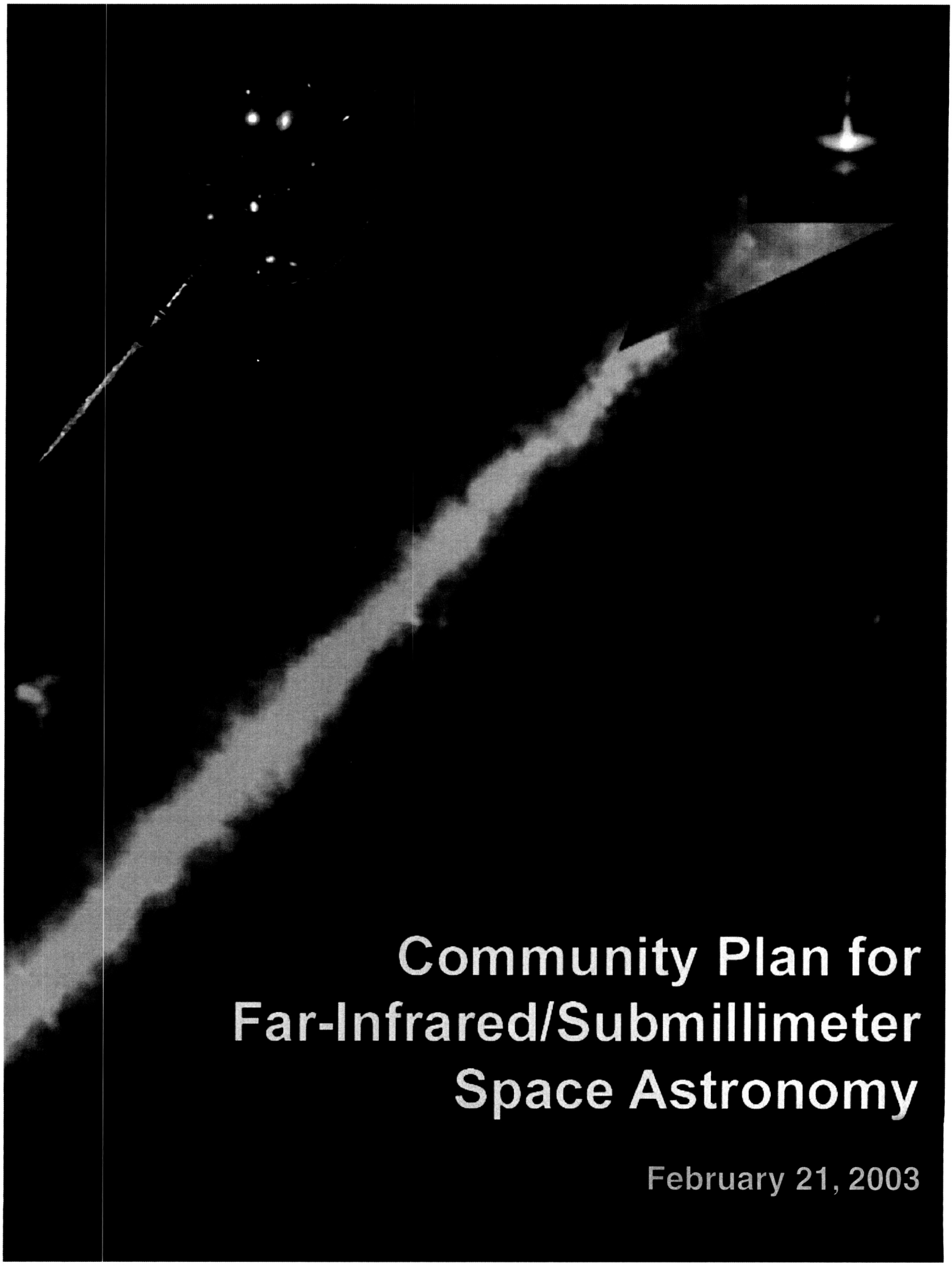


Community Plan for Far-Infrared/Submillimeter Space Astronomy

February 21, 2003

This paper represents the consensus view of the 124 participants in the "Second Workshop on New Concepts for Far-Infrared/Submillimeter Space Astronomy," which was held on 7 – 8 March 2002 in College Park, Maryland. The participants are listed below.

Peter Ade
Rachel Akeson
Shafinaz Ali
Michael Amato
Richard Arendt
Charles Baker
Dominic Benford
Andrew Blain
James Bock
Kirk Borne
Ray Boucarut
Francois Boulanger
Matt Bradford
Susan Breon
Charles Butler
Daniela Calzetti
Edgar Canavan
Larry Caroff
Edward Cheng
Jay Chervenak
Lucien Cox
William Danchi
Ann Darrin
Piet de Korte
Thijs de Graauw
Bruce Dean
Mark Devlin
Michael DiPirro
Terence Doiron
Jennifer Dooley
Mark Dragovan
Chris Dudley
William Duncan
Eliahu Dwek
Mick Edgar
Michael Egan
Lee Feinberg
Jacqueline Fischer
David Folta
Minoru Freund
Edward Friedman
Jianrong Gao
Jason Glenn
Matthew Griffin
Martin Harwit
Thomas Henning
Ross Henry
Stefan Heyminck
Sam Hollander
Joseph Howard
Wen-Ting Hsieh
Mike Kaplan
Jeremy Kasdin
Sasha Kashlinsky
Alan Kogut
Alexander Kutyrev
Guilaine Lagache
Brook Lakew
Jean-Michel Lamarre
Charles Lawrence
Peter Lawson
David Leisawitz
Dan Lester
Charles F. Lillie
Landis Markley
John Mather
Mark Matsumura
Gary Melnick
Michael Menzel
David Miller
Sergio Molinari
Harvey Moseley
Ronald Muller
Lee Mundy
Takao Nakagawa
Ted Nast
Bret Naylor
Hien Nguyen
Alain Omont
Francois Pajot
Charles Perrygo
Albrecht Poglitsch
Daniel Prober
Jean-Loup Puget
Marco Quadrelli
Manuel Quijada
Simon Radford
Jayadev Rajagopal
David Redding
Frank Rice
Paul Richards
George Rieke
Stephen Rinehart
Cyrille Rioux
Juan Roman
Goran Sandell
Paolo Saraceno
Rick Shafer
Peter Shirron
Peter Shu
Robert Silverberg
Howard Smith
Johannes Staguhn
Phil Stahl
Carl Stahle
Thomas Stevenson
John Storey
Guy Stringfellow
Keith Strong
Mark Swain
Peter Timbie
Wes Traub
Charlotte Vastel
Thangasamy Velusamy
Christopher Walker
Alycia Weinberger
Michael Werner
Juergen Wolf
Edward Wollack
Alwyn Wootten
Harold Yorke
Erick Young
Jonas Zmuidzinas

Community Plan for Far-Infrared/Submillimeter Space Astronomy

We recommend that NASA pursue the vision for far-IR astronomy outlined in the NAS Decadal Survey, which said: "A rational coordinated program for space optical and infrared astronomy would build on the experience gained with NGST[1] to construct [a JWST-scale filled-aperture far-IR telescope] SAFIR, and then ultimately, in the decade 2010 to 2020, build on the SAFIR, TPF, and SIM experience to assemble a space-based, far-infrared interferometer." SAFIR will study star formation in the young universe, the buildup of elements heavier than hydrogen over cosmic history, the process of galaxy formation, and the early phases of star formation, which occur behind a veil of dust that precludes detection at mid IR and shorter wavelengths. The far-infrared interferometer will resolve distant galaxies to study protogalaxy interactions and mergers and the processes that led to enhanced star formation activity and the formation of Active Galactic Nuclei, and will resolve protostars and debris disks in our Galaxy to study how stars and planetary systems form.

The following unified plan addresses practical issues and makes recommendations that would lead to the fulfillment of the Decadal Report's vision. This plan gives the consensus view of the participants in the "Second Workshop on New Concepts for Far-Infrared/Submillimeter Space Astronomy," which was co-sponsored by NASA Headquarters and the Goddard Space Flight Center and held at the University of Maryland on 7 – 8 March, 2002. The workshop participants were representatives of the community of scientists and technologists who would implement the plan.

We make these recommendations to NASA because information vital to the attainment of major SEU and Origins scientific objectives is uniquely available in the far-IR and submillimeter (FIR/SMM), a spectral range that spans the gap between the longest wavelength accessible to the JWST (formerly NGST), ~25 μm, and the shortest wavelength continuously accessible to ALMA through the atmosphere, ~800 μm. For example, to "understand the structure of the universe, from its earliest beginnings to its ultimate fate," we will need measurements of the emissions from protogalactic objects and galaxies most intimately related to the star formation process, namely emissions that reveal the physical conditions (elemental abundances, temperatures, densities) in the interstellar medium; we will need extinction-free views of the universe complementary to those provided by telescopes that operate at shorter wavelengths; and we will need telescopes that can measure the emissions from the pristine hydrogen clouds that collapsed to form the very first generation of stars. To "explore the ultimate limits of gravity and energy in the universe" we will need to peer into the dust-enshrouded nuclei of galaxies to see how matter behaves in the presence of a supermassive black hole. To "learn how stars and planets form" we will need to observe these objects where they emit most of their light – in the infrared – with telescopes that provide high enough spectral resolution to constrain theoretical models, and sufficient acuity to resolve extrasolar planetary systems. Some of the objects we wish to study – the youngest stars and galaxies – are not even visible at optical and near-IR wavelengths.

[1] See Appendix A for acronym definitions.

The value of infrared spectroscopy is evident in the information-rich data from NASA's Submillimeter Wave Astronomy Satellite (SWAS) and ESA's Infrared Space Observatory (ISO). Spectroscopic data give us information on chemical species, velocities, and the interaction of these in the chemodynamics that is virtually certain to play a dominant role in the next stage of astrophysical thought. High spectral resolution will therefore be an essential capability for future FIR/SMM missions.

The FIR/SMM is the least-explored spectral region in astronomy, even though COBE told us that half the luminosity of the universe, and 98% of the photons (aside from the cosmic microwave background), appear in the far-IR. Far-IR astronomy has been hampered by angular resolution worse than that of Galileo's first telescope, and by sensitivity limited by small apertures and early generations of detectors. Even SIRTF is still modest in size, only a little larger than the IRAS flown in 1982. The Herschel telescope at 70 K and the SOFIA telescope at 250 K will be about 4x and 3x larger, respectively, but are both relatively warm for this wavelength regime, and thus have limited sensitivity. The scientific yield of the upcoming missions SIRTF, SOFIA, and Herschel will whet our appetites for more sensitive FIR/SMM telescopes that can be used to detect the faint emissions from young, and therefore distant, galaxies. A further gain in sensitivity by several orders of magnitude is necessary to see these sources, and is attainable with a large aperture space observatory whose sensitivity is limited only by the insurmountable photon noise from astrophysical background radiation. New technology and mission concepts now enable a major breakthrough in this area, with the confident expectation of new discoveries.

First Step: SAFIR

The first step is to develop the technology and start the planning for a cooled JWST-class far-IR observatory called SAFIR (Single Aperture Far-IR telescope), to be operated like HST for a wide user community with a launch by the middle of the JWST lifetime in 2015. The scientific motivation and concepts for SAFIR are presented in the white paper *Charting the Winds that Change the Universe* (Appendix B). SAFIR should be background limited over a wavelength range from about 15 to 600 μm to overlap slightly with JWST and ground-based capabilities, and could be diffraction limited at around 40 μm. With a 10 m aperture (a little larger than JWST's) it would have 150 times the collecting area and an order of magnitude greater angular resolution at a given wavelength than SIRTF. Figure 1 shows the relevance of this improvement in angular resolution to the measurements needed to achieve Origins and SEU science objectives, and the striking gap in resolving power in the FIR/SMM that will be left in the wake of the next generation of telescopes. SAFIR will provide our first deep view of the sky at far-IR wavelengths that does not suffer the ill effects of extragalactic source confusion (multiple galaxies per resolution element), enabling detailed studies of the individual sources that give rise to the cosmic IR background.

