1950: the first generation of detector arrays (high performance photographic plates) will have been used extensively with modest sized telescopes (Mt Wilson 60 and 100-Inch), hopefully to make a number of important discoveries (resolution of galaxies into stars, Hubble expansion, Seyfert galaxies). The FIR/Submm capabilities will fall far short of those being envisioned for the surrounding spectral regions at the end of the next decade.

4.1 The Sensitivity Gap

Figure 4-1 shows the point source sensitivities of the Next Generation Space Telescope (NGST, 8-m, background limited at 10μm), SIRTF, FIRST, and the MMA. Other facilities generally are less sensitive than those indicated. We have plotted νF_ν, which is proportional to luminosity per logarithmic wavelength or frequency interval. The FIR/Submm *falls two to three orders of magnitude* less sensitive than an interpolation between NGST in the near infrared and the MMA in the mm-wave. It will be impossible to study faint objects to similar luminosity limits across the optical to mm-wave range.

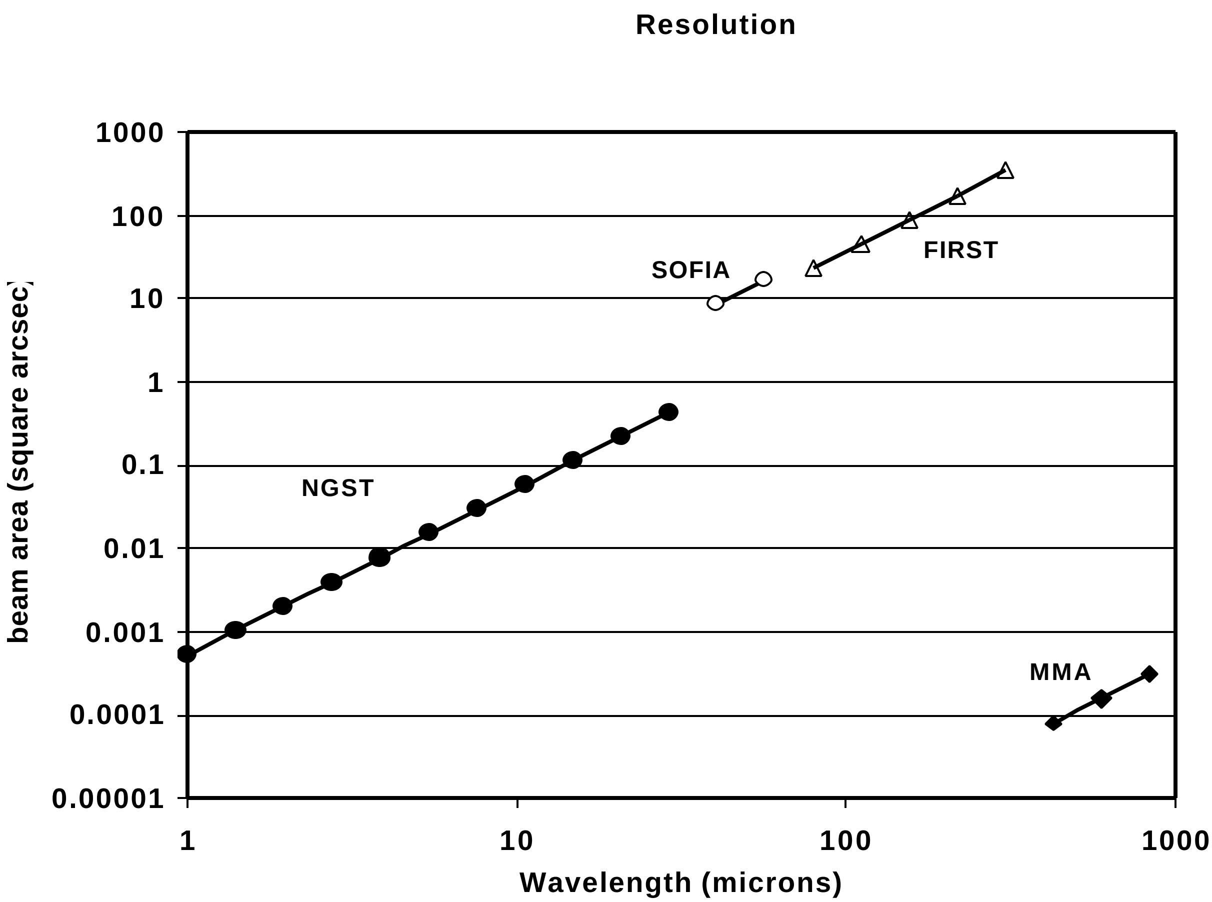
Figure 4-1. Envisioned capabilities in other spectral regions will outstrip the sensitivity achieved in the FIR/Submm by 2-3 orders of magnitude (only the most sensitive facilities at each wavelength are plotted).



4.2 The Resolution Gap

Figure 4-2 compares diffraction limited beam areas for the same suite of telescopes plus SOFIA. The angular resolution achieved in the FIR/Submm will be *three to six orders of magnitude* poorer than an interpolation between NGST (and major groundbased telescopes) in the near infrared and the MMA in the mm-wave. It will be impossible to measure source structures at anything approaching comparable resolution across the optical to mm-wave range.

Figure 4-2. Envisioned capabilities in other spectral regions will outstrip the resolution achieved in the FIR/Submm by 3-6 orders of magnitude (only the highest resolutions achievable are plotted)



4.3 The Technology Gap

Some existing groundbased submm telescopes use accurate yet lightweight panels that could be suitable for a deployable reflector. NGST is sponsoring development of even more accurate lightweight panels and of space qualifiable deployment mechanisms. SIRTF and FIRST are in the process of demonstrating radiatively cooled telescopes operating in space for unprecedented FIR/Submm performance. Taken together, the stage is set for a major FIR/Submm mission utilizing these telescope technologies in an optimum combination.

New, larger, and much better telescopes have played an important role in the explosive advances in optical, near, and mid infrared astronomy. However, the greatest expansion has derived from advances in detector array performance. Astronomy has benefited in these spectral regions from huge investments in the technology infrastructure for arrays to be used in commercial and military applications, as well as the highly developed capabilities to process electronic circuits in silicon. Only a relatively modest additional investment has gifted us with megapixel arrays operating at high quantum efficiency and with read noises of only a few photons equivalent.

Detectors for the FIR/Submm have not gained comparably from commercial and military investments, and they tend to be based on technologies without the leverage from integrated circuit development. The largest photoconductive detector array, operating to 120μm, is only 32x32 in format with a quantum efficiency of about 20%. Bolometer arrays for longer wavelengths offer of order only 100 pixels, with quantum efficiencies of about 50%. Although these single pixel devices and small arrays are starting to approach the desired performance limits for a new space mission, large format arrays can provide a further revolution in capabilities. Heterodyne receivers fall short of the fundamental quantum limit by factors of 10 to 20 in the high frequency submm and far infrared, and further work in support electronics is required for spatial arrays of significant size.

The large potential gains and the modest previous investment promise that expanded development programs in these sensor technologies will bring major returns to astronomy. Given the approach of sensors in other spectral ranges toward fundamental limits, it is nearly a unique advantage of the FIR/Submm that dramatic gains can be compounded with the advances in telescope size to produce orders of magnitude advances in capability.

5. New Tools to Explore the FIR/Submm Universe

5.1 Filled Aperture Space Telescopes

Following on the successes of IRAS and ISO, SIRTF and FIRST will expand our view of the FIR/submm Universe by combining the first generation of detector arrays with modest sized cold or cool telescopes. As an illustration of the potential for these missions, Figure 5-1 shows the anticipated advance with the MIPS imaging array on SIRTF in mapping the high Galactic latitude sky at 70μm.

