SPECS: The Kilometer-baseline Far-IR Interferometer in NASA's Space Science Roadmap

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ABSTRACT

Ultimately, after the Single Aperture Far-IR (SAFIR) telescope, astrophysicists will need a far-IR observatory that provides angular resolution comparable to that of the Hubble Space Telescope. At such resolution galaxies at high redshift, protostars, and nascent planetary systems will be resolved, and theoretical models for galaxy, star, and planet formation and evolution can be subjected to important observational tests. This paper updates information provided in a 2000 SPIE paper on the scientific motivation and design concepts for interferometric missions SPIRIT (the Space Infrared Interferometric Telescope) and SPECS (the Submillimeter Probe of the Evolution of Cosmic Structure). SPECS is a kilometer baseline far-IR/submillimeter imaging and spectral interferometer that depends on formation flying, and SPIRIT is a highly-capable pathfinder interferometer on a boom with a maximum baseline in the 30 – 50 m range. We describe recent community planning activities, remind readers of the scientific rationale for space-based far-infrared imaging interferometry, present updated design concepts for the SPIRIT and SPECS missions, and describe the main issues currently under study. The engineering and technology requirements for SPIRIT and SPECS, additional design details, recent technology developments, and technology roadmaps are given in a companion paper in the Proceedings of the conference on New Frontiers in Stellar Interferometry.

Keywords: infrared, submillimeter, interferometry, detectors, formation flying, cryogenic optics

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1. INTRODUCTION

Information vital to our understanding of the processes of galaxy, star, and planet formation lurks in the far-infrared and submillimeter spectral region, concealed not by interstellar dust, an affliction with which UV/optical astronomers must contend, but by a lack of angular resolution and sensitivity, a penetrable barrier which can be broken by space-based interferometers in the next couple of decades. In a single-aperture telescope of diameter d, the angular resolution ($1.22\lambda/d$) and the sensitivity (proportional to d^2) are coupled through a common dependence on telescope size. Even the faintest astronomical sources of interest – protogalaxies, low-mass protostars, and planetary debris disks – are detectable with cryogenically cooled telescopes having total light collecting areas in the tens of square meters. If this collecting area were provided in a single-aperture telescope, d would be about 10 m and $1.22\lambda/d$ would be about 2.5 arcsec at 100 μm. Unfortunately, protogalaxies, the nearest star forming regions, and all but a small handful of debris disks subtend sub-arcsecond angles in the sky. To build a single-aperture telescope large enough to resolve these objects, if not impossible, would be wasteful if there were another way to obtain the angular resolution without sacrificing sensitivity.

There is another way. An imaging interferometer provides angular resolution $\lambda/2b_{max}$, where b_{max} is the longest baseline length sampled, and, to a first approximation, its sensitivity is determined by the total light collecting area. In other words, the sensitivity and the resolution are decoupled. One can imagine (hypothetically) carving up a 10 m mirror into two or more pieces, providing the capability to move those pieces around within a circular area whose diameter is b_{max}, and the capability to combine the light they collect interferometrically. Such an instrument would do the trick.

Michelson did this nearly a century ago, and remarkably his “stellar interferometer” operated at visible wavelengths, where metrology and control must have been difficult, and through the Earth’s atmosphere, which introduced noise into his measurements. Nevertheless, Michelson and Pease[1] succeeded in measuring the diameters of stars with this technique. Surely, today, with a little bit of work, we could build an interferometer that operates at wavelengths 1000 times longer and does not have to deal with atmospheric wavefront distortions.

Indeed, there are technical challenges inherent in space-based far-infrared interferometry. Most of the challenges are common to other past, current, and next-generation infrared space telescopes, such as the need for sensitive detector arrays and cryogenic optics. As we shall discuss, other needs are common to space interferometry missions in more advanced stages of development, and one technology – tethered formation flying – is uniquely needed for SPECS. SPIRIT, a very highly capable interferometer, could be built with technology that is nearing maturation today.

This paper and its companion[2] in the SPIE Proceedings from the conference on *New Frontiers in Stellar Interferometry* update information about SPIRIT and SPECS originally provided in SPIE papers by Leisawitz et al.[3] and Shao et al.[4] As discussed previously, SPIRIT and SPECS are “double Fourier” interferometers.[5] That is, beam combination occurs in the pupil plane and a scanning optical delay line produces temporal fringe modulation, which is recorded on a detector onto which the combined light is focused. The Fourier transform of the resulting interferogram is the spectrum of the source, or “scene,” as spatially filtered by the interferometric baseline. Over time, many baselines are sampled (i.e., the *u-v* plane is filled or partially filled) and a new interferogram is collected for each baseline. A spatial-spectral “data cube” can be synthesized from the resulting interferometric data set. By using a natural extension to the double Fourier method,[6, 7, 8] a detector array can be substituted for the single-pixel detector traditionally used in a Michelson (pupil plane) interferometer to widen the accessible field of view without slewing the interferometer to a new position. In Sections 2 through 4 of this paper we describe, respectively, community planning activities, science planning, and new mission and subsystem concepts for SPIRIT and SPECS, emphasizing the progress made since 2000.