SAFIR instruments would provide imaging and spectroscopic capabilities with maximum spectral resolution $\lambda/\Delta\lambda \sim 10^6$. To achieve the goal of natural background-limited performance, the SAFIR mirror will have to be cooled to about 4 K, and new generations of detectors, operating at about 0.05 K, will have to have NEP $<10^{-20}$ W Hz$^{-1/2}$. With such

extraordinary sensitivity SAFIR could readily detect spectral line emission and spectral features from gas and dust in galaxies at redshift z ~ 4 – 5, as illustrated in Figure 2, and probe the gas dynamics and chemistry in forming planetary systems. Figure 2 further shows the importance of improving sensitivity by 4 - 5 orders of magnitude beyond the capabilities of SIRTF, SOFIA, and Herschel. Japan's SPICA mission, which is planned to have a 4 K, 3.5 m diameter primary mirror, will take a huge step in this direction. SAFIR, with its larger mirror, will bring the most distant galaxies into range.

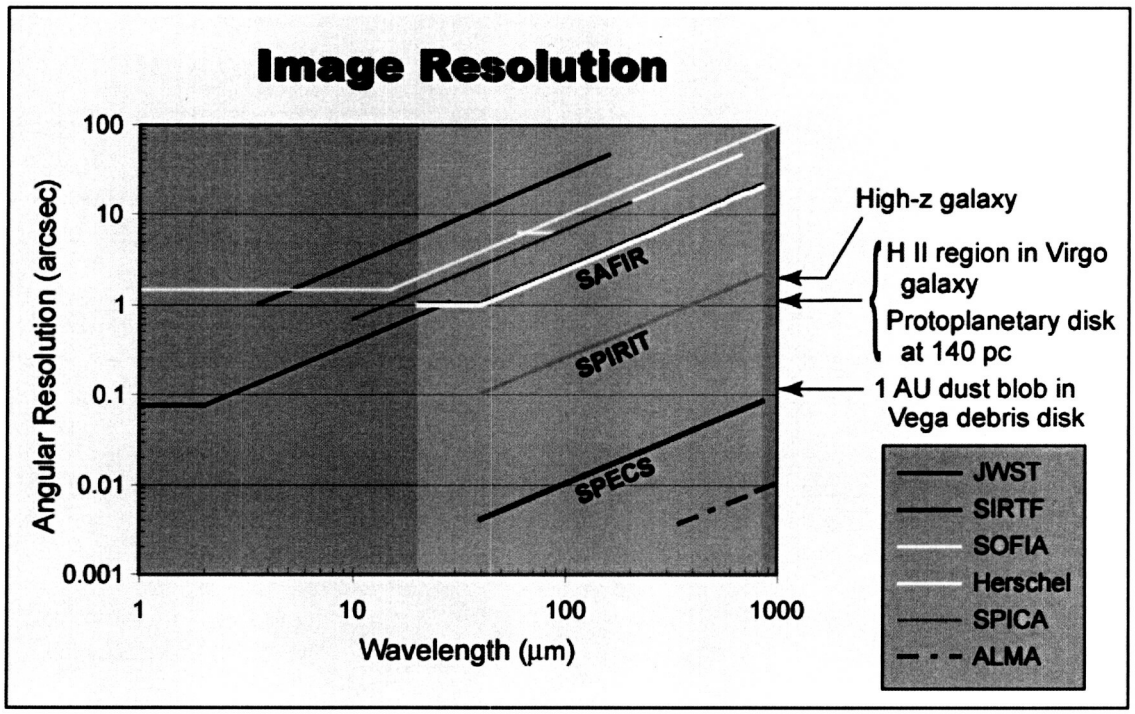


Figure 1. Vast improvements in angular resolution beyond those provided by the next-generation FIR/SMM missions will be needed to beat extragalactic source confusion, resolve the individual sources of interest, and achieve the science goals of NASA's Origins and SEU themes. Such improvements are also needed to align the FIR/SMM (shaded region) measurement capability with that available in the surrounding spectral regions, where JWST and ALMA will make complementary observations. ALMA provides complete spectral coverage at wavelengths longer than ~800 μm and observing capability into the submillimeter through atmospheric windows. With a 10 m aperture diameter SAFIR will take the first big step; interferometers like SPIRIT (assumed maximum baseline b_{max} = 40 m) and SPECS (b_{max} = 1 km) will be needed to provide the full resolution gain desired. SAFIR, SPIRIT, and SPECS are recommended in this plan.

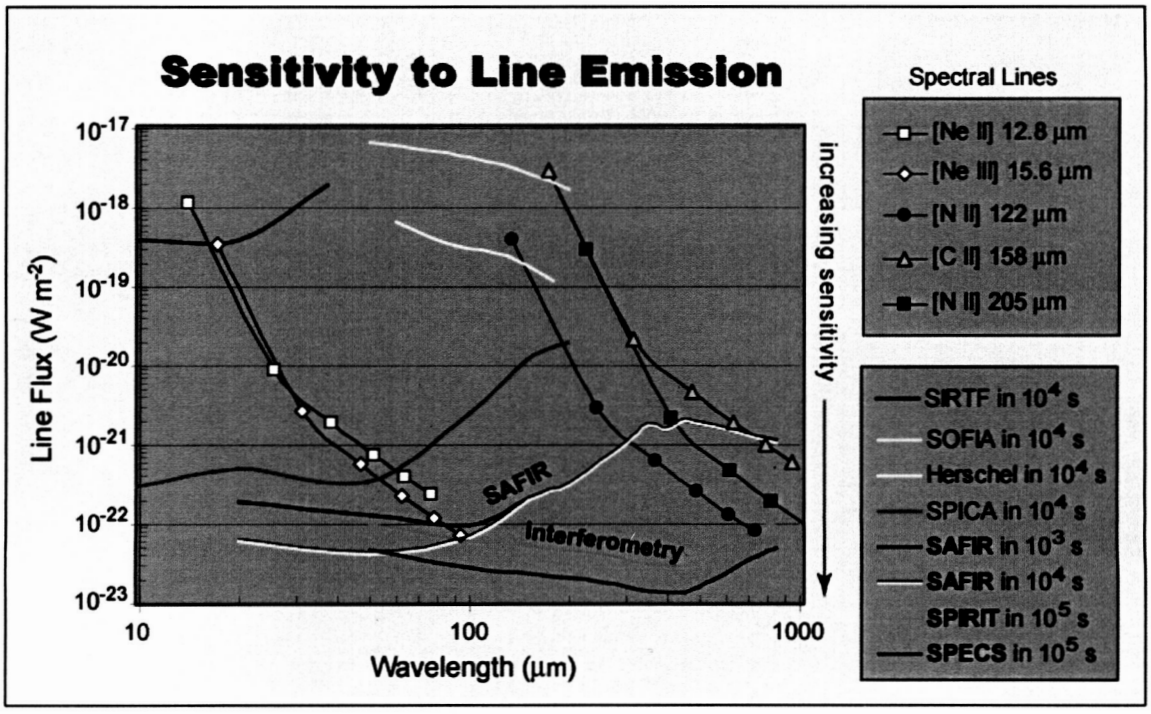


Figure 2. A spectrometer on SAFIR (with assumed $\lambda/\Delta\lambda = 10^3$) would be 4 to 5 orders of magnitude more sensitive than the corresponding instruments on SIRTF, SOFIA, and Herschel, and 1 to 2 orders of magnitude more sensitive than SPICA, enabling unprecedented studies of the star formation process and astrophysical conditions in distant, young galaxies. Estimated strengths of five important diagnostic and interstellar gas cooling lines are shown for a hypothetical "Milky Way" galaxy at redshifts of 0.1, 1, 2, 3, 4, and 5 (symbols along each curve, with redshift increasing from the upper left to the lower right). The rest wavelengths of the spectral lines are given in the inset. SAFIR could, for example, measure the [Ne II] and [Ne III] lines in "normal" galaxies out to z = 5 in modest exposure times. The relative intensity of these lines can be used to discriminate between AGN-dominated and star formation-dominated emission. Many galaxies are much more luminous than the Milky Way, making them even easier to see. At $\lambda > 200$ μm, SAFIR would reach the confusion noise "floor" in about 100 seconds[2]; longer exposure times would not help. However, because of their greater resolving power and still substantial total aperture areas, the interferometers SPIRIT and SPECS will break the confusion barrier and probe the universe to comparable depth (redshift z ~ 5) in the spectral lines that dominate the cooling of interstellar gas and allow the gas clouds to collapse and produce stars.

SAFIR will require investment in several technology areas. High-sensitivity far-IR detector technology, which is very promising but far from flight readiness, is one of the top priority items for SAFIR preparations. A total investment of the order of $50 M spread out over 10 years could produce large superconducting detector arrays with sensitivity one or two orders of magnitude beyond those now available, satisfying the performance goal. Even this budget is small compared with the investments made in

[2] We assume that the emission found in a single diffraction-limited beam cannot be reliably apportioned between multiple component sources. Therefore, we show the continuum confusion limit in a single $\lambda/1000$ spectral channel. The sensitivity would be less severely compromised by confusion if the redshift of each component were known from independent observations.

detectors at other wavelengths, but NASA is the only effective funding source in this area. Depending on the results and scientific opportunities developed from the Herschel mission, SAFIR might require coherent receivers that approach quantum-limited performance, as well as direct detectors.

Sensitivity in the FIR/SMM depends strongly on the temperature of the telescope, and it is imperative that improvements in detector technology be matched by efforts to cool large mirrors to very low temperatures. Because the optical tolerances on the SAFIR mirror are greatly relaxed relative to the JWST requirements, the possible use of precision machined, replicated mirror segments should be explored. Replication has the potential to speed fabrication and reduce cost. Based on JWST experience, we conclude that such a mirror study would cost $25M over three years, and the mirror technology could reach maturity (TRL 6) in a total of six years. The Advanced Cryocooler Technology Demonstration will provide a small TRL 5 cooler in 2005, but a much more powerful cooler will be needed to cool the SAFIR mirror. A development program for new cryocooler systems would cost about $30 M. Other projects, like JWST and TPF, and other government agencies (DoD and NRO) are already providing technology development funds for advanced coolers and deployable mirrors.

Whereas a JWST-like configuration flying at 3 – 4 AU from the Sun was shown in the Decadal Survey report, better thermal and sunshield engineering will permit SAFIR to operate at the JWST L_2 orbit and provide a larger aperture with the same launch vehicle. Other configurations should also be explored (Fig. 3).

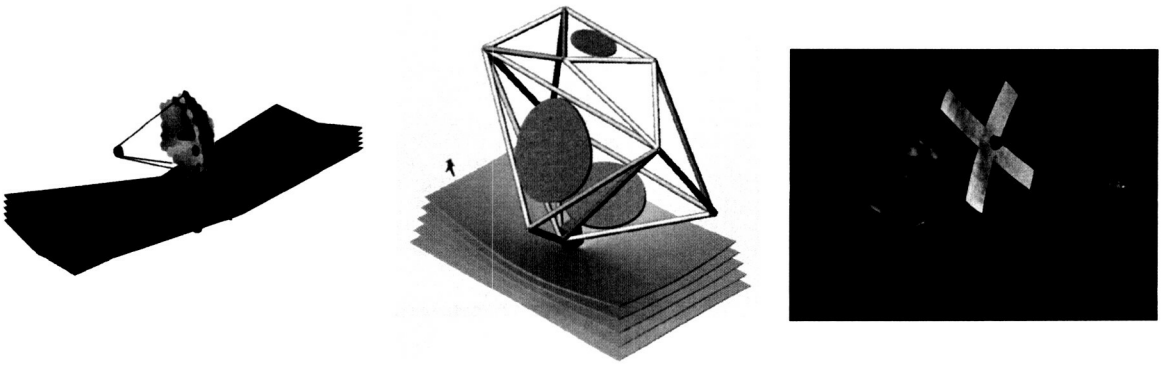


Figure 3. Further study of SAFIR mission designs will be needed before a single approach that accomplishes the highest priority science goals with ready technology, subject to programmatic considerations, can be selected. Three possible concepts are shown here: (left) based on JWST for maximum heritage and fidelity; (middle) based on stretched membrane mirrors to reduce aereal mass; and (right) based on a sparse aperture telescope to improve angular resolution.