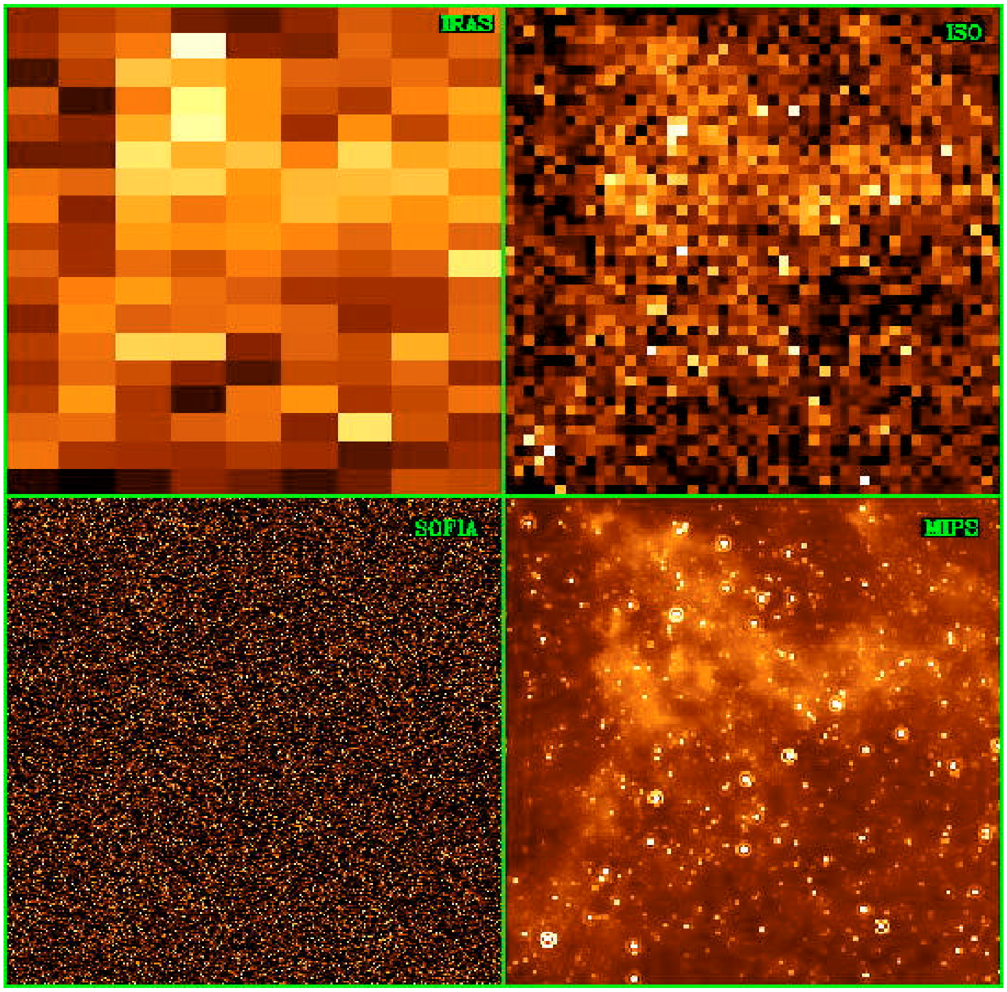


Figure 5-1. Comparison of past and planned missions. The frames are a simulation of a one day integration at 70μm on a 35x35 arcmin region of high Galactic latitude sky. The frame includes infrared cirrus and distant infrared galaxies, which appear point-like at the resolution (~ 15") of SIRTF. The large aperture of SOFIA is not effective because of the increased noise due to the thermal emission of a warm telescope. FIRST will be similar in resolution to SOFIA and a modest factor more sensitive. Cryogenic space missions with imaging arrays (e.g., as with MIPS) can bring huge advances to our ability to detect and understand distant infrared galaxies. Courtesy C. Engelbracht.

The science goals in Section 2 suggest that a major advance over these missions could be achieved with a telescope of about 10-meter aperture and correspondingly higher sensitivity and angular resolution. The investment for NGST in large scale, lightweight, deployable mirrors can enable such a FIR/Submm capability at lower cost than NGST because of the ~ 20 times reduction in surface precision for the optics. Many other aspects of NGST could be adapted to such a telescope, helping to constrain its cost. Additional thermal shields would allow the telescope to reach the required very low temperatures without a fundamental change in the NGST architecture. With the large aperture, sensitivities more than two orders of magnitude greater than with the current generation of facilities should result. Alternately, placing a FIR/Submm telescope into an orbit that reaches into the outer solar system can both provide increased radiative cooling to reduce the optics temperature and also reduce the natural far infrared background due to thermal emission by the zodiacal dust grains, providing even better performance.

As an example of a filled aperture FIR/Submm observatory, Figure 5-2 is a concept for a telescope that might be placed in an orbit at 4 AU. It combines features from SIRTF and NGST. To minimize power requirements at the large distance from the sun, its cooling utilizes a helium cryostat enlarged from the SIRTF design, rather than closed cycle mechanical coolers. A lifetime of more than 15 years should be possible, based on the projected performance of SIRTF. The sunshade and telescope deployment approach are adapted from an NGST concept. A larger solar array and telemetry antenna would be fitted to provide adequate power and data transmission bandwidth to Earth.

Such a telescope would be the logical next step beyond SIRTF and FIRST (and the H2L2 mission proposed in Japan) for very deep, moderately high angular resolution measurements in the 40 to 300μm spectral region where the atmosphere of the earth is opaque. It would have collecting area and resolution (in beam area) 100 times greater than SIRTF and 10 times greater than FIRST. It could close the sensitivity gap in Figure 4-1 and would also narrow the resolution gap in Figure 4-2 (but still leave 2-3 orders of magnitude to go in resolution). Allowing for an order of magnitude gain in detector performance, its gain in sensitivity is equivalent to a gain in throughput over SIRTF by a factor of 10^5. Put another way, its speed in carrying out observations, sometimes called ‘astronomical capability’ or ‘discovery efficiency’, can be 100,000 times greater than the most powerful predecessor mission. Its operation above the atmosphere will make it far more powerful than groundbased or airborne platforms for spectroscopy across the entire 20 to 800μm spectral range. Its angular resolution and sensitivity will address a significant portion of the science problems we have identified for this spectral region.

Because the telescope architecture can benefit from engineering studies of NGST, system-level studies for this telescope should be conducted in the early-to-middle part of the decade. The heritage from both NGST and SIRTF should allow a large FIR telescope to be developed economically. By the time the mission progressed into detailed definition late in the decade, it would benefit from ten years of progress in detector and heterodyne receiver technology.

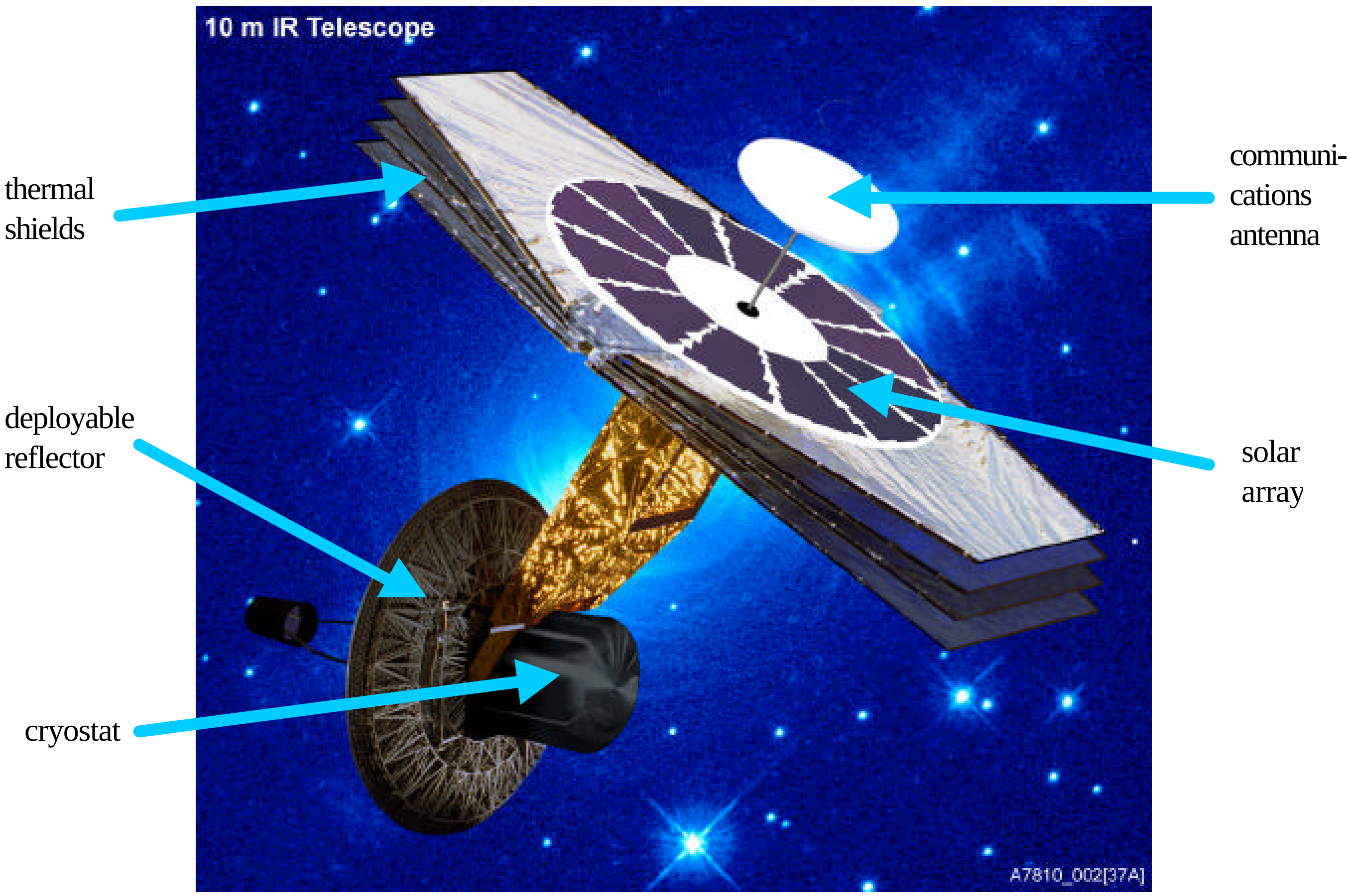


Figure 5-2. Possible large aperture far infrared/submm telescope. Thanks to Ball Aerospace.

We have baselined a 10m telescope because it provides a combination of sensitivity and resolution very well suited to the highest priority science problems for this spectral region. In addition, it has the potential to gain substantially from the technology investment in NGST. However, in the event that deployment is abandoned for NGST or if only a moderate far infrared mission can be provided, then a less challenging approach would be to launch the largest feasible fixed aperture. Such a telescope would still gain from the development of lightweight mirror technology for NGST. In fact, the relaxation of surface specifications would allow even lighter mirrors, which might be important in providing economical launch capability for a large fixed aperture. Figure 5-3 shows a 6-m fixed aperture concept studied by Lockheed for NGST. Their work included enough mechanical analysis to estimate masses and a demonstration that the telescope could be launched by an Atlas with a suitably modified fairing.