2. COMMUNITY PLANNING SINCE 2000

Several significant events which brighten the prospects for far-infrared/submillimeter (FIR/SMM) space interferometry have occurred since 2000. First, in response to recommendations made by the US National Academy of Science's Astronomy and Astrophysics Survey Committee, which gave the general US astronomical community’s priorities in the Decadal Report *Astronomy and Astrophysics in the New Millennium*,[9] NASA added the FIR/SMM missions SAFIR and SPECS to its Roadmap for Astronomy and Physics.

The *Second Workshop on New Concepts for Far-IR/Submillimeter Space Astronomy* was held in College Park, Maryland on 7 – 8 March, 2002. Participants from Australia, France, Germany, Italy, Japan, The Netherlands, the UK, and the USA numbered 124 in total. Those from the US represented the academic, industrial, and government sectors and included scientists, engineers, and technology developers. A white paper titled the *Community Plan for Far-Infrared/Submillimeter Space Astronomy*[10] gives the consensus view of the participants: SAFIR[11] and SPECS should be the next big space observatories for infrared astrophysics. The *Community Plan* additionally recommends the Space Infrared Interferometric Telescope (SPIRIT) and a far-IR all-sky mapping mission as smaller missions with important scientific returns, and it lists the mission-enabling technologies in which investments should be made as soon as resources permit. Subsequent community workshops were held for European planning (Madrid; 1 – 4 September 2003), and to incorporate recent results from the *Spitzer Space Telescope*[12] into plans for the near and long-term future FIR/SMM space missions (Pasadena; 7 – 10 June 2004).

Fertile ground exists for international cooperation to build future FIR/SMM observatories. Two white papers – *The Birth of Stars and Planets* and *The Formation and History of Galaxies* – were recently submitted to facilitate ESA's Cosmic Vision strategic planning. Each of these papers carries the endorsement of about 150 scientists from ESA member nations, and both urge the development of space-based FIR/SMM interferometry after *Herschel*, which is due to launch in 2007.[13] Our Japanese colleagues hope to launch the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) early in the next decade. SPICA is a 3.5 m cryogenically cooled telescope,[14] which requires many of the same technologies as SAFIR, SPIRIT, and SPECS and resembles a small version of SAFIR or one of the light collector telescopes required for SPIRIT or SPECS.

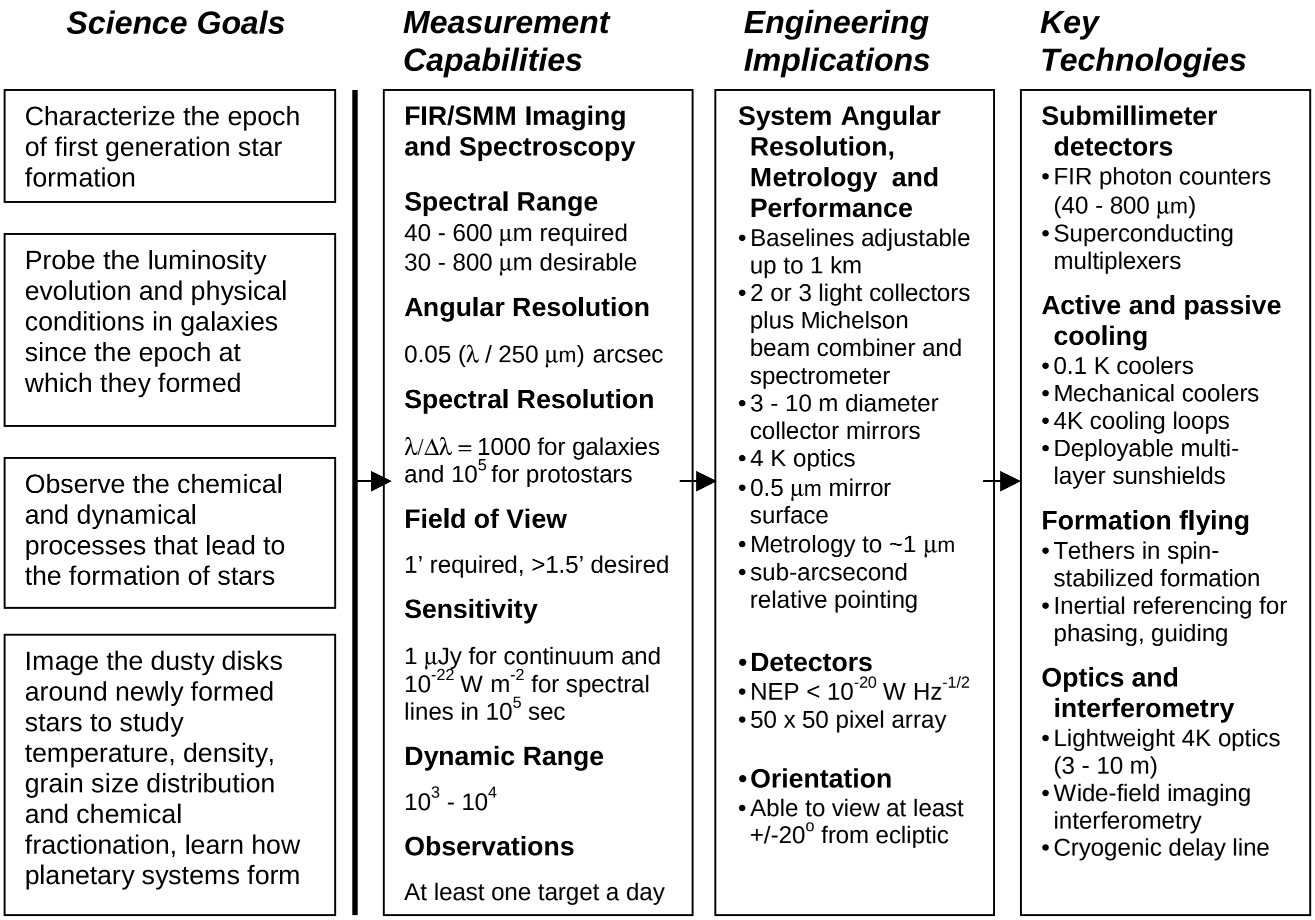
NASA selected from peer-reviewed proposals and approved study funding for SAFIR and SPECS in April 2004, and for SPIRIT in July 2004. SPIRIT is a candidate "Origins Probe" mission. The "Origins Probes" are envisaged by NASA as a new mission class with a mission lifecycle cost of $670M, and with launch opportunities at four-year intervals beginning in the next decade. SAFIR and SPECS are more expensive "Vision Missions," analogous to NASA's Great Observatories or the James Webb Space Telescope, with launch dates later than 2013.