Depending on the progress made with other planned instruments, a FIR/SMM all-sky survey mission with a 2 m class cryogenic telescope might be a scientifically compelling precursor to SAFIR. At other wavelengths, survey missions have greatly enhanced the science return of successive observatories. In the far-IR, the last sky survey, IRAS, was so insensitive that SAFIR will be blinded by every IRAS source. Given the immense discovery potential in this relatively unexplored spectral region, it is reasonable

to think that a deep FIR/SMM survey will be needed, and to plan accordingly. It is presently believed that there are many submillimeter-luminous galaxies at very high redshifts that do not have noteworthy optical counterparts, but which make up a substantial fraction of the total luminosity of the post-recombination universe. If these sources are not identified by SIRTF, Astro-F, NGSS, SOFIA, Herschel, or SPICA - because of their limited sensitivity, shorter wavelength range, or smaller survey area - then a FIR/SMM survey should be undertaken, and we believe that such a mission would be a strong competitor in the Discovery class. A sensitive FIR/SMM sky survey would answer important questions about the evolution of galaxies and would find the rare but important objects that act as signposts to the early universe, providing a rich database to build on with SAFIR and other missions.

Second Step: SPECS

The imaging sensitivity of SAFIR will be limited by the overlap of distant galaxy images at wavelengths greater than about 100 μm because its angular resolution will be ~ 3 arcsec, comparable to that of binoculars and to the spacing of galaxies seen in the Hubble Deep Field. A very large increase in angular resolution would be possible with an interferometer (Fig. 1). The scientific motivation and concepts for two FIR/SMM interferometry missions are presented in the white paper *Probing the Invisible Universe* (Appendix C). **A commendable long-range goal is to achieve HST-class resolution in the FIR/SMM, which would require an imaging interferometer with a 1 km maximum baseline**. Although this is not currently technically feasible, it is less challenging than X-ray or optical interferometry in space because the FIR/SMM wavelengths are much longer, and is comparable in overall difficulty to the other interferometry missions deemed meritorious by the astronomical community and included in the NASA Roadmap. We outline below the technical steps that will be required to build the km-baseline interferometer we call the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS).

A FIR/SMM interferometer with superconducting detectors, cold mirrors, and a total light collecting aperture in the tens of m^2 would provide ample sensitivity. To derive the sensitivity curve shown for SPECS in Figure 2, the interferometer was assumed to combine the light collected with three 4 m diameter mirrors. SPECS is a natural successor to SAFIR, as it would employ the same detector, mirror, and cooler technologies, although the interferometer mirrors would be smaller than the SAFIR mirror and could be monolithic.

Three additional technologies or techniques will be needed to enable long-baseline imaging interferometry: a long-stroke cryogenic delay line; highly-reconfigurable formation flying; and the technique of wide-field imaging interferometry. Initial funding for these technologies was awarded through competitive programs during the past several years, and continued support for these mission-enabling technologies is needed. High-risk technologies, such as tethered formation flying, should be demonstrated in space with inexpensive nanosats.

Following a recommendation made by the attendees of the first community workshop in this series, "Submillimeter Space Astronomy in the Next Millennium," which took place in February 1999, concepts were developed for a FIR/SMM interferometer on a boom. We call this the Space Infrared Interferometric Telescope (SPIRIT). Figures 1 and 2 show that such a telescope would have very powerful measurement capabilities. A suitable goal for SPIRIT would be a system with a 40 m span, which provides the same angular resolution as a filled aperture telescope nearly twice this diameter and matches the JWST's resolution, but at a wavelength 10 times longer (see Fig. 1). Such a structure is within reach of the expected technology base 5 to 10 years from now, as much larger booms are already in use in space. Good metrology and active control are required, but diffraction limited performance at 40 μm is quite easy to achieve relative to the performance required for an optical interferometer, and SIM is paving this path. The apertures should be as large and as cold as can be afforded, but for this step it is clear that angular resolution is more important than sensitivity. To estimate the sensitivity shown in Figure 2 we assume that SPIRIT has two 3 m diameter light collecting mirrors, and the mirror temperature is 4 K. **If the cost of SPIRIT is much less than that of a "roadmap mission" like SPECS, as preliminary studies indicate, then SPIRIT should precede SPECS. We recommend that FIR/SMM interferometry mission concept studies be continued.**

As illustrated in Figure 4, the new technology requirements for FIR/SMM interferometry largely overlap the requirements for SAFIR.

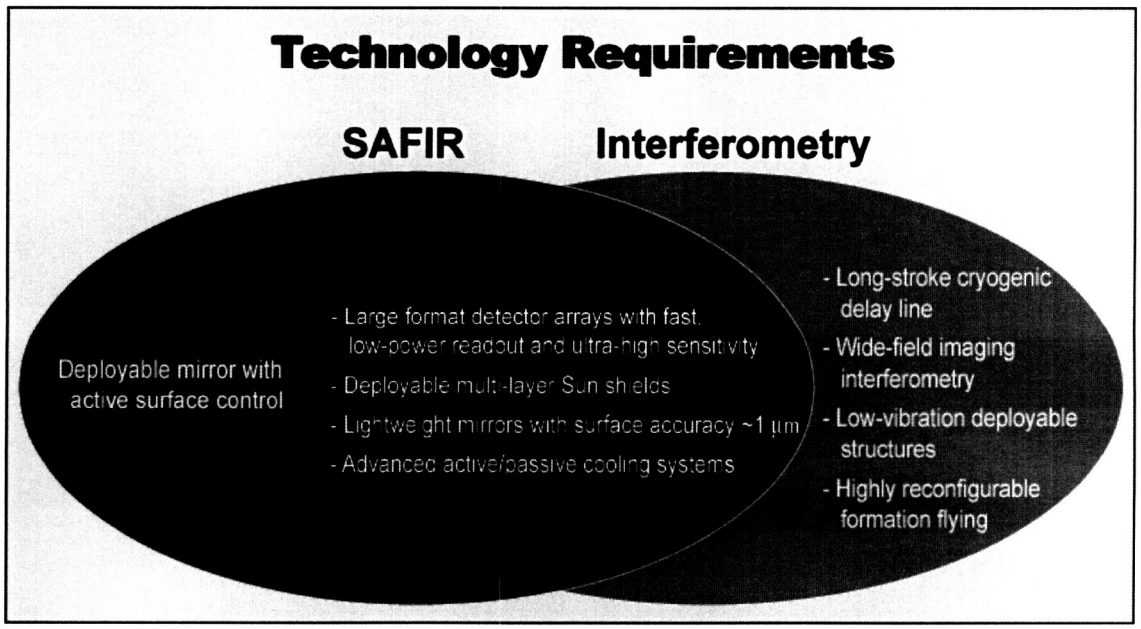


Figure 4. Investments in SAFIR technology will go a long way toward enabling FIR/SMM interferometry, and some of the interferometry technologies will be needed for LISA, SIM, and possibly TPF. New detectors and large mirror cooling technologies are particularly critical for FIR/SMM space astronomy, but a coordinated technology program would invest early in all the long lead time technologies shown here.

Supporting Research, Technology, and Missions

Several years will pass before it becomes necessary to choose design details for SAFIR and SPECS, and some decisions, such as the option to fly a far-IR sky survey mission, and the relative timing of the SPIRIT and SAFIR missions, will depend on future scientific progress, on experience with JWST, ALMA, and ground-based optical interferometers, on the available technology, and on budgetary constraints. However, a relatively modest investment is needed to prepare. **We recommend a coordinated technology program** that provides support for the development of:

1. 10^4 pixel arrays of direct detectors with NEP ~ 10^{-20} W $Hz^{-1/2}$,
2. advanced, high-efficiency cryocoolers capable of providing ~100 mW of cooling power at 4 K for mirror cooling, and capable of cooling the detectors to ~50 mK,
3. low-cost, low areal density (<15 kg/m^2) mirror technology for the FIR/SMM in a mirror development program that includes
   a) demonstration of fabrication techniques,
   b) demonstration of cooling strategies,
   c) demonstration of wavefront sensing and control, and
   d) development of test procedures,
4. interferometry testbeds that can be used to develop procedures, algorithms, and control systems,
5. broadband tunable coherent THz array receivers that approach quantum-limited performance,
6. long-stroke cryogenic delay lines and compact spectrometer technology for broadband FIR/SMM spectroscopy and wide-field imaging using direct detectors,
7. low-vibration deployable structures, and
8. highly-reconfigurable formation flying to enable interferometric (u, v) plane filling, and therefore high contrast imaging.

Successful development of the technologies listed above would serve many NASA purposes. All of the FIR/SMM missions demand new detector development, and there is a strong overlap of technology with some types of X-ray and UV detectors. For example, Con-X needs superconducting detectors and cryo-coolers. LISA, like SPECS, requires formation flying. Some of the interferometry technologies are shared with other planned NASA missions, such as SIM and the interferometer version of TPF, although SIM and TPF require much better precision to work at shorter wavelengths and make astrometric measurements or null out starlight.

We recommend that NASA support initial concept studies for SAFIR, SPIRIT, SPECS, and a sensitive FIR/SMM all-sky survey mission. SPIRIT and the sky survey mission would cost less than SAFIR or SPECS, but more than the current MIDEX cap, and would therefore require either $400M-class Space Science mission opportunities or collaboration with partners to bring down the NASA cost. NASA has been asked to collaborate on the planned Japanese SPICA mission, which would provide a 3.5 m class cold far-IR telescope at the Lagrange point L_2. NASA would benefit from the opportunity to deploy new generations of far-IR detectors and instruments in space. New detector technology can be tested and used first on SOFIA, but SPICA may be the nearest term opportunity to use next-generation far-IR detectors in space.

Finally, **we recommend that NASA be receptive to proposals for laboratory and theoretical astrophysics related to far-IR studies**. Relatively little is known about the chemical reactions that form large interstellar molecules or dust, or their role in the physical processes that govern star and planet formation. As new species and phenomena are recognized from observations, it will be very important to interpret them accurately. It is also clear that simulations are critically important in establishing the right observing strategies and instrument requirements.

European and Japanese astronomers are eager to collaborate with their US colleagues on SAFIR and FIR/SMM interferometry. The European community will desire opportunities to follow up the Herschel mission, and the Japanese community to follow up the SPICA mission.

Conclusion

Information needed to answer some of the most compelling astrophysical questions is uniquely available in the FIR/SMM spectral region. The time is right to place SAFIR on the NASA plan as one of the successors of SIRTF and JWST, to set our sights on a long-baseline FIR/SMM interferometric imaging telescope, to further develop FIR/SMM single-aperture and interferometric mission concepts, and to invest strategically in the technology that will enable future FIR/SMM missions. Supporting studies and smaller mission opportunities should be actively pursued.