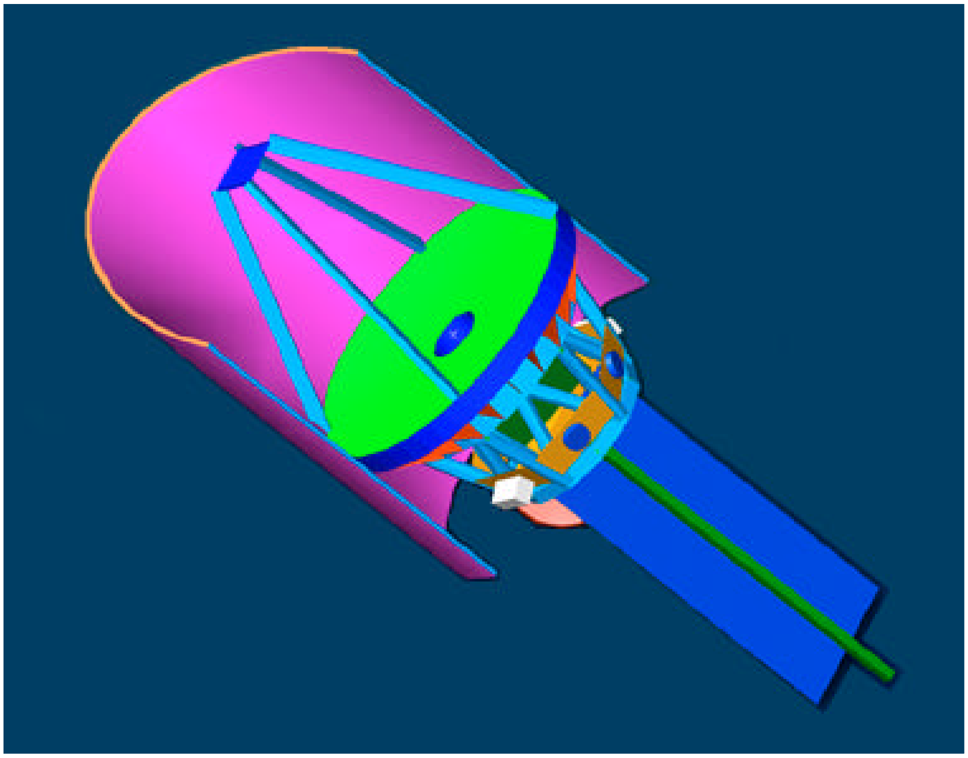


Figure 5-3. 6-m fixed aperture telescope. To achieve efficient radiative cooling, the solar panels are trailed behind the telescope and spacecraft. The telescope could be launched by an Atlas II with a modified fairing. (Courtesy LMMS)

A more ambitious and technically challenging approach would exploit and expand upon developments in ultra lightweight optics to allow a telescope significantly bigger than 10m. A 30m telescope operating at 25K would have sensitivity similar to that of a colder 10m, but with increased angular resolution. The higher operating temperature would simplify cooling (possibly allowing an all-radiative solution to this requirement) and also reduce the problems with contamination of the optics due to thruster effluvient (particularly if a hydrogen based jet system is used, according to a study by TRW).

Figure 5-4 shows a developmental model of a large, inflatable telescope as an example of the possibilities for new and ultra lightweight approaches.

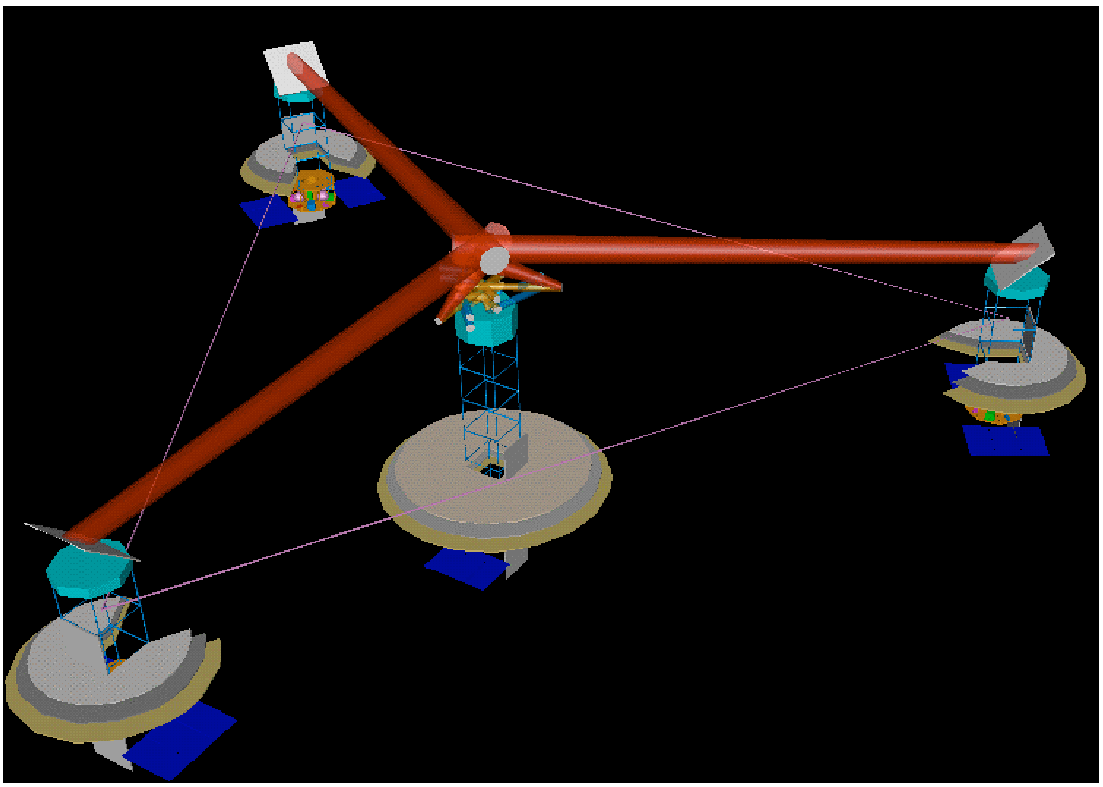
Figure 5-4. 7-m aperture inflatable telescope (thanks to L'Garde, Inc.). A 14-m inflatable telescope of similar design has also been used in an experiment from the Space Shuttle.

5.3 Space Interferometry

Many science objectives in Section 2 require angular resolution corresponding to baselines of 100 m to 10 km, obtainable only with an interferometer such as in Figure 5-5. Although there is no precedent for a FIR/Submm space interferometer, it too can build on other developments. The MMA will result in advances in receivers and backends essential for a coherent detector instrument. It will also help establish the scientific foundation for high angular resolution in the far infrared from space. The Space Interferometry Mission (SIM) will conduct astrometry in the visible and very near infrared, but it must explore many of the technical challenges for a FIR/Submm space-borne interferometer. The Terrestrial Planet Finder (TPF) is envisioned to operate with formation flying satellites to enable large baseline space-borne interferometry.

An appropriate goal for the 2010-2020 time frame is a km-baseline instrument optimized for the full range of wavelengths accessible only above the atmosphere, between 40 μm and the short wavelength limit of the MMA near 300 μm. The interferometer sensitivity will be approximately equivalent to that of a filled aperture of the temperature and with the total area of the interferometer elements. A suitably cold instrument with three 3-m aperture elements could in principle have sensitivity equivalent to a ~5-m cold telescope, although it is likely that practical considerations would impose a somewhat reduced limit. The combination of sensitivity and very high angular resolution is required for many of the most exciting science goals for this spectral region.

Figure 5-5. Concept for a major far infrared/submm space interferometer. Courtesy GSFC.



Given the lack of experience with many aspects of the full concept in Figure 5-5, it would be prudent first to explore FIR/Submm interferometry on a smaller scale. The unique issues to be addressed include the effectiveness of radiative cooling, the use of ultra-lightweight optics such as stretched membrane flat mirrors, the behavior of high speed direct detector systems in this application, the design and performance of the beam combiner, and the interpretation of interferometric data on the complex sources that will be of the greatest scientific interest in the FIR/Submm. In addition, some of the science goals in Section 2 would be advanced greatly even by a maximum baseline of 30 meters. For example, at 50μm one could observe cold cloud cores and the process of star formation on a tens of AU scale and could map accretion disks and other structures around the nuclei of the nearest active galaxies with a resolution of ~ 10pc. Perhaps the most exciting application, though, would be to make deep images of unbiased sky in the very far infrared and the submm, where even a 10m aperture telescope will be severely limited by confusion noise. In this application, a 30m baseline interferometer can make a definitive contribution to the study of star formation in the early Universe. A precursor mission within the 2000-2010 decade would therefore be both technically desirable and scientifically compelling.

Figure 5-6 shows a concept for a modest scale interferometer. A strip mirror is supported on a deployable boom of length 30 meters. A given baseline is provided by positioning the two flat mirrors over the central tower to reflect light from two appropriate sections of the strip mirror into the beam combiner, within the tower. Underneath these flats is a single focusing mirror with two secondaries (not shown) that direct the light into the beam combiner. Different baselines are selected by articulating the two mirrors above the boom. This arrangement can provide the multiple baselines required for imaging complex sources, but without the complexities of tethers that are required for a km-scale instrument. All the optics are cooled radiatively to enhance the sensitivity. UV plane coverage is achieved by spinning the interferometer around the axis of the central tower. This concept could also be used as a novel telescope, by substituting a strip secondary mirror for the two flats. The dimensions the interferometer apertures, and whether refinements such as the telescope option can be included, all need to be determined from a detailed definition based on launch capability and overall cost.

The mission concept for an interferometer will benefit from similar sensor efforts as the 10-m telescope. In addition, the technical approach to interferometry will gain from SIM and the feasibility studies for TPF. Thus, a definitive consideration of mission architectures and selection of a concept for detailed definition and development will be possible early in the decade. The mission could be built and deployed rapidly and in a cost-capped manner. It needs to be operational by 2009, to provide the greatest possible technical benefit and an appropriate experience base for concepts for the km-baseline instrument to be built in the next decade.