NASA and ESA have recently agreed to share the cost of developing a mid-IR nulling interferometer for extrasolar terrestrial planet detection and characterization, with a launch expected in 2019.[15] In the US, this mission has been called the Terrestrial Planet Finder (TPF-I, where I represents "interferometer"), while in Europe the mission is called *Darwin*. Although the metrology, control, and intensity balance requirements are less demanding for FIR/SMM interferometry compared to the requirements for nulling interferometry at shorter wavelengths, SPIRIT and SPECS will be able to take advantage of some of the substantial investment currently being made in the US and Europe to develop technologies for the planet-finding missions.

NASA's strategic planning is conducted on a three-year cycle. New Roadmap Committees for NASA's Astronomy and Physics Programs are slated to meet in December 2004 to hear reports from the teams sponsored to conduct mission studies, including the SAFIR team led by D. Lester, the SPECS team led by M. Harwit, and the SPIRIT team led by D. Leisawitz. As noted above, SAFIR and SPECS are currently in NASA's roadmap, so the goal will be to retain that position by demonstrating that these missions are technically feasible and have compelling and unique science capabilities aligned with NASA's interests. Further goals will be to persuade the Roadmap Committees of the importance of technology investment relevant to the community's desired FIR/SMM missions, and to seek endorsement for the Origins Probe mission line, with a particular recommendation that SPIRIT be included among the first Origins Probes to launch in the 2010 – 2020 time frame.

3. A DESIGN REFERENCE MISSION FOR SPECS

To begin the mission design process, the SPECS Vision Mission Study team developed a "Design Reference Mission" consisting of a set of observations which could be made with a 1 km maximum baseline FIR/SMM imaging and spectral interferometer to learn about galaxy, star, and planet formation and the development of structure in the universe. Thirteen "use cases" were outlined, spanning a broad range of science topics. Measurement requirements were specified for each use case, and these were combined to develop the measurement requirements for the mission shown in Figure 1.



Science Goals

- Characterize the epoch of first generation star formation
- Probe the luminosity evolution and physical conditions in galaxies since the epoch at which they formed
- Observe the chemical and dynamical processes that lead to the formation of stars
- Image the dusty disks around newly formed stars to study temperature, density, grain size distribution and chemical fractionation, learn how planetary systems form

Measurement Capabilities

FIR/SMM Imaging and Spectroscopy

Spectral Range
40 - 600 μm required
30 - 800 μm desirable

Angular Resolution
0.05 (λ / 250 μm) arcsec

Spectral Resolution
$\lambda/\Delta\lambda = 1000$ for galaxies and 10^5 for protostars

Field of View
1’ required, >1.5’ desired

Sensitivity
1 μJy for continuum and 10^{-22} W m^{-2} for spectral lines in 10^5 sec

Dynamic Range
$10^3 - 10^4$

Observations
At least one target a day

Engineering Implications

System Angular Resolution, Metrology and Performance
- Baselines adjustable up to 1 km
- 2 or 3 light collectors plus Michelson beam combiner and spectrometer
- 3 - 10 m diameter collector mirrors
- 4 K optics
- 0.5 μm mirror surface
- Metrology to ~1 μm
- sub-arcsecond relative pointing

- **Detectors**
- NEP < 10^{-20} W $Hz^{-1/2}$
- 50 x 50 pixel array

- **Orientation**
- Able to view at least +/-20^o from ecliptic

Key Technologies

Submillimeter detectors
- FIR photon counters (40 - 800 μm)
- Superconducting multiplexers

Active and passive cooling
- 0.1 K coolers
- Mechanical coolers
- 4K cooling loops
- Deployable multi-layer sunshields

Formation flying
- Tethers in spin-stabilized formation
- Inertial referencing for phasing, guiding

Optics and interferometry
- Lightweight 4K optics (3 - 10 m)
- Wide-field imaging interferometry
- Cryogenic delay line

Figure 1 – Derivation of measurement capabilities, engineering and technology requirements from SPECS science goals.