Appendix A. Acronyms

AGN – active galactic nucleus
ALMA – Atacama Large Millimeter Array
Astro-F – Japanese Infrared Imaging Surveyor
Con-X – Constellation X
ESA – European Space Agency
FIR/SMM – the far-infrared and submillimeter wavelength range from ~25 – 800 μm
IRAS – Infrared Astronomical Satellite
ISO – Infrared Space Observatory
JWST – James Webb Space Telescope, formerly NGST
LISA – Laser Interferometer Space Antenna
MIDEX – NASA's Medium-class Explorer program
NEP – Noise Equivalent Power
NGSS – Next Generation Sky Survey, a MIDEX mission
NGST – Next Generation Space Telescope, now called JWST
SAFIR – Single Aperture Far-Infrared Telescope
SEU – NASA's Structure and Evolution of the Universe theme
SIM – Space Interferometry Mission
SIRTF – Space Infrared Telescope Facility
SOFIA – Stratospheric Observatory for Infrared Astronomy
SPECS – Submillimeter Probe of the Evolution of Cosmic Structure
SPICA – Space Infrared Telescope for Cosmology and Astrophysics, formerly HII/L2
SPIRIT – Space Infrared Interferometric Telescope
SWAS – Submillimeter Wave Astronomy Satellite
TPF – Terrestrial Planet Finder
TRL – technology readiness level

Appendix B. *Charting the Winds that Change the Universe, II. The Single Aperture Far Infrared Observatory (SAFIR)*

The original version of this document is available at
http://mips.as.arizona.edu/MIPS/fircase3.pdf
and is sometimes reproduced here for the reader's convenience.

Charting the Winds that Change the Universe, II
The Single Aperture Far Infrared Observatory (*SAFIR*)

Abstract: "***SAFIR*** will study the birth and evolution of stars and planetary systems so young that they are invisible to optical and near-infrared telescopes such as NGST. Not only does the far-infrared radiation penetrate the obscuring dust clouds that surround these systems, but the protoplanetary disks also emit much of their radiation in the far infrared. Furthermore, the dust reprocesses much of the optical emission from the newly forming stars into this wavelength band. Similarly, the obscured central regions of galaxies, which harbor massive black holes and huge bursts of star formation, can be seen and analyzed in the far infrared. ***SAFIR*** will have the sensitivity to see the first dusty galaxies in the universe. For studies of both star-forming regions in our galaxy and dusty galaxies at high redshifts, ***SAFIR*** will be essential in tying together information that NGST will obtain on these systems at shorter wavelengths and that ALMA will obtain at longer wavelengths." – page 110, Astronomy and Astrophysics in the New Millenium, National Research Council, National Academy Press, 2001.

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 until 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. The Milky Way and other galaxies show two broad spectral peaks, one produced directly by stars and thoroughly studied in the visible and the second powered indirectly by young stars and AGNs and comparatively unexplored in the far infrared. The far infrared peak in the cosmic background arises from young stars and AGNs in the early universe. 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.

Accessible advances in technology can produce huge advances in our capabilities for far infrared and submm astronomy. A large, cooled telescope can now be built that both probes the fundamental processes regulating AGN evolution and star formation and opens a huge discovery potential. Consequently, the Astronomy and Astrophysics Survey

Committee recommended ***SAFIR***, a large, space-borne far infrared telescope, as a high priority to be started in this decade (page 10, Astronomy and Astrophysics in the New Millenium, National Research Council, National Academy Press, 2001).

2. *SAFIR* and the Goals of the SEU Theme

2.1 Formation and Evolution of AGNs

It appears that central supermassive black holes are a universal component of galactic bulges. Do the central black holes form first and serve as condensates for galaxies? Or do they built up as galaxies grow and merge? The low lying H_2 lines at 17 and 28.2μm are one of the few conceivable ways to study warm molecular gas condensations prior to the formation of metals, for example molecular gas around primordial massive black holes. A number of processes, such as formation of a small number of stars, can heat molecular clouds above the ~100K threshold for high visibility of these lines. The lines are undetectable together from the ground until $z > 50$ (both must be detected to confirm the identification). ***SAFIR*** will be well suited to searching for them. Line widths and profiles would indicate whether the central mass is highly compact, or if the molecular cloud is just in a mild state of turbulence (as expected if it is self gravitating without a central black hole).

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. "Distinguishing starbursts from supermassive black holes is complicated by the fact that AGNs are often shrouded in dust, so that much of the direct emission is hidden from view. Long wavelengths penetrate the dust more readily, so .. ***SAFIR*** and NGST with an extension into the thermal infrared are .. suitable for separating the two phenomena (page 85, Astronomy and Astrophysics in the New Millenium, National Research Council, National Academy Press, 2001).

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? Do AGNs at high redshift differ in basic properties from nearby ones? Models of the cosmic xray background indicate that the great majority of AGNs at high redshift are heavily absorbed (Gilli et al.; Comastri et al.). Thus, these answers must be sought in the far infrared where optical depths are low (ISM optical depths are similar at 20μm and 6kev and rapidly decrease below the former and above the latter).

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 by an AGN. Figure 2.1, 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.

The full suite of infrared fine structure lines probe a very wide range of excitation energy and, with a large far infrared telescope, could establish the UV spectra of AGNs

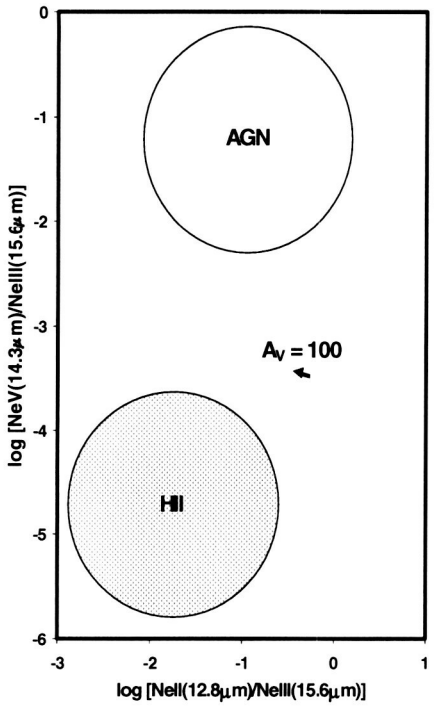
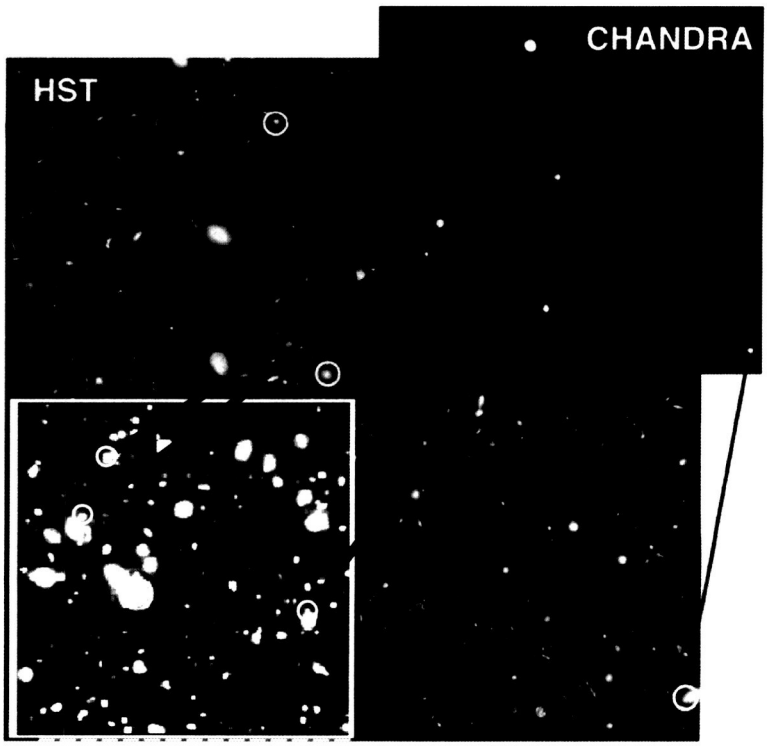


Figure 2.1. Ne V is not excited appreciably by hot stellar spectra, but is produced by the hard UV spectra of AGNs. Hence, the line ratios plotted distinguish the two types of ionizing source unambiguously. The plotted ratios are virtually extinction independent; the short arrow shows the effect of 100 magnitudes of visible extinction on the line ratios. Even this level of extinction has little effect compared with the separation of excitation mechanisms.

over large lookback times, extending work with the Infrared Space Observatory (ISO) on a few nearby Seyfert galaxies. In addition, many of these lines have relatively high critical densities (up to ~ $10^{10}/cm^{-3}$), so they have a unique ability to probe the density of the gas around AGNs.

The angular resolution of ***SAFIR*** is a critical contribution to these studies. Figure 2.2 shows the Hubble Deep Field and the xray sources discovered there in a deep Chandra exposure. A portion of the HDF is degraded to 1" resolution, the beam diameter of a 10-m telescope operating at 50μm. The individual galaxies are adequately isolated for study. To date, no telescope larger than 1 meter in aperture has been used routinely in this spectral region, resulting in extreme source confusion in attempts to isolate individual sources such as faint xray identifications in the HDF.

Figure 2.2. Deep Chandra detections of xray sources in the HDF. In the degraded portion, the resolution has been reduced to the diffraction limit of a 10m telescope operating at 50μm. The individual galaxies, including the xray identifications, are readily



2.2 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?

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 percent 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. N^+ lines at 122 and 205μm also play important roles in cloud cooling. Study of the molecular hydrogen and these emission lines from 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.

The far infrared fine structure lines also control the cooling of molecular clouds in the Milky Way. Understanding this process is a key to advancing our knowledge of how these clouds begin their collapse into stars and planets.

3. *SAFIR* and the Goals of the Origins Theme

3.1 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 along with photometry and spectroscopy using large groundbased telescopes. 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 the visible-near infrared cosmic background (see Figure 3.1). 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 telescope with detection limits of 0.1mJy or less would probably resolve most of this high redshift background into individual galaxies, thus showing the dominant phases of dust embedded star formation and nuclear activity throughout the Universe.

Ultradeep optical images (e.g., Hubble Deep Field) reveal many galaxies too faint to contribute significantly to the submm diffuse background. To complete the study of star formation in the early Universe requires that we extend our understanding to these small systems and possible galaxy fragments. In this luminosity range and over $1 < z \leq 5$, the Atacamba Large Millimeter Array (ALMA) and other groundbased submm telescopes are mostly sensitive to infrared cirrus emission and the output of cold dust that

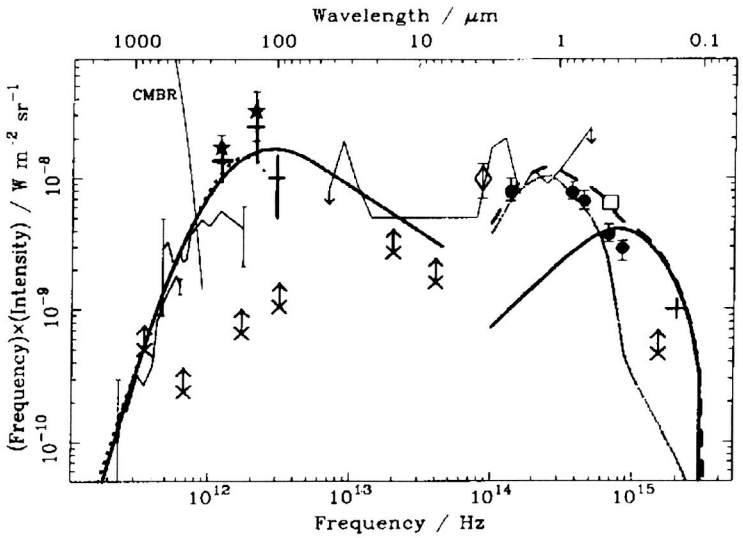


Figure 3.1. Cosmic energy density. Upward pointing arrows indicate counts of point sources, while the heavy lines show the results of large beam measurements and sky brightness models. This plot and subsequent ones are in νF_ν or similar units, so a horizontal line represents constant energy per logarithmic frequency or wavelength interval

are not necessarily heated by recent star formation. The rate of star formation in modest galaxies for $1 < z \leq 5$ can best be determined through high sensitivity imaging from 20 to 200μm. As illustrated in Figure 2.2, the angular resolution of ***SAFIR*** will be adequate; its sensitivity limit of ~10μJy would allow measurements to galaxy luminosities well below 10^{11} $L_\odot$.