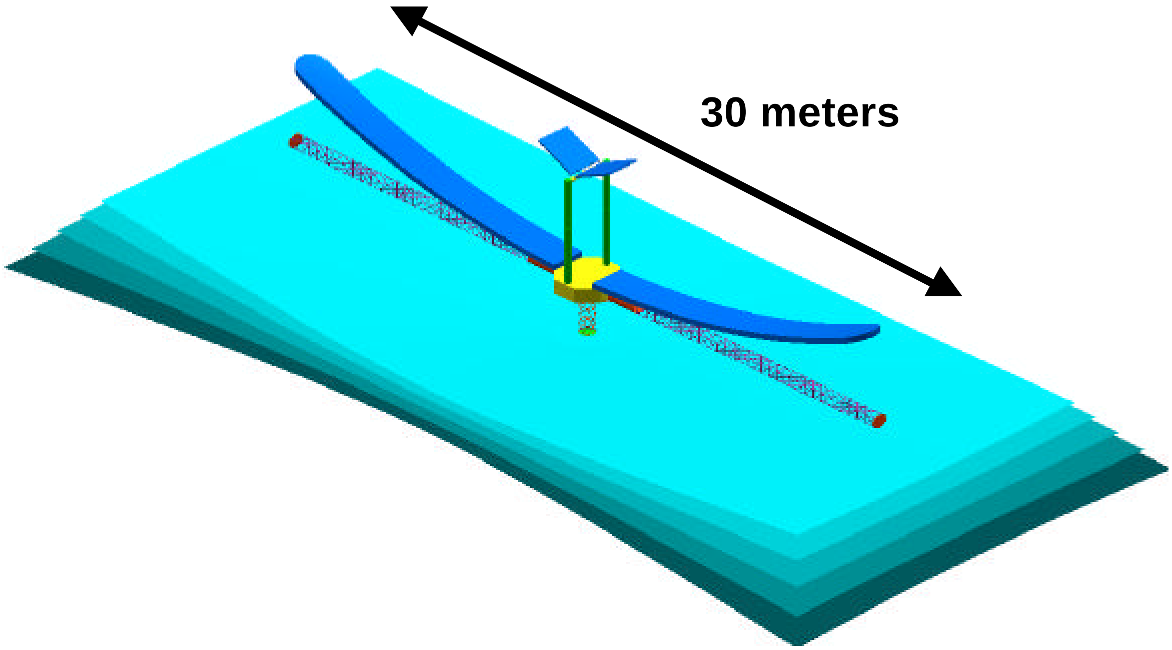


Figure 5-6. A moderate scale interferometer concept. Different baselines are selected along the strip mirror by positioning the two flats in the central tower. From JPL and TRW.

5.4 Focal Planes and Supporting Electronics

Detection techniques across most of the electromagnetic spectrum have been pushed very close to theoretical limits -- megapixel arrays with virtually perfect quantum efficiency and read noises of a few photons equivalent. In the FIR/Submm, however, current capabilities fall short of the performance needed to reach fundamental astronomical performance limits. Continuum imaging and spectral mapping at modest spectral resolution require arrays of photoconductors or bolometers with many thousands of high quantum efficiency pixels operating at about ten photons read noise equivalent. High spectral resolution imaging needs the spectral and spatial multiplexing provided by coherent receiver arrays of many hundreds of pixels that approach the quantum limit at far infrared wavelengths.

Fortunately, there are promising developments toward these goals. Particularly with increased support, future missions will be able to take advantage of rapidly improving capabilities. For example, the first true integrated high performance photoconductor arrays have been developed for SIRTF, as shown in Figure 5-7. They will provide natural-background-limited performance to the cutoff wavelength of Ge:Ga, near 120µm. The technical approach employed for these devices should be capable of expansion beyond the current 32x32 pixel format. Stressed Ge:Ga photoconductors can provide similar levels of performance to beyond 200µm, but the complications in manufacturing large format arrays have not yet been solved.

However, a larger scale array concept is under development for the Photoconductor Array Camera and Spectrometer (PACS) instrument on FIRST. Photoconductors based on GaAs rather than Ge may extend the range of this detector type to 300µm.

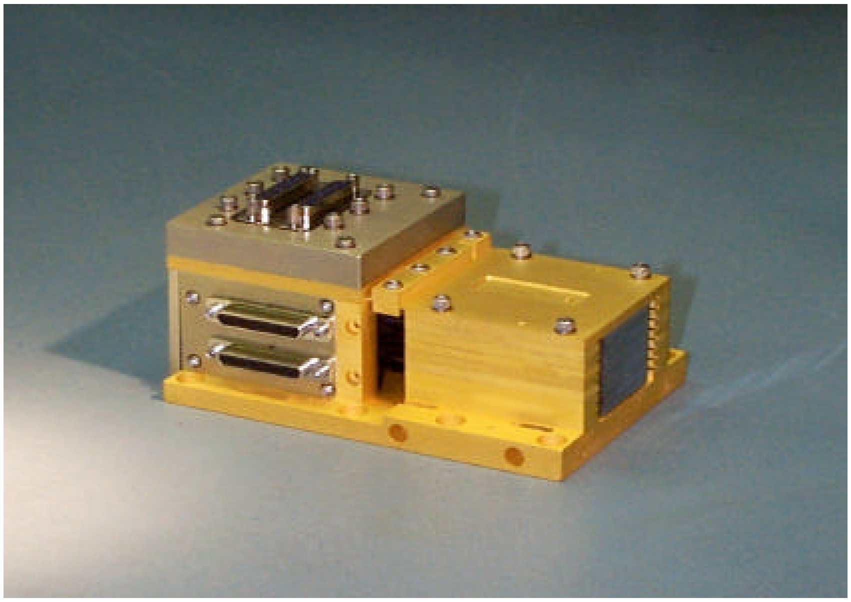


Figure 5-7. Prototype 32x32 Ge:Ga array for SIRTF. Thanks to E. Young. The largest previous Ge:Ga array for space astronomy was 3x3 pixels used for ISOPHOT.

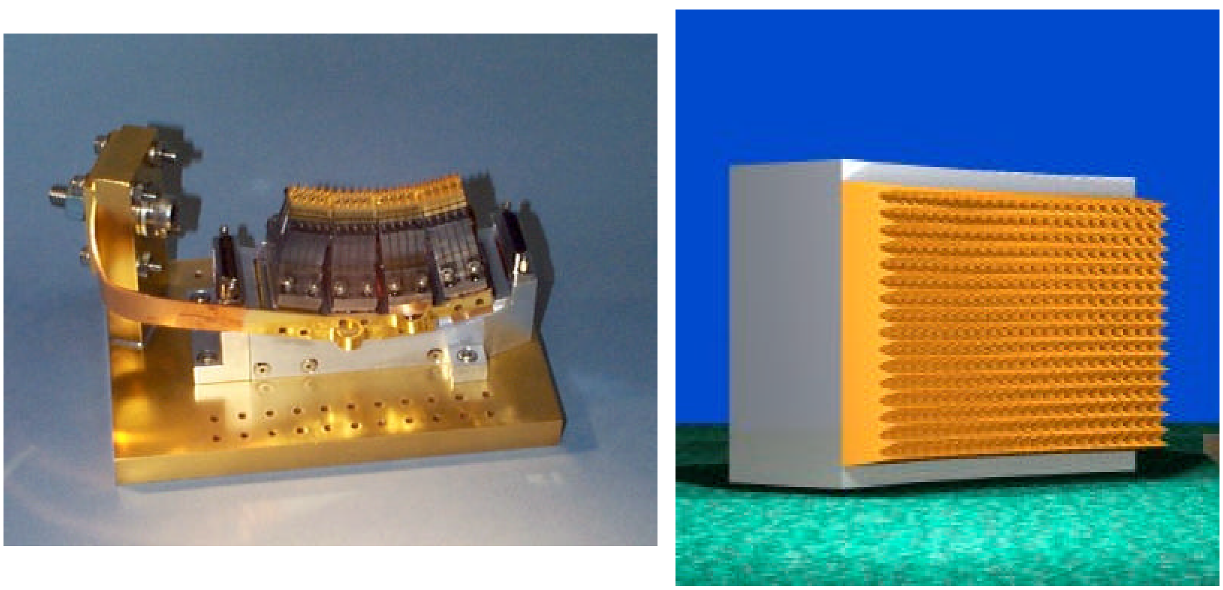


Figure 5-8. Left: 2x20 stressed Ge:Ga array for SIRTF. The largest previous similar array for space astronomy was 2x2 pixels used for ISOPHOT. Right: 16x25 stressed Ge:Ga array concept for PACS.

Bolometers operating at 50-300mK are the most sensitive continuum detectors in the submm and short mm wavelengths. The developments of metal film absorbers and lithographed support membranes such as for the GSFC 'popup' and JPL 'spider web' devices (see Figure 5-9) are beginning to solve the problems in producing large arrays. However, the necessity for individual high impedance JFET readout amplifiers operating near 50K creates major complexities in high performance bolometer arrays.

A new generation of bolometers is being developed which will make use of a superconducting film which is voltage-biased at the superconducting/normal transition edge to produce a detector with strong negative electrothermal feedback. This feedback increases the bolometer dynamic range and speed and suppresses Johnson noise. The current that holds the bolometer temperature constant is measured with a SQUID ammeter. The SQUID readouts operate at low temperatures, dissipate very little power, and have large noise margin. A readout multiplexing scheme involving SQUID switches and a single SQUID amplifier is under development, and a 1x8 multiplexer has been demonstrated. When large scale multiplexed readouts become available, arrays of 1000 or more bolometers will become practical.