Figures 2, 3, and 4 illustrate the need for high angular resolution. Figure 2 depicts two stages in the development of a low-mass protostar. Following an initial developmental phase lasting a small fraction of a stellar lifetime, current theory, backed by observational evidence, suggests that a disk forms around a protostar and serves as the reservoir of material out of which planets may form. The disk size is thought to be comparable to the size of the solar system. At a distance of 140 pc, where one of the nearest interstellar molecular clouds undergoing low-mass star formation is located, a protostellar disk subtends an angle <1 arcsecond. In the past couple of decades, much has been learned about the early stages of cloud collapse and protostar development, and much more will be learned with *Spitzer* and the upcoming *Herschel* mission. However, even the information-rich spectra provided by these missions will leave important questions unanswered because, until protoplanetary disks can be spatially resolved, the spectra can only be interpreted with the aid of models, and the models are plagued with degeneracy related to uncertain gas and dust spatial distributions, and dust and planetesimal size distributions and compositions. To understand the late stages of star formation and the planet formation process, astrophysicists will need multi-wavelength far-infrared images of the disks surrounding Young Stellar Objects (YSOs) to resolve model degeneracy and measure the distributions of molecules, such as the life-enabling water molecule, in a variety of protoplanetary systems, with different stellar masses and ages.

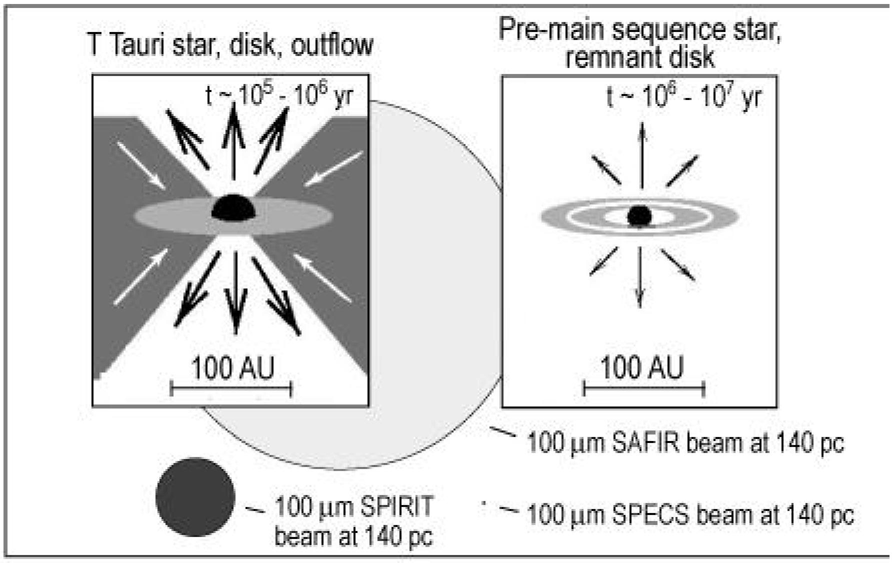


Figure 2 – The FIR/SMM interferometers SPIRIT and SPECS are able to resolve protostars and their surrounding disks during the late stages of star and planet formation, when these objects are about 100 AU in diameter. The 10 m single aperture telescope SAFIR can resolve younger protostars (<10^5 yr), before they collapse down to this size, but interferometers will be needed to image the evolutionary stages during which planets form.

Figure 3 shows a model for the ε Eri "debris disk,"[16] an analog to the interplanetary dust in the solar system. Many tens of debris disk candidates have been observed around nearby stars with the *Spitzer Space Telescope*.[17] Asteroids and comets serve as the source of dust in a debris disk. The dust particle dynamics are well understood. Poynting-Robertson drag causes the grains to spiral inward toward the star, and planets perturb these orbits gravitationally, concentrating dust at orbital resonant locations. Thus, the masses and orbits of planets can be derived from measurements of the dust distribution. The dust grains are warmed by the star they orbit and glow brightly at thermal infrared wavelengths. Like theoretical models for the younger protostellar disks discussed above, debris disk models suffer from degeneracy because plausible variations in the spatial distribution and the dust grain size distribution and composition produce similar features in the spectra of spatially unresolved sources. Only an image can definitively show the spatial structure in a debris disk. *Spitzer* far-IR images of the nearest debris disk systems (ε Eri, Fomalhaut, β Pic, and Vega) are available now.[18] However, to measure a statistically meaningful sample of debris disks and understand evolutionary effects, it is essential to obtain images of systems as far away as 100 pc. That, in turn, translates into a requirement for sub-arcsecond angular resolution in the far-infrared.