3.2 Birth 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. 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 (≤ 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. 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.

The spectrum predicted for a collapsing cloud core is shown in Figure 3.2. 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

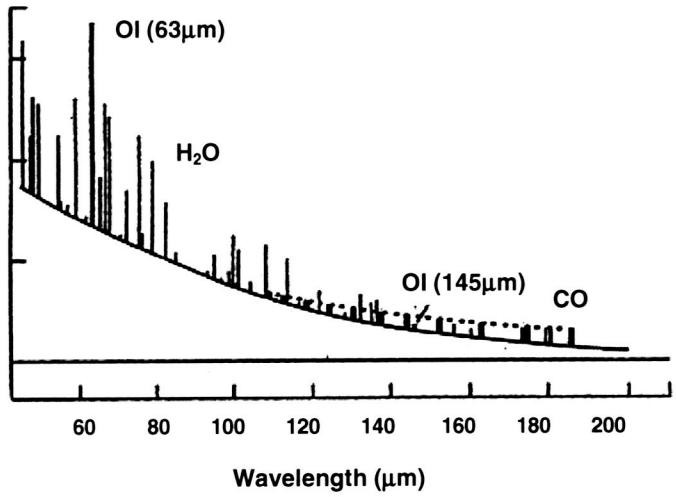


Figure 3.2. Predicted far infrared spectrum of a collapsing cold cloud core, from Ceccarelli, Hollenbach, and Tielens. The spectrum is dominated by OI and complexes of CO and H_2O.

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.

3.3 Evolution of Planetary Systems and the Origin of Life

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 faint reflected light. It has become clear that there is a large population, including objects of large size, rivaling the largest asteroids. KBOs appear to have a broad variety of surface characteristics. To interpret the clues they provide for evolution 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 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.

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 3.3 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.

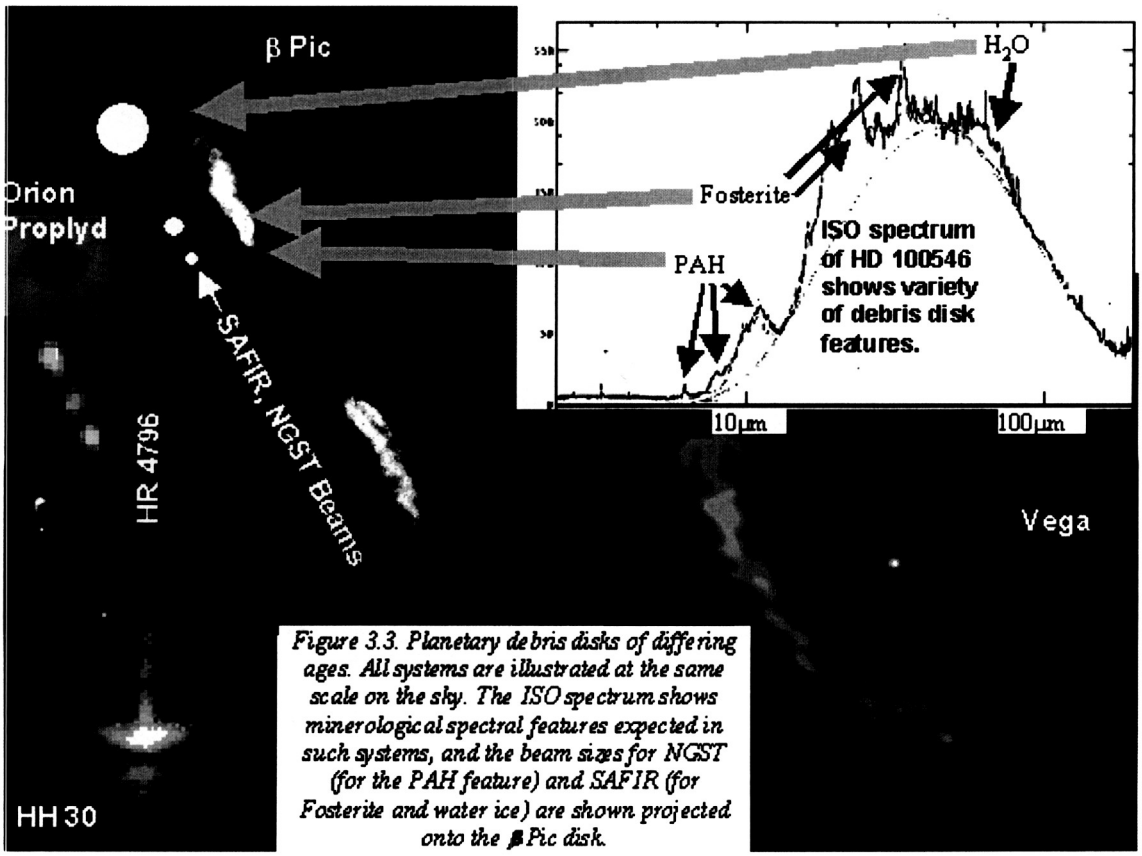


Figure 3.3. Planetary debris disks of differing ages. All systems are illustrated at the same scale on the sky. The ISO spectrum shows minerological spectral features expected in such systems, and the beam sizes for NGST (for the PAH feature) and SAFIR (for Fosterite and water ice) are shown projected onto the β Pic disk.

4. Potential to Discover New Phenomena

Technological advances enable astronomical discoveries. Harwit tried to quantify this relation in "Cosmic Discovery." 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 and the telescopes available to date have been very modest in aperture.

The previous decadal survey developed a parameter to describe the discovery potential of new missions, which they called astronomical capability. This parameter is proportional to the time required to obtain a given number of image elements to a given sensitivity limit. ***SAFIR*** will have astronomical capability exceeding that of past far infrared facilities by a factor of about 10^{10}, and will still offer a gain of about 10^5 after SIRTF and Herschel have flown. A gain of 10^5 is similar to the gain from the initial use of the Hooker 100-Inch Telescope on Mt. Wilson to the Hubble Space Telescope.

5. Mission Development

5.1 Telescope

With the imminent selection of the NGST prime contractor, it is timely to begin mission concept studies for ***SAFIR***. There are two general possibilities, as indicated in Figure 5.1. The development of the NGST telescope may result in approaches that can be readily adapted to the far infrared, with the differing requirements of (1) colder operating temperature; (2) relaxed image quality; and (3) larger aperture (now that NGST has decreased in size to 6m). However, these three important differences may lead to unique architectures for the far infrared telescope. This basic decision must be made as soon as possible to guide further development of the mission. It is also timely to consider international collaborations in the mission concept.

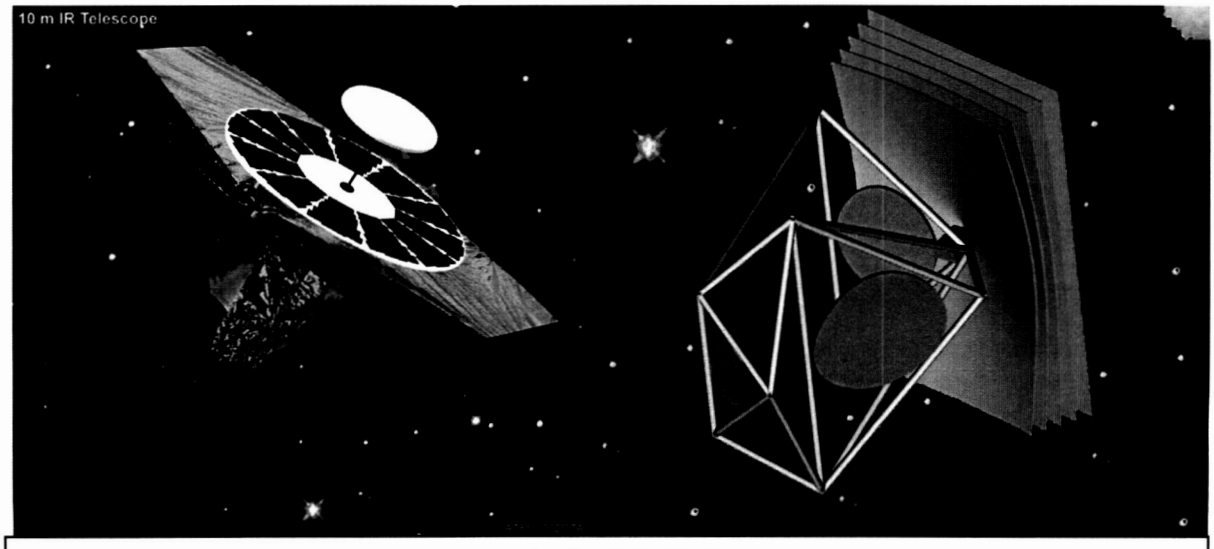


Figure 5.1. Two possible development paths for SAFIR. The figure to the left illustrates the potential for a telescope based on NGST developments, in this case placed at about 4AU to obtain greater radiative cooling (courtesy Ball Aerospace). The figure on the right illustrates that focused developments for the far infrared may also be promising. In this case, the telescope uses a stretched membrane approach that may offer a lower construction cost than NGST-based telescopes (courtesty M. Dragovan).

5.2 Detector Technology

The far infrared and submillimeter ranges have benefited relatively little from investments in detector technology by non-astronomical pursuits. In this regard, they

differ dramatically from the visible, near and mid-infrared, and radio regions. Detectors in many spectral regions closely approach theoretical performance limits. For example, in the visible CCDs have quantum efficiencies greater than 90%, read noises of about two electrons, and formats including many millions of pixels. In the far infrared, the much smaller prior investment has left the possibility for orders of magnitude further progress toward fundamental limits. NASA missions are the best customers for this technology, and an augmented NASA investment will return substantial benefits to ***SAFIR*** and other far infrared and submillimeter astronomy projects.