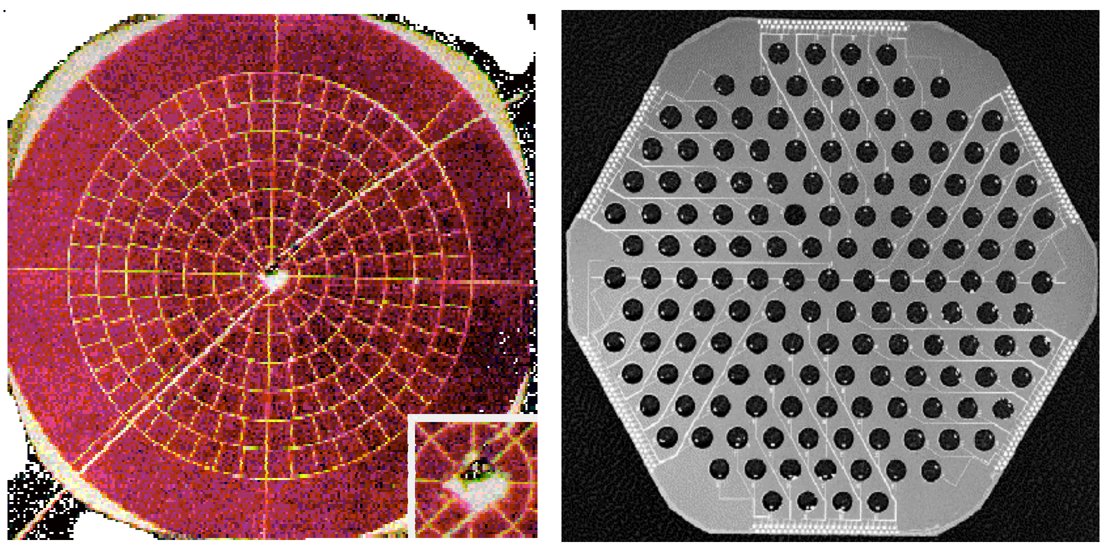


Figure 5-9. 'Spider Web' bolometer (left). To provide a large absorber area with minimum mass, a thin structure is etched in a Si_3N_4 membrane and then coated with a thin film of metal to absorb submm photons. The temperature rise associated with the photon absorption is measured by monitoring the electrical resistance of a suitably doped germanium thermistor, shown in the inset. Spider web bolometers are typically ~ 4mm in diameter. To the right is a 151 element array of spider web bolometers. Courtesy BoloCam Project.

There are also important new concepts for antenna-coupled detectors. A hot electron microbolometer has been demonstrated in which photons heat the free electrons in a copper film that terminates an antenna. The electron temperature is read out through a normal metalinsulator-superconductor tunnel junction. There is also a promising proposal for a detector in which the antenna is terminated by a superconducting Al film. The excited quasiparticles in the Al tunnel through the superconductor-insulator-superconductor (SIS) junction to a superconducting radio frequency single electron transistor. In principle, this device could operate as a submillimeter single quasiparticle photon counter. Multiplexed arrays appear possible if the transistors are excited at individual frequencies.

Submillimeter (Terahertz) heterodyne mixers are required for high spectral resolution and coherent interferometry in this spectral region. Receivers based on SIS quasiparticle mixers are within a factor of five of the fundamental quantum limit up to the 600 GHz limit (500µm) for Nb technology. The production of high quality SIS mixer junctions from superconductors with wider bandgaps, and hence capable of operating at higher frequencies, has proceeded more slowly. However, good results are now reported with NbTiN, which has a bandgap nearly twice as large as Nb and hence can operate at twice the frequency. The antenna-coupled hot electron bolometers discussed above provide a suitable approach for high quality mixers operating at still higher frequencies. The device in Figure 5-10 uses a microstrip of Nb as the hot electron carrier, and has been used up to 2500 GHz (120µm). Although all these devices need relatively little local oscillator power, stable and tunable devices to generate this power also require attention.

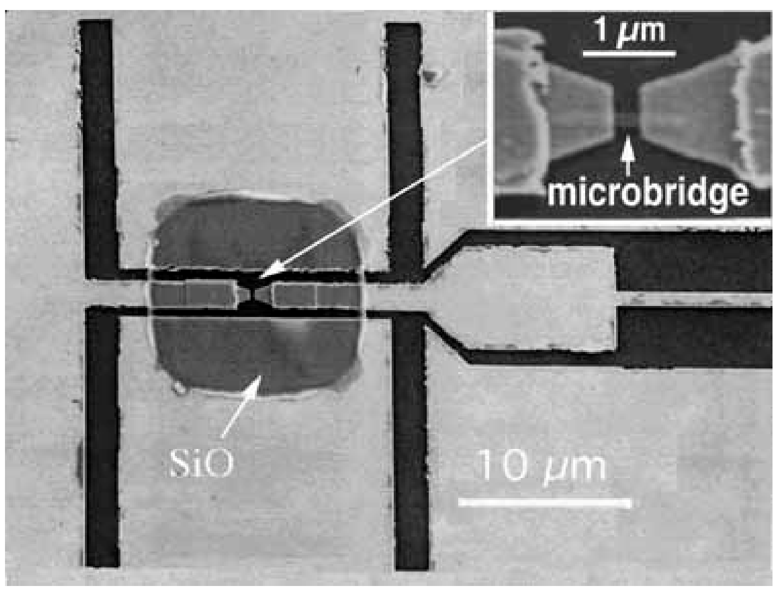


Figure 5-10. Superconducting Nb hot electron microbridge bolometer mixer. This device extends high performance heterodyne receiver technology to 120mm, with future efforts pushing toward even shorter wavelengths. Its small size contributes to its ability to operate over a large spectral bandwidth. Thanks to JPL.

Although a number of very promising approaches are being pursued, a significant investment by NASA will be required to address the development issues for high performance detector arrays and heterodyne receivers in the FIR/Submm region. NASA must assume a position of leadership in these technologies because of the lack of substantial prior investment from the commercial and military sectors. Experience with missions such as SIRTF demonstrates the value of a vigorous program initiated well before designs are frozen for construction of flight hardware. In this stage, a number of efforts need to be funded to encourage competition and communication of alternate ideas. University-based groups, NASA centers, industrial/governmental laboratories, and various combinations have all made critical contributions and can be expected to play similar roles in the future.

One goal for this development should be to advance single detector performance to the fundamental limits imposed by the environment of the envisioned missions in space. Direct detectors (photoconductors, bolometers) require significant funding as well as an augmentation for heterodyne receivers. A second goal should be to advance array technology substantially, so the dramatic benefits of spatial multiplexing can be provided for this spectral region. Third, to the extent feasible, the new technologies need to be demonstrated in demanding astronomical observation to understand the nuances of their performance that might affect use on a major space mission.

6. Implementation of the FIR/Submm Program

Figure 6-1 shows the expected performance of the instruments discussed above. From 15 to about 80μm, the filled aperture telescopes are more sensitive than interferometers because we have assumed they can have larger total mirror areas. At longer wavelengths, the telescopes will limited by confusion noise and the interferometers have greater sensitivity because of their higher resolution.

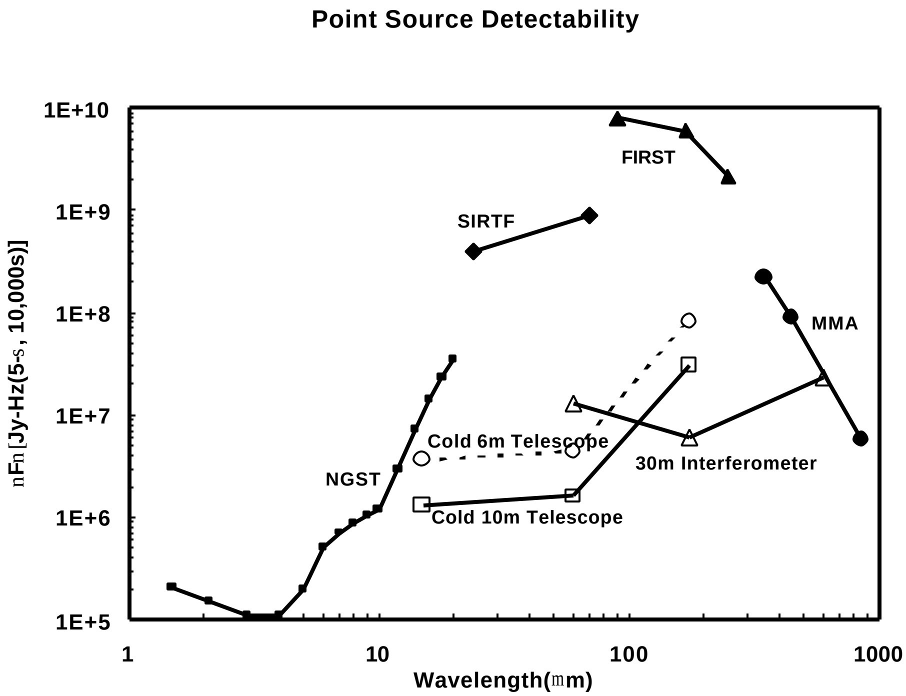


Figure 6-1. Relative performance of 6-m and 10-m cold, filled aperture telescopes and of a 30m baseline cold interferometer with 3m collectors.

Figure 6-2 shows how a 10m telescope and 30- and km-baseline interferometers would close the gap in angular resolution.