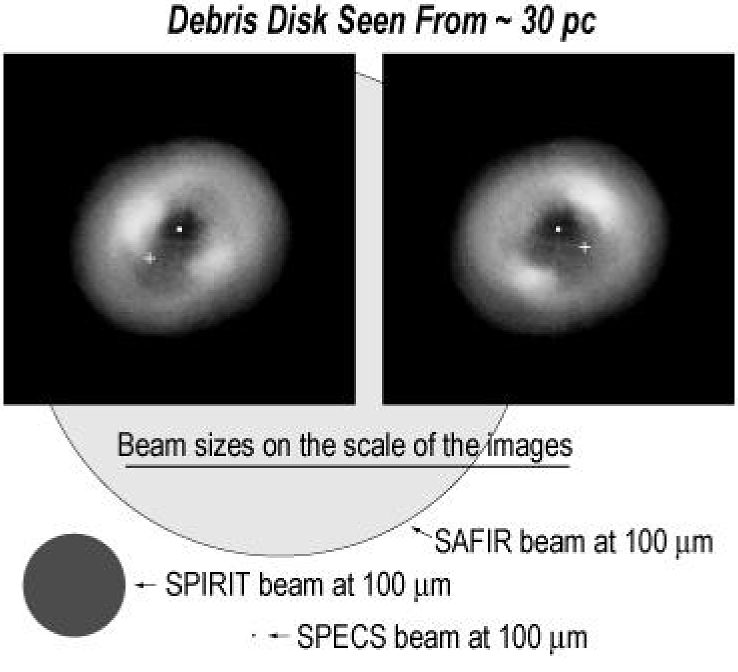


Figure 3 – SPECS will image dust in debris disks, revealing the presence of planets. This model of ε Eri shows the effects of a planet (+) at two orbital phases. The beam sizes are scaled to show resolution of a debris disk like that of ε Eri at 10 times its actual distance of 3.2 pc. These gray scale images are based on color images in which the predicted 40 µm emission is shown in blue, 60 µm emission in green, and 100 µm emission in red. Color differences reflect differences in the dust temperature. At these wavelengths, close to the peak in the emission spectrum, dust concentrations can be seen in high contrast to the smooth debris disk. SPIRIT will resolve many more debris disks than the four nearby disks resolvable by *Spitzer* (the *Spitzer* beam is 12 times larger than that of the SAFIR beam shown here).

Figure 4 shows a simulated extragalactic “deep field,” from which important information about galaxy formation and evolution can be gleaned. A galaxy like our own Milky Way, if observed at a large redshift, say z > 1, would subtend an angle of about 1 arcsecond. We have learned in recent years, especially from observations made with the Hubble Space Telescope, that high-z galaxies, or, more aptly “protogalaxies,” because they are thought to be lumps of material out of which later generations of galaxies formed, are smaller than the Milky Way; their sizes are typically a couple of tenths of an arcsecond. Spectrally, a galaxy like the Milky Way emits about half of its light at UV, optical and near-IR wavelengths, and about an equal portion of luminous energy in the far-infrared. The short wavelength spectral “bump” comes directly from stars, and the bulk of the far-IR radiation comes from interstellar dust grains warmed by stars. Another important discovery made in recent years is that many high-z galaxies and protogalaxies have spectra skewed toward the far-IR; it is not uncommon to find extragalactic objects at submillimeter wavelengths that produce no detectable optical emission. Spectroscopic followup observations at millimeter wavelengths show that these objects often lie at redshifts z >> 1, corresponding to vast distances and look-back times. These measurements are difficult, in part because the positions of the submillimeter sources are poorly defined. The angular resolution available with present-day submillimeter telescopes, such as the James Clerk Maxwell Telescope, is such that many extragalactic objects lie within a single resolution element.

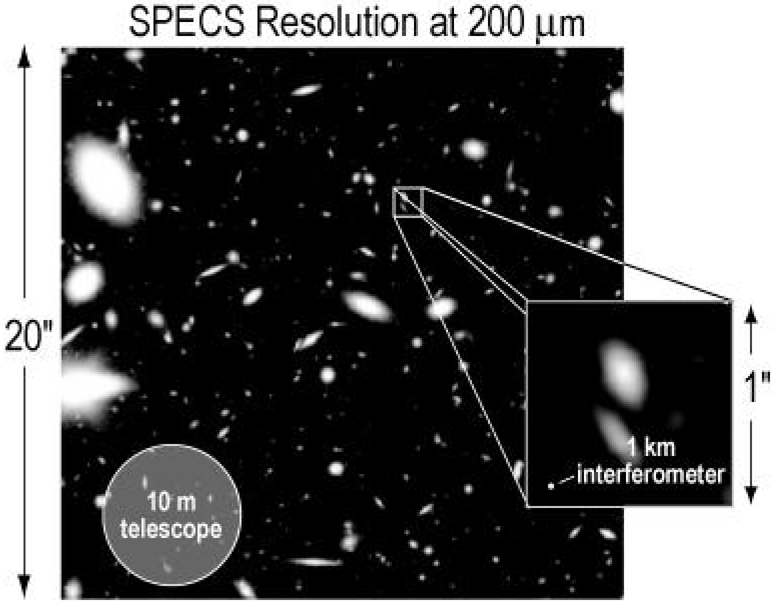


Figure 4 – SPECS will resolve individual galaxies in a deep extragalactic field still confusion limited with a 10 m single aperture telescope. SPIRIT will provide the first FIR/SMM spectra of individual high-redshift sources uninhibited by confusion effects. The SPECS resolution at 200 μm is indicated by the small dot in the lower-left corner of the 1 arcsec inset. (Simulated JWST deep field by A. Benson.)