Figure 5.2 illustrates the three major detector technologies. Each has current strengths and weaknesses. Far infrared photoconductors are the most advanced in array construction, as shown by the space qualified SIRTF array in the figure, and require relatively modest cooling. However, they fall somewhat short of theoretical limits in potential performance and respond only up to the excitation energy. Development should

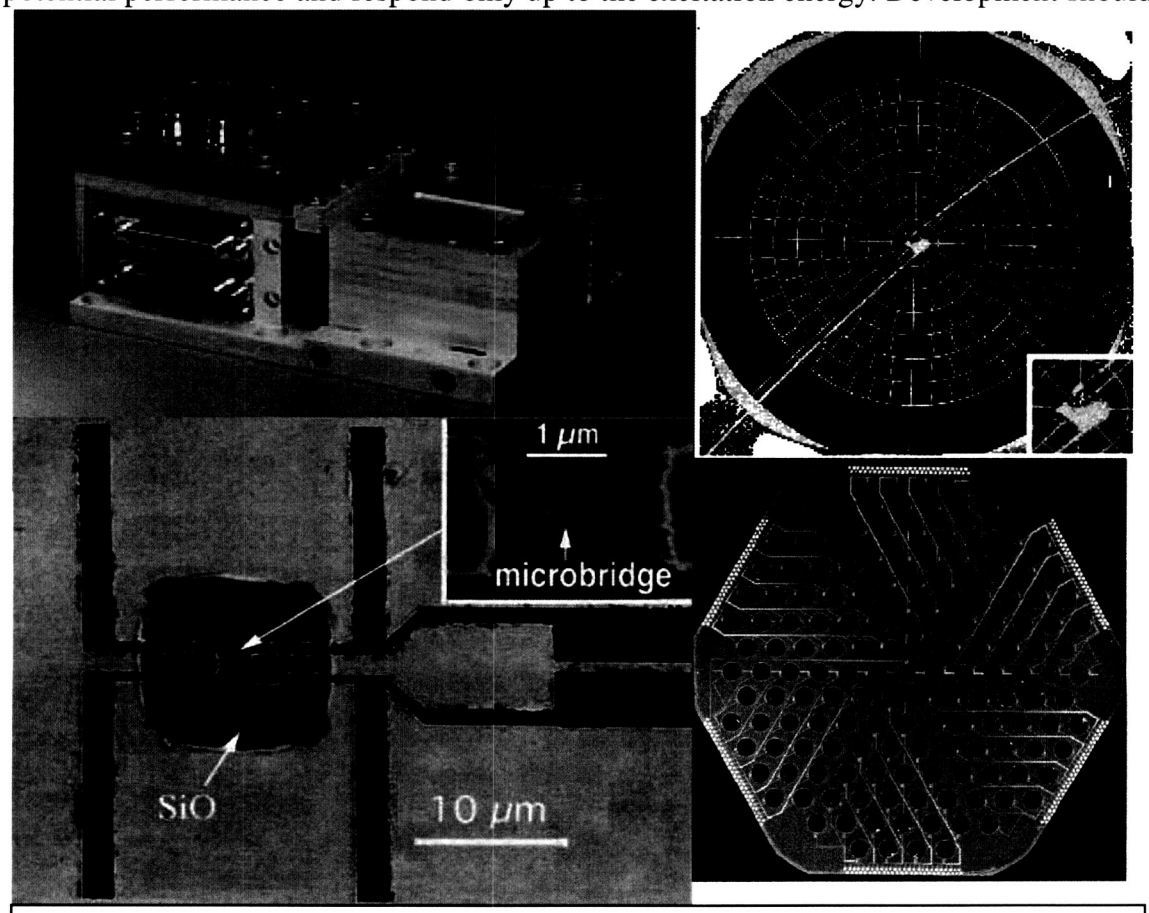


Figure 5.2. Far Infrared and Submillimeter Detector Approaches. Clockwise from upper left: (1) the SIRTF 32x32 Ge:Ga far infrared photoconductor array; (2) a spiderweb bolometer element; (3) an array of spiderweb bolometers; and (4) a hot electron bolometer mixer.

address larger arrays, at least 128x128. Bolometers have broad spectral response and are the most advanced submm continuum detectors. They require extremely low operating temperatures. Development needs to emphasize improved array technology, such as SQUID-based multiplexing. Hot electron bolometer mixers provide the best heterodyne operation above the superconducting gap frequency of Nb, around 600 GHz. They can

have large advantages for spectroscopy over photoconductors and bolometers. Development needs to address reducing noise temperatures and developing support electronics to allow large scale spatial arrays.

5.3 Budget

Goddard Spaceflight Center carried out an estimate of the budget for ***SAFIR*** for the UVOIR panel of the decadal survey. They drew on their experience estimating the cost of NGST, so the comparison of the two missions is also pertinent. Their results are in Table 5.1. They assumed that no additional development would be required beyond that for NGST, although the report indicated that this was probably not entirely correct. We should probably allow for a significant development program, perhaps even departing significantly from the NGST telescope architecture. In the spirit of the above estimate, we take this program to be half that for NGST, or an additional $125M, for a total cost of $620M. For comparison, the estimate of the UVOIR panel for NGST is $1114M.

Construction (assumes an ESA instrument)	$310M	
Launch (using a new mid-sized EELV)	$85M	
Science and Mission Operations (5 yrs)	$100M	
Total		**$495M**

Table 5.1. Cost estimate for SAFIR from the decadal UVOIR panel report.

The decadal survey committee also recommended a budget over the decade for the technology development that would support ***SAFIR*** and other projects in the far infrared and submillimeter, as shown in Table 5.2.

Increment in budget for far infrared detector arrays	$10M
Very low temperature refrigerators for space environments	$50M
Large, lightweight optics	$80M

Table 5.2. Technology investments for SAFIR and other far infrared/submillimeter projects.

6. Summary

SAFIR can contribute substantially to both the Structure and Evolution of the Universe and the Origins themes of NASA space science, through realizable technology developments of a moderate scale. "***SAFIR***...will study the relatively unexplored region of the spectrum between 30 and 300μm. It will investigate the earliest stage of star formation and galaxy formation by revealing regions too shrouded by dust to be studied by NGST, and too warm to be studied effectively with ALMA.... It will be more than 100 times as sensitive as SIRTF or the European [Herschel] mission....To take the next step in exploring this important part of the spectrum, the committee recommends ***SAFIR***. The combination of its size, low temperature, and detector capability makes its astronomical capability about 100,000 times that of other missions and gives it tremendous potential to uncover new phenomena in the universe." – pages 39, 110 Astronomy and Astrophysics in the New Millenium, National Research Council, National Academy Press, 2001.

Appendix C. *Probing the Invisible Universe: The Case for Far-IR/Submillimeter Interferometry*

This document is available at http://xxx.lanl.gov/abs/astro-ph/0202085 and is sometimes reproduced here for the reader's convenience.

Probing the Invisible Universe: The Case for Far-IR/Submillimeter Interferometry

D. Leisawitz, T. Armstrong, D. Benford, A. Blain, K. Borne W. Danchi, N. Evans, J. Gardner, D. Gezari, M. Harwit, A. Kashlinsky, W. Langer, C. Lawrence, P. Lawson, D. Lester, J. Mather, S. H. Moseley, L. Mundy, G. Rieke, S. Rinehart, M. Shao, R. Silverberg, D. Spergel, J. Staguhn, M. Swain, W. Traub, S. Unwin, E. Wright, and H. Yorke

Abstract

The question "How did we get here and what will the future bring?" captures the human imagination and the attention of the National Academy of Science's Astronomy and Astrophysics Survey Commitee (AASC). Fulfillment of this "fundamental goal" requires astronomers to have sensitive, high angular and spectral resolution observations in the far-infrared/submillimeter (far-IR/sub-mm) spectral region. With half the luminosity of the universe and vital information about galaxy, star and planet formation, observations in this spectral region require capabilities similar to those currently available or planned at shorter wavelengths. In this paper we summarize the scientific motivation, some mission concepts and technology requirements for far-IR/sub-mm space interferometers that can be developed in the 2010-2020 timeframe.

1. Science goals

The Decade Report posed a number of "theory challenges," two of the most compelling of which are that astrophysicists should strive to: (a) *develop an "integrated theory of the formation and evolution of [cosmic] structure";* and (b) *"develop models of star and planet formation, concentrating on the long-term dynamical co-evolution of disks, infalling interstellar material, and outflowing winds and jets."* (Decade Report, p. 106)

Rieke et al. (2002; hereafter the "SAFIR white paper") explain the vital role that will be played by future far-IR/sub-mm observations in confronting these challenges and the need for a 10-m class Single Aperture Far Infrared Observatory (SAFIR). SAFIR will represent a factor 10^5 gain in astronomical capability relative to the next-generation missions SIRTF and Herschel, yet it will have the visual acuity of Galileo's telescope. An additional hundred-fold increase in angular resolution can be achieved with interferometry after SAFIR and within the NASA Roadmap time horizon. In this section we explore the science potential of sub-arcsecond resolution in the far-IR/sub-mm, picking up where the SAFIR white paper leaves off. In particular, we don't bother to explain why the far-IR spectrum (line and continuum radiation) is rich in information content, as doing so would only restate facts already eloquently presented in the SAFIR white paper.

1.1 The heritage and destiny of cosmic structure

After we locate in space and time the first generations of stars, galactic bulges, galactic disks, and galaxy clusters, we will want to relate these early structures to the "seeds" of structure seen in the cosmic microwave background fluctuations and learn how they formed. We will need measurements that show us how the cosmic structures changed over time to the present day. We will want to lift the veil of dust that conceals galactic nuclei, including our own, from view at visible wavelengths. How did the Milky Way form, and why is there a black hole at its center? What happens to the interstellar medium when galaxies collide, and how does a starburst work?

Did bulges form first and disks form later, or did disks merge to form bulges? What accounts for the diversity of galaxy types? How might the universe and its constituents look when it is twice or ten times its current age?

It will take a telescope much bigger than 10 m to see structure in galaxies at redshift z ~ 1 or greater in the far-IR/sub-mm. These objects subtend angles of ~1 arcsec. SAFIR will measure far-IR spectra of huge numbers of high-z galaxies, and they will be analyzed statistically and with the aid of models and complementary NGST and ALMA observations. However, to study the astrophysics of distant galaxies it will be important to resolve them in the far-IR/sub-mm, where they emit half or more of their light (Trentham et al. 1999). As noted by Adelberger & Steidel (2000), high-z galaxies "are undeniably dusty.... Large corrections for dust extinction will be necessary in the interpretation of UV-selected surveys, and only IR observations can show whether the currently adopted corrections are valid or suggest alternatives if they are not." The far-IR spectrum tells us the amount of dust present, but says little about how the dust is distributed. The dust distribution, which will be seen directly when the galaxies are resolved in the far-IR/sub-mm, strongly influences the extinction (Calzetti 2001). The galaxy assembly process could be studied via high spatial resolution spectral line maps. For example, a C^+ 158 μm line map at $\lambda/\Delta\lambda \sim 10^4$ would provide vital information about the gas dynamics in merging and interacting systems and reveal the rotation speeds and velocity dispersions within and among galaxies and protogalaxy fragments.

M31 in the visible.

ISO map of M31.
(wavelength of 175 microns)
North is up, east is left.

Figure 1. A far-IR/sub-mm interferometer that provides HST-class resolution would resolve as much detail in a galaxy at z = 10 as ISO did in M31. These images illustrate that it is impossible to deduce the far-IR appearance of a galaxy from an optical image. The far-IR image reveals the sites of star formation and the reservoir of interstellar matter available for new star formation (Haas et al. 1998).

As noted in the SAFIR white paper, far-IR continuum and line emissions are excellent indicators of the star formation rate and the physical conditions in star forming molecular clouds. At 10 Mpc, the distance of a nearby galaxy, a giant H II region subtends about 1 arcsec, and the typical spacing between neighboring regions is about 10 arcsec. SAFIR could be used to study individual sites of star formation spectroscopically. Later, with HST-class resolution, we could make similarly detailed observations of objects at much greater distances to learn how star formation works in protogalaxies and systems having very low heavy element abundance. With the same resolution we could study star forming regions in Virgo cluster galaxies at the linear scales sampled by past IR missions (IRAS and ISO) in the Milky Way. This would help us to understand the chemical and energetic effects of star formation on the interstellar and intergalactic medium and better interpret measurements of the high-z universe.

"The central regions of galaxies were likely heavily dust enshrouded during their formation epoch. Future far-IR observations can provide a window into this formation process and help determine the relationship between bulge formation and black hole formation." (Spergel, 2001) Black hole masses could be routinely measured with high spatial resolution spectral line mapping in the far-IR/sub-mm. High angular resolution submillimeter timing observations of the black hole at the Galactic center have the potential to enable a measurement of its spin (Melia et

al. 2001). Such a measurement could substantially advance our understanding of the role played by supermassive black holes in galaxy formation and evolution (Elvis et al. 2002), and could yield new insight into fundamental physics, perhaps with cosmological implications.