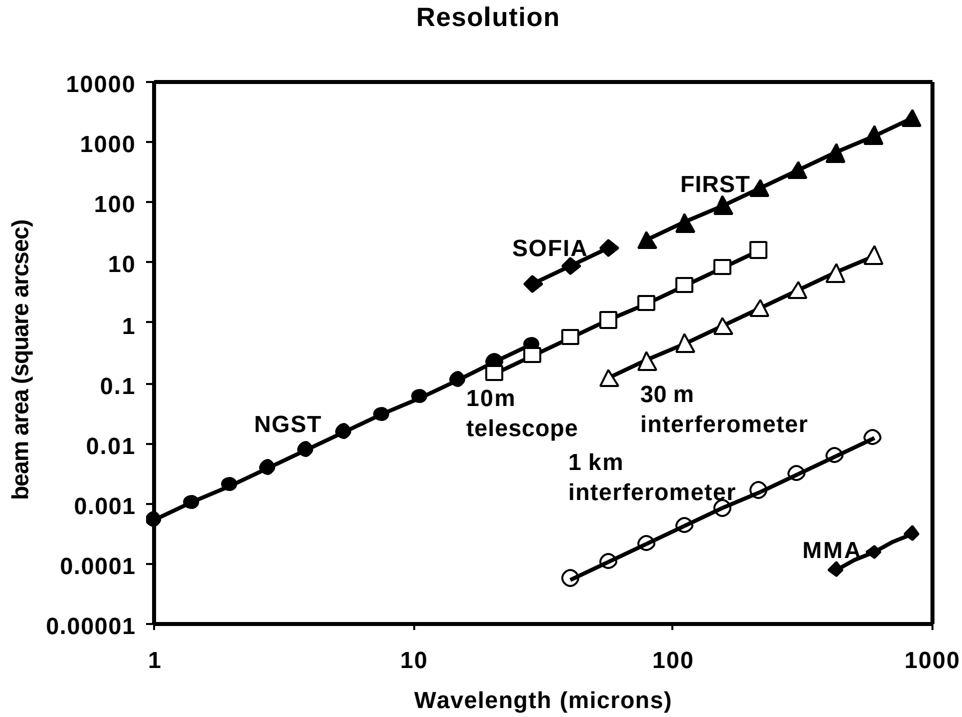


Figure 6-2. Resolution achievable with proposed instruments.

The remainder of this section illustrates how these capabilities would allow carrying out the science investigations described in Section 2. It will also make clear how, with adequate tools, FIR/Submm astronomy can make important contributions that could not be gleaned in other ways.

6.1 How stars and Galaxies Emerged from the Big Bang

The far infrared emission of normal galaxies consists of two main components: 1.) infrared cirrus emission, seen in virtually all galaxies; and 2.) emission powered by hot, young stars typical of starburst galaxies. The second component is characterized by a dust temperature of about 60K, leading to its being dominant in the 15 to 80μm spectral range for a galaxy undergoing a modest level of star formation. Its role increases with starburst luminosity, and it can account for virtually the whole spectral energy distribution in extreme cases.

To illustrate the role of the FIR/Submm in determining the emergence of stars and galaxies in the early Universe, we have taken a galaxy of typical far infrared luminosity for the current epoch, $L^* \sim 2 \times 10^{10} L_{\odot}$. We have assumed that 1/3 of this luminosity is due to infrared cirrus and 2/3 due to recent star formation. Figure 6-3 compares its output with the sensitivity of the various missions, where we plot only the 2/3 of the luminosity due to recent star formation for z = 1, 3, and 5. For comparison, at z = 3 we also show the total spectrum, including the infrared cirrus. However, to track the recent star formation in galaxies, it is probably the starburst component that is more relevant.

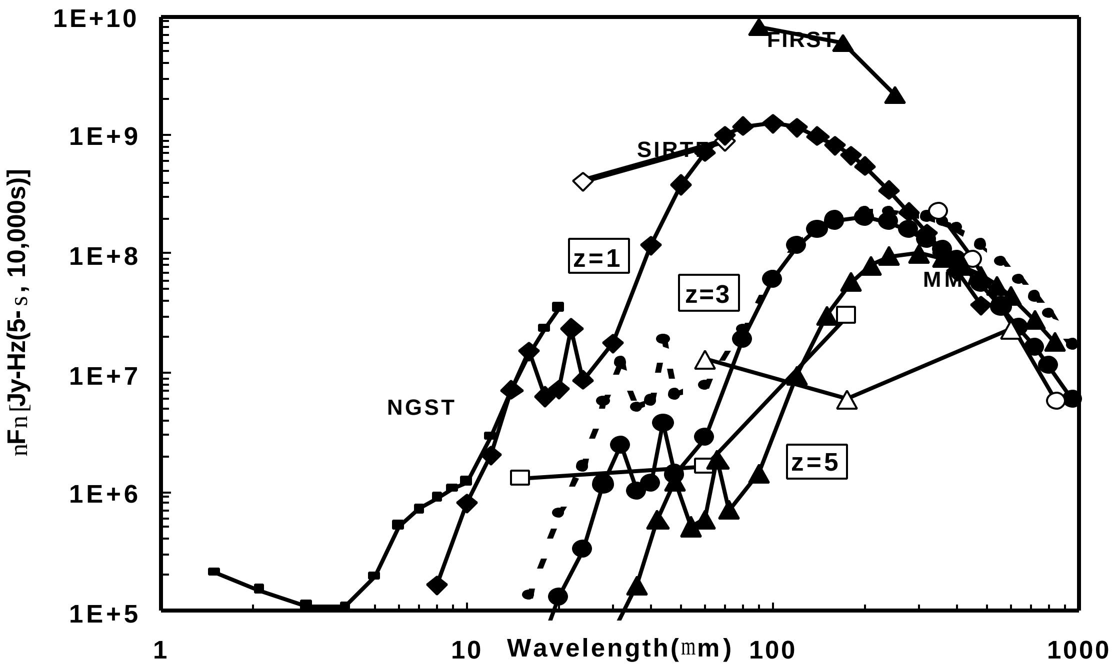


Figure 6-3. Starburst powered far infrared output of an L*(IR) galaxy. We also indicate the performance of NGST, SIRTF, FIRST, the MMA, a 10m cold telescope, and a 30m cold interferometer (see Figure 6-1). For the z=3 case, we have shown the total (starburst plus IR cirrus) spectrum as a dashed line. The FIR/Submm missions have unique capability for investigating galaxies of this type over their period of formation. In particular, even a modest (30m) interferometer could study them well to very high redshifts.

6.2 Extreme Environments and Discovery Potential

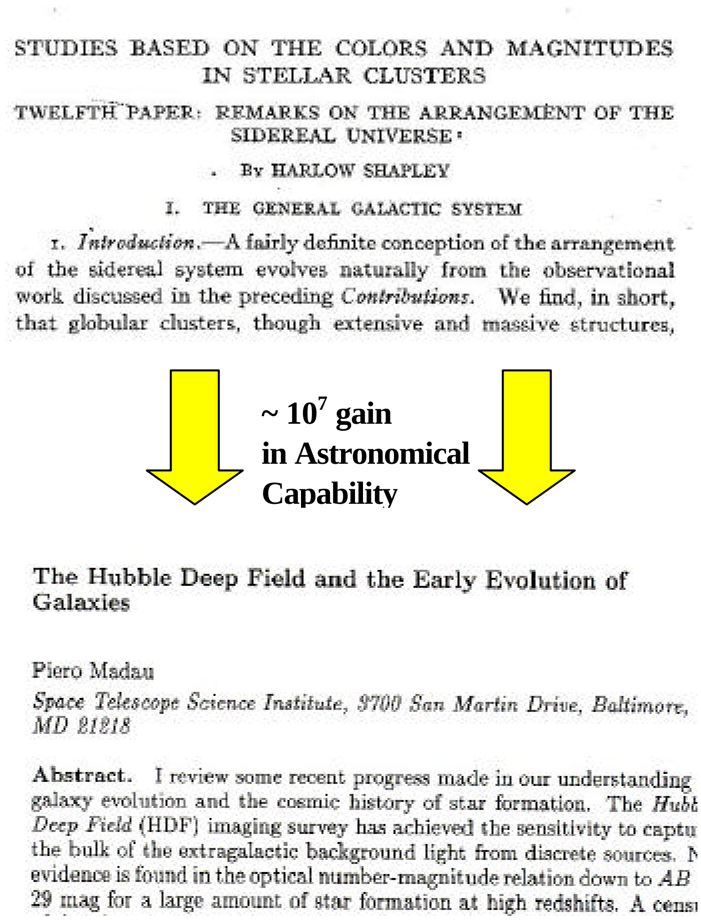
6.2.1 Mid Infrared Fine Structure Lines

To be furnished

6.2.2 Discovery Potential

To compare the discovery potential of different missions operating over the same spectral region, the Bahcall Committee developed a figure of merit they called "Astronomical Capability." This parameter is defined as the lifetime X the efficiency X the number of pixels / the sensitivity squared. It scales the amount of data that can be obtained in given mission, if all other things were equal such as optical parameters defining the projection of the pixels onto the sky. Compared with our current knowledge about the far infrared sky (from ISOPHOT between 20 and 100µm) and what could be achieved with the best currently available detector arrays on a 10m cold telescope, the gain in Astronomical Capability is about a factor of 10^9! With improvements in detectors, a factor of well over 10^{10} should be possible.

To place this gain on a more familiar scale, the improvement from the work of Shapley on the size and shape of the Milky Way to the Hubble Deep Field represents a gain of about 10^7 in Astronomical Capability. Thus, our ability to predict what will be found in future FIR/Submm missions is probably no better than Shapley would have done in predicting the contents of the HDF; recall that at the time of the article in Figure 6-4, he did not believe in extragalactic astronomy.