The interstellar gas in a galaxy, the reservoir of material from which stars form, cools by emitting spectral line radiation, enabling cloud collapse and star formation. The C^+ (singly-ionized carbon) line at 158 μm is the strongest line in the spectrum of the Milky Way; approximately 0.1% of the total luminosity of our Galaxy is emitted in this line. For reasons not yet well understood, the 158 μm line tends to account for a smaller fraction of the energy emitted by galaxies of other types,[19] but this line and a handful of others in the far-infrared[20] are generally among the strongest seen in the spectra of disk galaxies. Information about the physical conditions (e.g., interstellar gas temperature and density) and star forming activity in galaxies is obtainable from measurements of the intensities of these lines. The relative intensities of several highly-ionized neon lines, emitted at rest-frame mid-IR wavelengths, are excellent diagnostics of excitation conditions, revealing whether a galaxy’s emission is dominated by star formation or nuclear activity. These neon lines are redshifted to far-IR wavelengths, while the far-IR lines mentioned above are redshifted into the submillimeter when they come from distant sources. The redshifts of these objects, and therefore their distances, can be derived from the observed wavelengths of the spectral lines. In summary, observations of galaxies and protogalaxies in the FIR/SMM spectral region are important not only because half or more of a galaxy’s emission can be found there, but because information vital to our understanding of the cosmic history of star formation and the formation and evolution of galaxies is available uniquely at these wavelengths. High angular resolution is needed, first to be sure which object is the source of emission (i.e., to beat source confusion), and second to resolve the structure of individual sources, many of which, based on *Hubble* observations, are believed to be interacting and merging at high redshifts.

Figure 5 summarizes the science-driven angular resolution requirements and compares the resolution provided by current and next-generation telescopes with the resolution achievable with SPIRIT and SPECS.

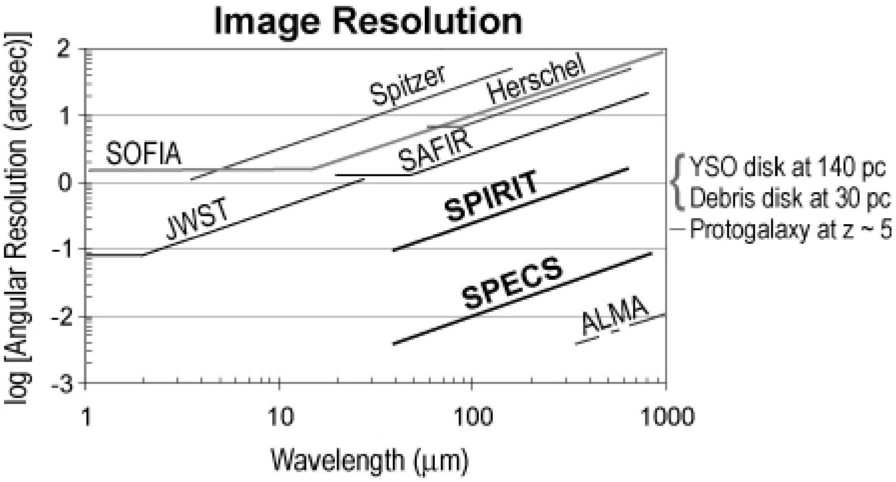


Figure 5 – A 40 m FIR/SMM interferometer (SPIRIT) would have angular resolution comparable to that of the JWST, surpassing current and next generation FIR/SMM space telescopes in resolution by more than an order of magnitude. A 1 km interferometer (SPECS) would provide resolution comparable to that of the Hubble Space Telescope or the ground-based millimeter interferometer ALMA.

In addition to angular resolution, the use cases that comprise the SPECS Design Reference Mission indicate the need to cover the wavelength range ~40 – 800 μm, and to provide μJy-level sensitivity, a field of view about 1 arcmin, spectral resolution $R = \lambda/\Delta\lambda > 1000$, and image dynamic range >1000. Much higher spectral resolution – $R > 10^5$ – is desired to enable chemodynamical studies of evolved protostars.