Figure 2. Multiple optical emission line sources were seen near the central active nucleus of Circinus with HST (Wilson et al. 2000). These sources would lie within a single SAFIR beam (circle). A far-IR/sub-mm interferometer could produce high-resolution images and spectral line maps and provide valuable information about the physical conditions, gas dynamics, and star formation in Active Galactic Nuclei, unequivocally testing AGN emission and orientation hypotheses.

High resolution is important for another, subtler reason. At wavelengths $\lambda > 200$ μm, the sensitivity of SAFIR will be confusion limited to ~10 μJy (Blain 2000); at these long wavelengths it could detect starburst galaxies out to $z > 5$, but L_* galaxies only out to $z \sim 2$. However, an observatory with only three times better angular resolution than SAFIR would have a significantly lower confusion limit and could detect even a galaxy like the Milky Way out to $z \sim 10$. At far-IR/sub-mm wavelengths galaxies do not decrease in brightness with increasing redshift as $(1+z)^{-2}$, as one might expect, because an increasing portion of the emission is shifting *into* the observed wavelength band. At sub-mm wavelengths this so-called "negative K correction" compensates cosmological dimming out to $z \sim 10$. While a single aperture telescope larger than SAFIR may be possible, a factor of three seems very challenging. However, the nature of the far-IR sources is such that adequate sensitivity can be achieved with smaller apertures, and hence the spatial resolution can better be provided with interferometry. Thus, by beating confusion, far-IR/sub-mm interferometers could follow up on *all* the galaxies and proto-galaxies seen by HST, NGST, and ALMA. An important observational goal is to sample a representative volume of the high-z universe in the far-IR/sub-mm with HST-class angular resolution and spectral resolution sufficient to resolve the velocity structure in distant objects.

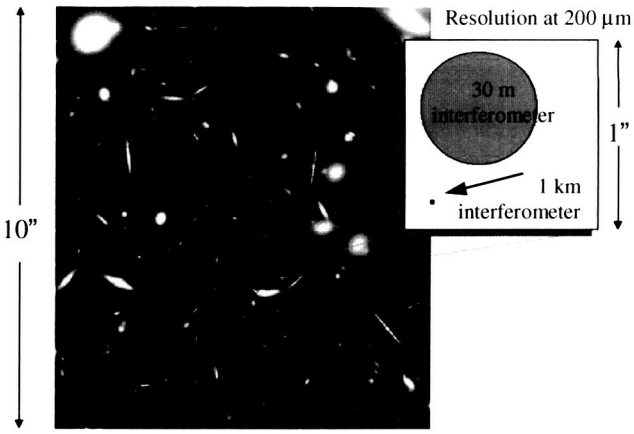


Figure 3. A far-IR/sub-mm interferometer with 10^{-20} W/m^2 sensitivity (equivalent bolometric magnitude 31.2) would slice through the Milky Way and between nearby galaxies to image galaxies and protogalactic objects out to $z \sim 10$. (Credit: A. Benson near-IR simulation for NGST)

It would be a great scientific achievement to image the pristine molecular hydrogen that must have allowed primordial gas clouds to cool, collapse, and give birth to the first generation of stars, before any heavier elements existed (Haiman et al. 1996). The most likely signature is a pair of H_2 cooling lines (rest wavelengths 17 and 28 μm) redshifted to $z > 10$ (Abel et al. 2002). SAFIR could detect this emission if it arises at $z < 10$, but its discovery may have to await a far-

IR/sub-mm interferometer if it comes from higher redshifts and is concentrated in discrete objects. An interferometer would resolve out confusing background emission and could have sufficient sensitivity to make the measurement.

1.2 The formation of small structures: stars, planets, and their inhabitants

How did the solar system and the Earth form? What are the various possible outcomes of the star and planet formation process, and how does the process work? How are the initial conditions in protostellar disks reflected in the properties of planetary systems? What chemical processes occur during star and planet formation?

Star and planet formation are parts of a single process that involves the movement of matter from envelopes extended over about 10,000 AU to disks on scales of 1 - 100 AU, and ultimately into stars and planets on much smaller scales (Evans 2001). The nearest protostellar objects are at 140 pc, where 1 AU subtends an angle of 7 mas. Future astrophysicists will need high spatial and spectral resolution measurements that reveal the bulk flows of material and the physical conditions (density, temperature, magnetic field strength, and chemical abundances) in dense molecular cores, protostars, protoplanetary systems, and debris disks (Evans 1999). The SAFIR white paper explains the essential need for far-IR continuum and spectral line measurements of these systems and the capability of SAFIR to resolve protostars down to the 100 AU scale.

With a far-IR/sub-mm interferometer we will be able to probe much smaller physical scales, particularly the scales relevant to studies of planet formation. Far-IR interferometric studies of circumstellar disks will reveal dust concentrations that represent the early stages of planet formation, and measurements of exozodiacal debris disks will show gaps and structures produced by resonances with already-existing planets (Ozernoy et al. 2000). By observing planetary systems in a wide range of evolutionary states and following individual systems over a period of years we could learn how protostellar material migrates and coalesces to form planets. Observations such as these would almost surely revolutionize our understanding of how the solar system formed. The rich far-IR line spectrum would be exploited to "follow the evolution of chemical abundances and locate reservoirs of biogenic materials" (Evans 2001). We will want to understand chemical evolution from molecular cores to planets in a unified way. The spectra of gas giant planets, which emit most of their light in the far-IR, could be measured with an interferometer.

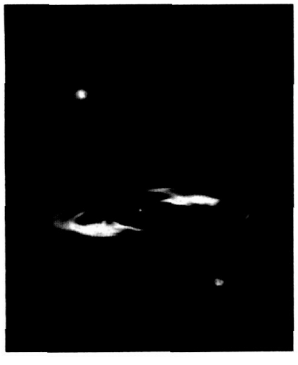


Figure 4. This artist's concept of the Vega debris disk illustrates the resonance features that could be studied with far-IR/sub-mm interferometers. At Vega's distance 1 AU subtends an angle of 128 mas. Studies of the structure of protoplanetary and debris disks will go a long way toward advancing our understanding of planet formation. (Credit: D. Wilner, M. Holman, P. Ho, and M. Kuchner; CfA Press release http://cfa-www.harvard.edu/newtop/previous/011802.html).

The next generation of far-IR and submillimeter observatories – SIRTF, SOFIA, and Herschel – will be very sensitive, but will have insufficient spatial resolution to achieve the observational goals outlined above. The key to making further progress will be to increase angular resolution

by many orders of magnitude without sacrificing sensitivity or spectral resolution. About a decade from now ALMA will provide unprecedented spatial and spectral resolution at millimeter and submillimeter wavelengths, far out on the Rayleigh-Jeans tail, and probe regions with very high dust column densities. SAFIR will look where protostars are most luminous, in the far-IR, image them at ~100 AU scales for the first time, and chart the velocity structure to provide definitive evidence of envelope collapse. An additional factor of 10 - 100x improvement in spatial resolution will be needed to image protoplanetary and planetary debris disk structure in the spectral region where these objects emit the bulk of their energy.

2. Desired measurement capabilities

Table 1 summarizes the measurement capabilities needed to achieve the science goals outlined in sections 1.1 and 1.2 and shows that the desired capabilities are similar for the two applications. Table 2 summarizes the capabilities of the next-generation observatories NGST, SAFIR, and ALMA. SAFIR will pry open the door to the "invisible" far-IR universe and leave the astrophysics community desiring the next critical capability: better angular resolution. As can be seen by comparing the SAFIR column of Table 2 with Table 1 an improvement by two orders of magnitude in angular resolution is desired.

Table 1. Desired Measurement Capabilities for the Mid-IR to Millimeter Spectral Range

Science goal	Formation and evolution of cosmic structure	Formation of stars and planetary systems
Sample targets	Hubble Deep Fields, gravitational lens sources, interacting galaxies	Nearest protostars, Orion prolyds, Vega, HH 30, and other disks
Wavelength range (peak emission) (μm)	40 – 1000	30 – 300
Angular resolution (mas)	20	10
Spectral resolution ($\lambda/\Delta\lambda$)	$>10^4$	3×10^5
Point source sensitivity, νS_ν (W/m^2)	10^{-20}	10^{-20}
Field of view (arcmin)	4	4

Table 2. Measurement Capabilities of Next-Generation Observatories

Observatory	NGST	SAFIR (10 m)	ALMA
Wavelength range (μm)	0.6 – 30	30 – 300	850 –10,000 plus windows at 350, 450
Angular resolution (mas)	50 at 2 μm	2500 at 100 μm	10 at 1 mm
Spectral resolution ($\lambda/\Delta\lambda$)	10^3	10^6	$>10^6$
Point source sensitivity, νS_ν (W/m^2)	$10^{-21} - 10^{-20}$	10^{-20}	10^{-19} at 1 mm
Field of view (arcmin)	4	4	0.3 at 1 mm, bigger field with mosaicing

3. Mission concepts

How will we satisfy the inevitable desire for detailed far-IR/sub-mm views of the high-redshift universe and protoplanetary disks? An interferometer with total aperture comparable to that of SAFIR (78 m^2) would have the desired sensitivity *and* could provide the desired angular resolution (Table 1). The resolution of an interferometer with maximum baseline b_{max} is $\Delta\theta = 10$ mas (λ/100 μm)(b_{max}/1 km)$^{-1}$. Thus, a 1 km maximum baseline is needed to provide the angular

resolution ultimately desired in the far-IR/sub-mm. To obtain excellent image quality all spatial frequencies would have to be sampled in two dimensions; in other words, measurements would have to be made on many baselines $b < b_{max}$, and at many baseline position angles. This so-called "u-v plane" filling is accomplished with ground-based interferometers by deploying many apertures, allowing for array reconfiguration, and relying on Earth rotation. In space there is more freedom to move apertures to desired locations, so one can tailor the u-v coverage to the problem at hand. There is a substantial cost advantage to limiting the number of apertures, particularly because to achieve background-limited performance and the desired sensitivity, the mirrors would have to be very cold (~5 K). However, in space, where there is no atmosphere to distort the wavefront, 2 or 3 apertures would suffice. The preferred location for the interferometer is the Sun-Earth L2 point, as it is distant enough to help with cooling and pointing, yet near enough to handle a large data rate.

A Michelson interferometer, in which parallel beams are combined using a half-silvered mirror or the equivalent, offers several advantages. First, a relatively modest number of detectors would be required. In a conventional Michelson interferometer a single-pixel detector is needed for each baseline, or two such detectors can be used because there are two "output ports." Detector arrays would provide a multiplex advantage that could be used either to widen the field of view or improve signal-to-noise by spectrally dispersing. The field of view could be as large as 5 arcmin $(N_{pix}/100)$ $(\lambda/100\ \mu m)$ $(d/4\ m)^{-1}$, where d is the diameter of the individual aperture mirrors and N_{pix} is the pixel count in one array dimension. A 100 x 100 pixel array would provide the desired field size. Second, a Michelson interferometer can be operated in "double Fourier" mode (Mariotti & Ridgway 1988), so it naturally provides high spectral as well as high spatial resolution. The spectral resolution $R = 10^4\ (2\Delta/1\ m)\ (\lambda/100\ \mu m)^{-1}$, where Δ is the length of the delay line stroke (i.e., 2Δ is the optical delay), so a 0.5 m stroke would yield the desired spectral resolution in every spatial resolution element. A small additional optical delay would be needed to compensate for geometric delay associated with the off-axis angles in the wide field.