STUDIES BASED ON THE COLORS AND MAGNITUDES IN STELLAR CLUSTERS

TWELFTH PAPER: REMARKS ON THE ARRANGEMENT OF THE SIDEREAL UNIVERSE

By HARLOW SHAPLEY

I. THE GENERAL GALACTIC SYSTEM

1. *Introduction.*—A fairly definite conception of the arrangement of the sidereal system evolves naturally from the observational work discussed in the preceding *Contributions.* We find, in short, that globular clusters, though extensive and massive structures,

The Hubble Deep Field and the Early Evolution of Galaxies

Piero Madau

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Abstract. I review some recent progress made in our understanding galaxy evolution and the cosmic history of star formation. The *Hubb Deep Field* (HDF) imaging survey has achieved the sensitivity to captu the bulk of the extragalactic background light from discrete sources. N evidence is found in the optical number-magnitude relation down to *AB* 29 mag for a large amount of star formation at high redshifts. A cens

Figure 6-4. Illustration of the discovery space opened by a gain of 10^7 in Astronomical Capability.

It would probably be foolish to try to leap a factor of 10^{10} in one step. SIRTF should advance us about half this way. That is, it will provide an increase in Astronomical Capability by about 10^5, leaving a similar factor for future missions like the ones we have discussed.

6.3 Dynamical and Chemical Evolution of Galaxies and Stars

To be furnished

6.4 Birth and Evolution of Stars and Planetary Systems

To estimate the measurement requirements for determining what is happening inside a cold cloud core, we started with submm data for one such object, VLA 1623, from Andre et al. (1993, ApJ, 406, 122). We then predicted the far and mid infrared SED through a radiative transfer model consistent with Wolfire & Cassinelli (1986, ApJ, 310, 207). We plot in Figure 6-5 the surface brightness per square arcsec in the core (13.5") of the source. We also show a pure blackbody fitted to the radio, submm, and far infrared data. The hot interior of the cloud and radiative transfer process is reflected by the difference over the range 10 to 100µm between the predicted SED for VLA 1623 and the pure blackbody spectrum (which would fit the source if it were isothermal throughout). The proposed instruments, particularly the filled aperture telescope, can study this part of the cloud at high signal to noise.

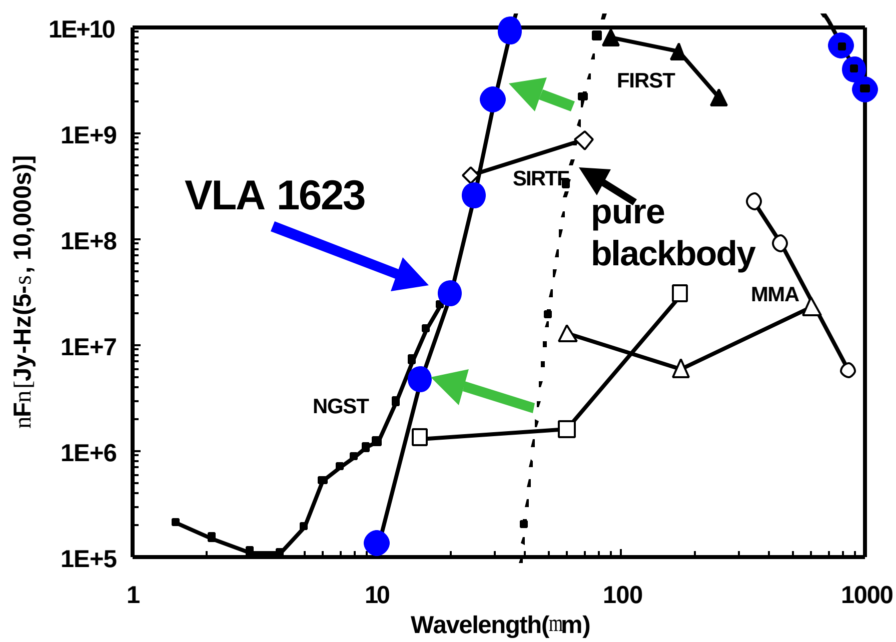

Figure 6-5. A model prediction of the short wavelength SED of a cold cloud core. Observations of star and planet formation within the core need to be made largely in the wavelength range where the spectrum deviates from the pure blockbody curve.

6.5 Nature and Formation of the Solar System

The fluxes from Kuiper Belt Objects (KBOs) can be estimated readily from first principles. We show one example in Figure 6-6. The calculations are for a small body (diameter 10km) with low albedo (0.04) at the inner edge of the Kuiper Belt (40 AU from the sun). The large margin of sensitivity to detect this object is indicative of the broad variety of albedoes, sizes, and distances from the sun that could be probed by large far infrared telescopes.

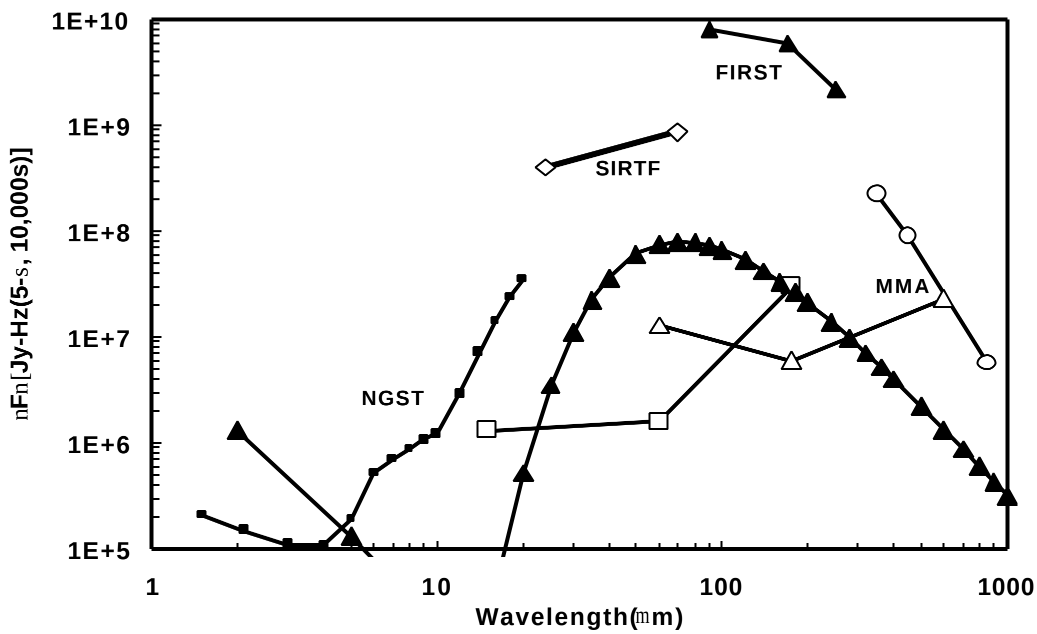

Figure 6-6. Spectrum of a 10km diameter, low albedo KBO at 40AU.

6.6 Comet and Asteroid Impacts and the Origin of Life

To study debris disks in detail requires measurements of their structures over a range of wavelengths. This point is illustrated in Figure 6-7. The spectrum of the debris disk is based on a model of the solar system zodiacal cloud plus the Kuiper Belt, placed at 10pc to represent what might be seen around a nearby star. The calculation has been normalized to allow 100 resolution elements over the disk at each wavelength, the minimum which would give good information on the structure. Detailed models of the radial profile of the thermal emission at four fiducial wavelengths are shown in the lower panels. They emphasize that the shorter wavelengths will probe the inner portions of the system, for a solar-like system the zodiacal cloud. The longer wavelengths progressively probe increasing distances from the star; in the case of a solar-like system, 350μm would be a good choice to study the parts of the system at a 100 or more AU radius. By combining observations at all the wavelengths, a detailed model of the system could be derived.