We are conducting studies aimed at determining the minimum and optimal *u-v* plane coverage requirements for alternative source types. Far-IR debris disk and extragalactic deep field simulated images are used as input, and the test scenes are "observed" with a hypothetical interferometer. The density of *u-v* plane coverage and the size of the gap in short baseline coverage are varied, and images are reconstructed and CLEANed in each case for comparison with the input images. Preliminarily, we have found that sparse sampling is tolerable, but perhaps with a dilution relative to complete sampling limited to ~25%. With 4 m diameter light collectors, a gap in short baseline coverage is tolerable if the the shortest baseline length observed is not much larger than 10 m. Very dilute sampling or a greater deficit in short spacing information produce undesirable artifacts and would significantly degrade the scientific value of the data. These factors, in addition to the basic measurement requirements summarized above and in Figure 1, are driving our mission design and engineering studies.

The SPIRIT study, which is just getting underway, will also begin with the development of a Design Reference Mission.

4. MISSION CONCEPTS FOR SPIRIT AND SPECS

Engineering tradeoffs associated with alternative mission architectures for SPIRIT and SPECS are among the subjects of the studies in which we are presently engaged, along with subsystem and overall system designs, assessments of technology readiness, technology roadmap development, and integration and test plans.

The original SPECS concept[3, 21] had three 4-m siderostats as light collectors arranged in an equilateral triangle around a central beam combiner, a configuration reminiscent of Michelson's stellar interferometer, except that Michelson used two siderostats. The SPECS optics were cooled to 4K and direct detectors were used instead of heterodyne receivers to take maximum advantage of the sensitivity achievable in space. Formation flying techniques were used to move the siderostats to sample the *u-v* plane. The plane containing the siderostats and the combiner was oriented perpendicular to the line of sight to the source. The light collectors were tethered together to enable dense *u-v* plane coverage with a maximum baseline length of 1 km in a reasonable amount of time (a few days), and with a very small expenditure of thruster propellant. A prohibitive amount of propellant would be required to accomplish the same objectives if tethers were not used.[22] The beam combining station contained three telescopes to catch the siderostat beams, beamsplitters to split those beams, and a scanning optical delay line for each of the three interferometric baselines.

The delay line serves two purposes. First, the delay scan provides optical path length modulation for the Michelson (pupil plane) interferometer, which serves as a Fourier Transform Spectrometer, yielding spectral resolution Δ_{FTS}/λ proportional to the delay range Δ_{FTS} scanned. Second, it provides path length equalization, compensating for deviations of the siderostats from their ideal locations, both within the plane of the array and along the line of sight to the source, and for the geometric delay associated with viewing field angles outside the primary beam of the interferometer. The primary beam diameter $\theta_p = 1.2\lambda/d$, where d is the collector mirror diameter, and this is much smaller than the desired 1 arcmin field of view at the wavelengths of interest and for collector telescopes large enough to provide the required sensitivity. Therefore, the delay scan range is increased by $\Delta_{FOV} = b\sin(\theta_{FOV}/2)$, where b is the interferometric baseline length and $\theta_{FOV} \sim 1$ arcmin.

Pupil plane beam combination is the natural choice for FIR/SMM space interferometry. Fizeau, or image-plane beam combination, requires very large detector arrays, causes a loss of sensitivity due to increased read noise, works best when many light collectors are used to sample the *u-v* plane, and has more demanding alignment (metrology and control) requirements. Far-IR detector arrays are custom-made devices. It will be difficult to obtain arrays much larger than about 100 x 100 pixels. Two detector arrays are needed, one for each output port of the Michelson beam combiner. It will be impractical to build a system with many collectors because the collectors, with cryogenic optics, will be expensive.

Based on analyses done since 2000, and especially the work conducted in recent months under the auspices of a NASA-funded Vision Mission study, the original SPECS design concept has evolved, and alternative mission architectures have been considered. A few of the interesting architecture options are: a single-baseline system with the combiner located midway between a pair of collectors; a single-baseline system with the combiner and collectors arranged in a triangle and the collectors equidistant from the combiner; a similar, but three-baseline, system comprised of three identical elements, each of which doubles as a collector and a combiner; a modified version of the original design concept in which counterweights are used to limit spin-up when the collectors are moved to sample short baselines; a formation flying array with a structure in the center that holds light collectors which provide short spacing (low spatial frequency) information; and a system built on a large truss-like structure, which could be assembled in space by robots. None of these alternative architectures has been ruled out on the basis that it fails to satisfy science requirements, and perhaps all merit further study, but clearly some are easier, less expensive, or less risky to implement than others. A truss with a reasonable cross-section and a length of 1 km will behave dynamically like a tether in a rotating system, to first approximation, but will weigh much more than a tether, so the last option listed above is not currently receiving a lot of attention. The near-term goal is to develop a single “proof of principle” design that satisfies the science requirements. The philosophy of the SPECS Vision Mission study team is to make the most conservative design choices consistent with this goal, such as the choice, for the time being, to limit the number of collector telescopes to two.