Mather et al. (1999) first suggested the possibility of a 1 km maximum baseline far-IR/sub-mm imaging and spectral interferometer space mission called SPECS (Submillimeter Probe of the Evolution of Cosmic Structure). The concept and a technology roadmap were further developed with science and engineering expertise provided through the February 1999 community workshop on "Submillimeter Space Astronomy in the Next Millennium" (http://space.gsfc.nasa.gov/astro/smm_workshop/). The concept of a science and technology pathfinder mission called SPIRIT (Space IR Interferometric Telescope) originated at the workshop. SPIRIT is much like SPECS, except that the interferometer would be built on a boom and have $b_{max} \sim 30$ m ($\Delta\theta \sim 0.34$ arcsec at 100 μm). SPECS, like the original concept for TPF, would use formation flying to maneuver the interferometer apertures. For more information on the SPIRIT and SPECS concepts see Leisawitz et al. (2000).

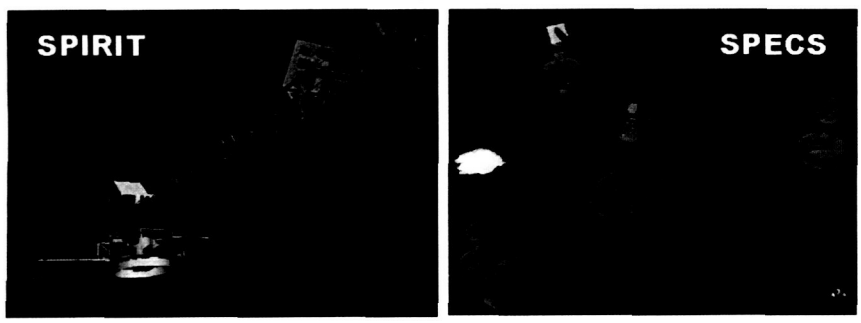


Figure 5. SPIRIT, a scientific and technology pathfinder for SPECS, could achieve the spatial resolution of a 60 m filled aperture telescope on a 30 m boom.

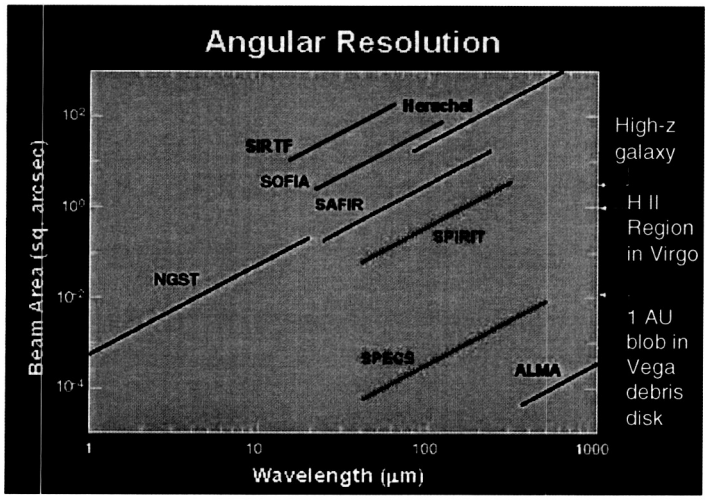


Figure 6. After SAFIR an additional hundred-fold improvement in angular resolution will be needed to achieve the science goals outlined in section 1 and attain resolution comparable to that of NGST and ALMA in the spectral regions that bracket the far-IR/sub-mm. The resolution gain could be accomplished in two steps, first with the pathfinder mission SPIRIT, and then with SPECS. N.B. A protoplanetary disk at 140 pc is about the same size as an H II region in the Virgo cluster.

4. Enabling technologies

"The [Radio and Submillimeter Wave Astronomy] panel supports the recommendation of the Panel on Ultraviolet, Optical, and Infrared Astronomy from Space that NASA pursue technology development leading toward a far-infrared/submillimeter interferometer in space." – Decade Report, Panel Reports, p. 170.

New technology will be needed in four areas: 1) detectors, 2) cooling, 3) optics and interferometry, and 4) large structures and formation flying. In this section we summarize the requirements in each area and cite possible solutions, then we conclude with a brief discussion of technology validation on space missions due to launch in the coming decade. More information on the enabling technologies for far-IR/sub-mm interferometry is given by Shao et al. (2000).

4.1 Detectors

The detector goal is to provide noise equivalent power less than 10^{-20} W $Hz^{-1/2}$ over the 40 – 850 μm wavelength range in a 100 x 100 pixel detector array, with low-power dissipation array readout electronics. This low noise level is a prerequisite for background-limited telescope performance. The ideal detector would count individual photons and provide some energy discrimination, which would enable more sensitive measurements. Among the encouraging recent developments in detector technology are superconducting transition edge sensor (TES) bolometers (Benford et al. 2002), SQUID multiplexers for array readout (Chervenak et al. 1999), and single quasi-particle counters built out of antenna-coupled superconducting tunnel junctions and Rf-single electron transistors (Schoelkopf et al. 1999).

4.2 Cooling

The cooling requirements for space-based far-IR/sub-mm interferometry are similar to those for a large single-aperture telescope like SAFIR. To take full advantage of the space environment, the mirrors will have to be very cold (~5 K) and the detectors even colder (<0.1 K). Active coolers will have to operate continuously and not cause significant vibrations of the optical

components. The coolers should be light in weight. Cooling power will have to be distributed over large mirror surfaces. Thermal transport devices will likely have to be flexible and deployable. Large, deployable sunshades will be needed, and they will have to provide protection without seriously compromising sky visibility. Since several stages of cooling must be used to reach the required temperatures, the devices that operate in each temperature range must be able to interface with each other both mechanically and thermally. The Astro E-2 mission will use a three-stage cooling system for its X-ray microcalorimeters, which operate at 65 mK (Breon et al. 1999; Shirron et al. 2000), and important advances in cooler technology will be made for NGST. Cryogenic capillary pumped loops, which have already been tested in space, have the potential to distribute cooling power over long distances (Bugby et al. 1998).

4.3 Optics and Interferometry

The mirrors needed for far-IR/sub-mm space interferometry are similar to those needed for SAFIR, only smaller. The mirrors must: (a) be light in weight (1 – 3 kg m^{-2}), (b) have a surface roughness not exceeding ~0.5 μm rms, (c) be able to be cooled to <10 K, and (d) maintain their shape to a small fraction of a wavelength when subjected to cooling or mechanical stress. Flat mirrors, perhaps stretched membranes (Dragovan 2000), could be used for the light collecting elements of the interferometer. The additional requirements for interferometry are beamsplitters that can operate at ~4 K and over the far-IR/sub-mm wavelength range, and long-stroke cryogenic delay lines. For a 5-year SPIRIT mission the delay line would have to be able to stroke (full amplitude) at ~10^{-2} Hz and survive at least 10^6 cycles; for SPECS the ideal delay line would move 100x faster and survive a proportionately greater number of cycles. (These numbers are based on the assumption that the mirror movement is fast enough to completely sample the synthetic aperture plane in the time required to build up the typical desired sensitivity.) The delay line would have to impart minimal disturbance on the metering structure. Finally, mosaicing techniques and algorithms for wide-field interferometry will have to be developed. Research on cryogenic delay lines and beam combiners (Swain et al. 2001; Lawson et al. 2002) and wide-field imaging interferometry (Leisawitz et al. 2002; Rinehart et al. 2002) is now underway.

4.4 Large Structures and Formation Flying

A variety of architectures are possible for SPIRIT, but all of them depend on the availability of a lightweight, deployable truss structure measuring at least 30 m in length when fully expanded. Any parts of the truss that will be seen by or in thermal contact with the mirrors must be cryogenic. One possible design requires the deployed structure to be controllable in length. Another requires tracks and a mirror moving mechanism. A third design solution uses a series of mirrors along the structure to provide non-redundant baseline coverage. In all cases the boom would spin to sample different baseline orientations. Any repeating mirror movements will have to be smooth and rely on a mechanism that is robust enough to survive at least 10,000 cycles. Structures designed to meet the challenges of space-based optical interferometry have been under study for a long time for SIM (Laskin & San Martin 1989), which has far more demanding control and metrology requirements than those of SPIRIT because SIM will operate at much shorter wavelengths.

Free-flying spacecraft will be needed to accomplish imaging interferometry with maximum baseline lengths in the 1 km range. The requirement is to sample the u-v plane completely, yet avoid the need for an unaffordable amount of propellant for formation flying. It may be necessary to combine tethers with formation flying to form a long-baseline observatory that maintains symmetry while rotating. The system will have to be deployable, stable, and capable of being pointed at a variety of targets. A modeling effort is now underway, and early results suggest that tethered formation flying is feasible (Farley & Quinn 2001).

4.5 Technology Validation

> *"SAFIR, the [UVOIR from Space] panel's top-priority moderate-size mission, ... will enable a distributed array in the decade 2010 to 2020...The single most important requirement is improved angular resolution. The logical build path is to develop a large, single-element (8-m class) telescope leveraging NGST technology on time scales set by NGST's pace of development. A later generation of interferometric arrays of far-infrared telecopes could then be leveraged on SIM or TPF technologies ...."* – Decade Report, Panel Reports, p. 329.

Table 3 shows that there could be a rich heritage in space-validated technologies for far-IR/sub-mm interferometry by the beginning of the next decade. Ground-based laboratory or field research and testbed experiments are already underway, and more such research will be proposed to advance the technology readiness of components (e.g., detectors and array readout devices), systems (e.g., cryogenic delay line), or techniques (e.g., wide-field imaging interferometry) this decade.

Table 3. Technology Heritage for Long-baseline Far-IR/Sub-mm Interferometry [a]

Technology	SIRTF 2002	SOFIA 2004	Astro-E2 2005	StarLight 2006	NGST 2009	SIM 2009	SPIRIT 2010	ST-? [b] ~2010	SAFIR 2012
Detectors	X	*					**		**
Coolers	X		*		*		**		**
Optics & Interferometry	X			* **	*	*	**		**
Large structures & Formation Flying				**	*	*	X	**	X

NOTE: X denotes mission contributing to technology development; * denotes mission critical to success of SPIRIT (similar to technology inheritance for SAFIR); ** denotes mission critical to success of SPECS

[a] TPF will contribute substantially to the technology heritage if an interferometric solution is selected from among several concepts under consideration

[b] A hypothetical New Millennium Mission designed to validate tethered formation flying

5. Recommendations

> *"A rational coordinated program for space optical and infrared astronomy would build on the experience gained with NGST to construct SAFIR, and then ultimately, in the decade 2010 to 2020, build on the SAFIR, TPF, and SIM experience to assemble a space-based, far-infrared interferometer."* – Decade Report, p. 110.

A coordinated, intensive technology program this decade is the key to success on this timescale. The critical technology areas outlined in section 4 – detectors, cooling systems and components, large optics, interferometric techniques, cryogenic delay lines, deployable structures, and formation flying – deserve particular attention. Much of this investment will apply to SAFIR as well as far-IR/sub-mm interferometry.

A study program for far-IR/sub-mm space astronomy should be initiated as soon as possible. To ensure that the technology funds will be wisely invested it is essential to take a system-level look at the scientific, technical, and design tradeoffs. SAFIR and far-IR/sub-mm interferometry concepts could be studied together to ensure that each mission takes the best advantage of its architecture type, and to explore the possibility that overall cost savings could accrue through, for example, reuse of test facilities, hardware, design solutions, and coordinated technology validation. The study might identify presently unplanned but necessary technology demonstration experiments.

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Acronyms

ALMA – Atacama Large Millimeter Array
HST – Hubble Space Telescope
NGST – Next Generation Space Telescope
ISO – Infrared Space Observatory
SAFIR – Single Aperture Far-IR Telescope
SIM – Space Interferometry Mission
SIRTF – Space Infrared Telescope Facility
SOFIA – Stratospheric Observatory for IR Astronomy
SPECS – Submillimeter Probe of the Evolution of Cosmic Structure
SPIRIT – Space Infrared Interferometric Telescope
TPF – Terrestrial Planet Finder