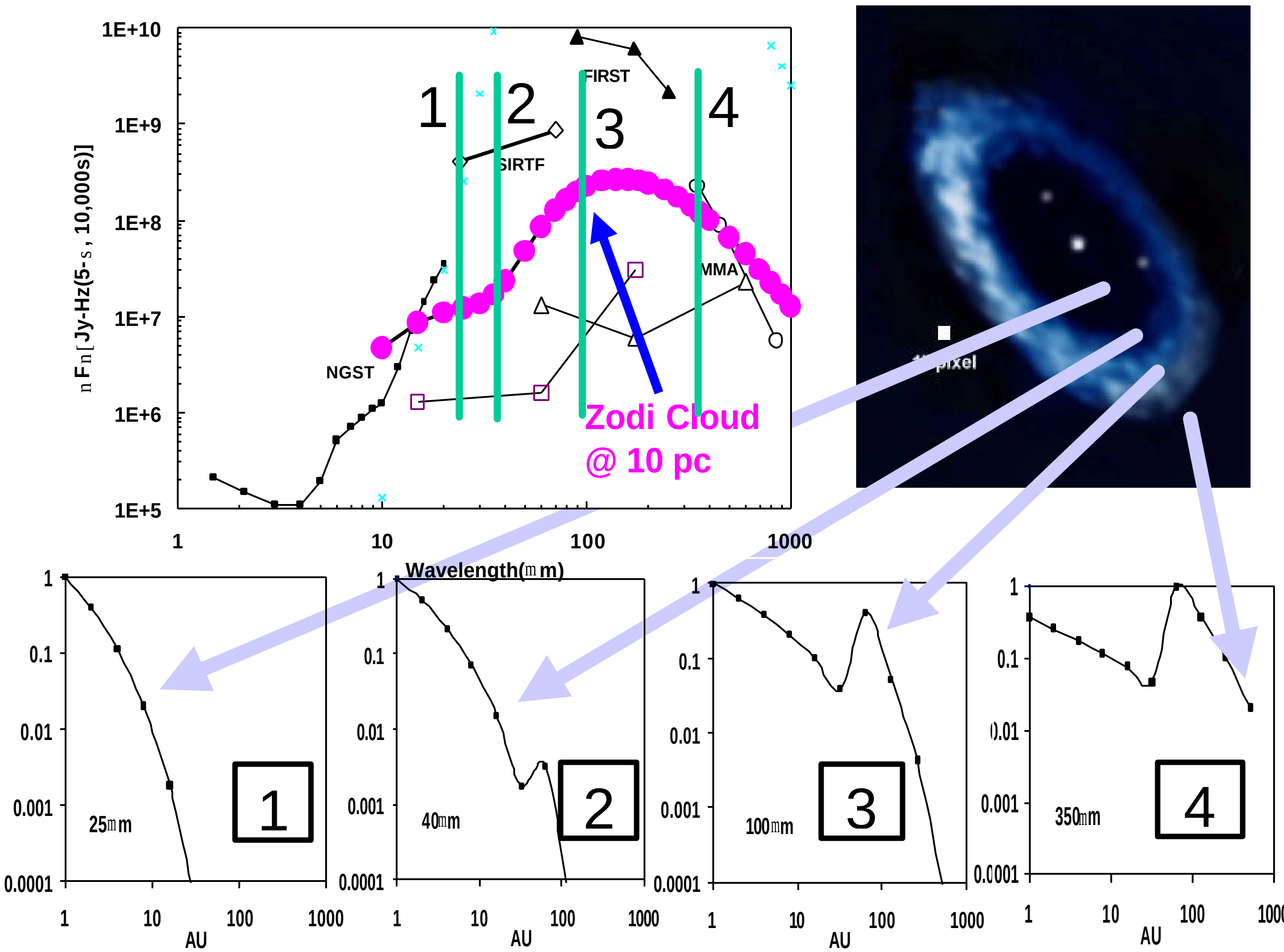

Figure 6-7. Emission from a debris system like that around the sun, viewed from a distance of 10pc. Different wavelengths probe different zones of the system. The zones are shown (not to scale) relative to the artist's concept of the Vega system used in Section 2.

6.7 Angular Resolution

The angular resolution for many of the investigations under discussion is implicit from considerations like confusion noise and hence has been included in the sensitivity charts above. In some cases, however, the required resolution is independent of the seisitivity achieved. A number of representative examples are shown in Figure 6-8. In the case of debris and protoplanetary disks, the scale size of the system increases with longer wavelengths, since one probes with them the cooler, outer parts of the system. In the case of cold cloud cores, we have assumed that one wishes to maintain a constant resolution of 1 arcsec to study structure and radiative transfer in a homogeneous fashion (with a few hundred resolution elements over the typical size of the nearest examples). In the case of distant galaxies, the resolution is set by confusion considerations. We have included this case to emphasize the match of a 30m baseline to the desired angular scale. In addition, the plot illustrates that a 10m telescope would have adequate resolution to make significant contributions to many of the problems discussed (the examples not plotted are included implicitly in the sensitivity charts). However, as emphasized by the lines for resolving protoplanetary disks and terrestrial planet formation, there is a distinct set of science objectives that require the much higher angular resolution that will only be possible with a km-baseline interferometer.

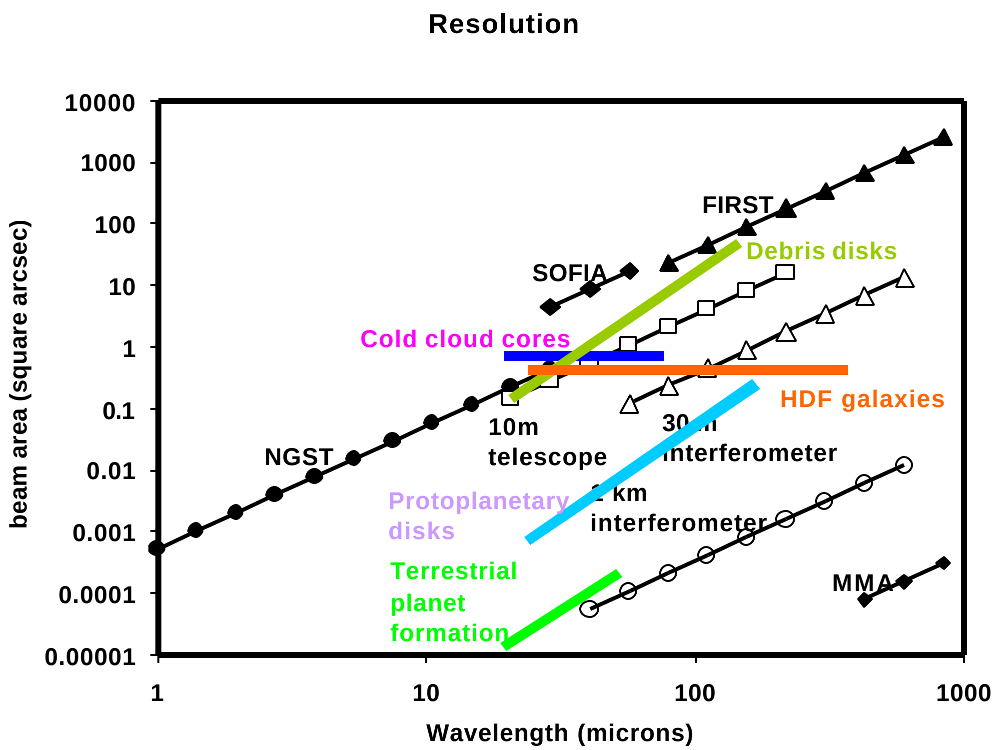

Figure 6-8. Angular resolution required for some typical science investigations.

7. Technical Developments

The missions for the far infrared and submillimeter will benefit from and demonstrate the new technical developments already envisioned in the OSS Strategic Plan. In many respects, the proposed missions provide an ideal opportunity to use work already required for other OSS objectives and apply it to achieve scientific breakthroughs in another area. The serendipitous nature of the FIR/Submm technical needs within the OSS Strategic Plan is illustrated by the following listing of the relevant items with their application to the FIR/Submm program:

- Advanced Structures Deployment and Control (for large, deployable telescopes and for interferometers)
  - Ultra-precise deployment of lightweight structures
  - Control of structural shape and vibration in space
  - Precise pointing of large structures
- Communications (interferometers in particular can generate large data volumes; if it is decided to place a large telescope at > 1AU for better cooling, it will also require advanced communications)
  - High-data-rate telecommunications technologies
  - Lightweight, low-power, robust electronics systems
  - Lightweight antenna materials
- Lightweight Optics (because of relaxed surface specifications, the FIR/Submm missions can make excellent use of lightweight and possibly ultra-lightweight optics)
  - Advanced segmented optical systems with high-precision controls
  - Large lightweight mirrors
- Metrology (essential for a km-baseline interferometer)
  - Extremely precise measurement of orientations of in-space structures using stabilized lasers
  - ➢ In addition, attention is needed for precise satellite tethering systems to control angular momentum and centripetal force in large interferometers (both for TPF and the km-baseline FIR/Submm interferometer)
- Power (improvements in power generation could enable placing a telescope at > 1AU)
  - High efficiency solar arrays tolerant of extreme thermal and radiation environments
- Science Instruments (advances in sensors, sensor arrays, and coolers play a central role in the FIR/Submm strategy, and would yield unique discovery potential)
  - New sensors and detectors for telescopes, interferometers, and….
    1.) very low temperature electronics, such as advanced CMOS readouts and SQUID superconducting devices, are needed to read out detector arrays;
    2.) advances in bolometer array construction are possible through silicon/silicon nitride etching techniques and transition edge superconducting thermistors;
    3.) photoconductor detector arrays can be increased significantly beyond the current formats and possibly can be developed for longer wavelengths than at present;
    4.) hot electron microbolometer mixers can extend sensitive heterodyne detection to 100μm or even shorter wavelengths;
    5.) other high frequency mixers should be explored, such as large bandgap SIS devices and superconducting single electron transistors; and
    6.) new approaches to backends can enable larger arrays of heterodyne receivers.
  - Coolers and other instrument support systems (an emphasis is needed on advanced radiative cooling, building on the heritage from SIRTF, as well as low power, high efficiency coolers)

8. Recommendations

The Far Infrared/Submm offers great opportunities for future astronomy space missions. It can provide important insights to the central problems of astrophysics. The investment in spectacular capabilities in the adjacent spectral regions will allow sophisticated studies of new phenomena discovered in the FIR/Submm. Finally, the possible growth in sensor and telescope capabilities promises unparalleled discovery potential.

We recommend the following steps be taken in the 2000-2010 decade to take advantage of these opportunities:

- Invest in the enabling technologies for this spectral region:
  1.) Direct detectors and heterodyne receivers
  2.) Detector array technologies
  3.) Cryogenic systems
  4.) Lightweight and deployable optics and antennas
- Begin system studies for a major space FIR/Submm filled aperture observatory in the early-to-middle part of the decade
- Begin formal definition (Phase B) of this observatory by the end of the decade
- Prepare for the construction of a km-baseline space interferometer in the 2010-2020 decade, both by developing the necessary technologies and by demonstrating them in a moderate-scale interferometer to be operational by 2009.

Future FIR/Submm missions will also benefit greatly from relevant theoretical, laboratory, and observational initiatives. We recommend support for

- Theory and laboratory astrophysics relevant to FIR/Submm astronomy
  1.) Line frequency determination
  2.) Study of dust properties
  3.) Modeling early stages of star and planet formation
  4.) Modeling AGN accretion disk properties
  5.) Probing the physics of jet acceleration and confinement.
- Advanced instrumentation on SOFIA, long duration ballooning, and groundbased submm telescopes
  1.) Develop scientific foundation for space missions
  2.) Train young scientists in this area
  3.) Demonstrate technology pathfinders