Afocal telescopes can be used as light collectors instead of siderostats, and our optical system design studies indicate that the total mirror area can be minimized if the beam is compressed at the light collectors. Smaller mirrors are better not only because they are easier to manufacture and less expensive, but because the required power and cost associated with cryocooling and thermal control also diminish as the mirror size shrinks. The telescope used at the combiner to catch the beam from the collector has to be sized to allow for diffraction in the far-IR over the roughly half-kilometer distance from the collector, and to allow as well for the coverage of field angles with a 1 arcmin range. Beam compression beyond a certain point at the collectors leads to the need for a very large telescope at the combiner, defeating the purpose of compression. Our studies have shown that beam compression by a factor of ~5 at the collector is optimal from an optical and thermal perspective, but this tentative conclusion is subject to modification if it complicates the overall system design (e.g., baffling for stray light rejection will eventually weigh into the equation).

An afocal telescope can also be used to capture the compressed, collimated beam from the collector telescope, as additional beam compression by a factor of ~10 is tolerable from the standpoint of diffraction over the relatively short path length between this telescope and the beam splitter used for Michelson beam combination. In our current optical system concept, the light collectors are 4 m off-axis Cassegrain telescopes, similar but smaller (~1 m) telescopes at the combiner station capture the beams from the collectors, compressing them to about 8 cm, and a collimated 8 cm beam traverses the instrument up to the light-combining beamsplitter.

Stray thermal radiation is an important factor in the SPECS design. Each collector telescope will have associated with it a warm spacecraft with solar cells for power generation, radiators, cryocooler compressors, and multi-layer Sun shades. When viewed from a distance of ~500 m, the warm components and the compressed beam from the collector telescope will be separated by a small angle. Actively cooled baffles will be used, as required, to prevent stray radiation from reaching the detectors. In the coming months we will refine the optical system design, derive requirements for the cold baffles, and design the baffle system.

Analyses of alternative tether architectures, the dynamics of rotating tethered spacecraft formations, and tether materials conducted since 2000 have yielded encouraging results, thus far indicating the viability of this approach. Farley and Quinn[22] describe a stable, constant angular momentum triangular architecture in which counterweights are used to limit spin-up while the collector telescopes are reeled in along a spiral path, and they explain how thrusters can be used to slew a spin-stabilized tethered array to a new target with a modest consumption of thruster propellant. Lorenzini et al.[23] describe a stable linear array and explain how an impedance-matched damping mechanism can be used to control tether oscillations. Quinn and colleagues, with funding from NASA's Cross-Enterprise Technology Development Program, wrote a requirements document for SPECS and developed analytical and mission design tools for tethered formation flying systems.

Our design concept for the beam combining instrument and focal plane arrangement is evolving. The detector arrays located at complementary Michelson output ports can be "tuned" differently to expand the overall dynamic range of the system: one set of detectors can be designed to measure faint emission while the other one can be tuned to measure bright emission without saturating. Dichroic beamsplitters can be used to divide the broad 40 – 800 μm spectral range into octaves to limit the photon noise and enable optimization of the detectors for each band. Subdivision of the FIR/SMM spectrum would also allow SPECS to take best advantage of the dark band between the zodiacal and Galactic cirrus foregrounds and the cosmic microwave background (essentially the two octaves between 80 μm and 320 μm).

Fewer pixels are needed at longer wavelengths to cover the same field of view. If the detector arrays are sized to Nyquist sample the primary beam, then the pixel count decreases by a factor of 4 with each octave increase in wavelength, as θ_p is proportional to λ. If the collector telescopes are 4 m in diameter, for example, $\theta_p \sim 3.8$ arcsec in the wavelength range 40 – 80 μm, so a 32 x 32 pixel array would cover a 1 arcmin field of view. In this case, the array dimensions would decrease to 4 x 4 for the octave spanning 320 – 640 μm.

Spectral resolution of the order of 1000 is achievable in FTS mode with a long-stroke delay line, but a different spectrometer design will be needed to provide the very high spectral resolution desired for certain studies. Conceivably, a heterodyne spectrometer could be used as a backend in conjunction with the Michelson interferometer, after the beam combiner, and the delay line could be dithered around ZPD to sample the fringe visibility. When used in this mode, the instrument would provide a separate fringe visibility measurement in each spectral channel for each baseline, rather than a complete white light interferogram recorded on a direct detector for each baseline. The heterodyne spectrometer is envisioned as an auxiliary system, not as a system that would displace the direct detectors. For most observations, particularly those that require the maximum sensitivity, the direct detectors would be used. If highly discriminating energy-sensitive, photon counting direct detectors can be developed for the far-IR, then the heterodyne approach may not be necessary, but this seems unlikely. Presently our aim is to assess the feasibility of these alternative approaches. A heterodyne system would be provided only if the additional cost is deemed to be justified by the scientific gain.

SPIRIT was conceived as having many attributes in common with SPECS, but with less ambitious measurement capabilities (limited, though still unprecedented, angular resolution and sensitivity in a FIR/SMM observatory), lower cost, and easier technical implementation, based on flight-ready or currently maturing technology. Like SPECS, SPIRIT is a wide field-of-view double Fourier interferometer, and it covers the same wavelength range. SPIRIT will have smaller light collectors than SPECS, and the collectors and combiner will be attached to a deployable boom, limiting access to interferometric baselines up to distances much less than 1 km. We are planning to consider collector telescopes in the 1 – 3 m diameter range and boom (maximum baseline) lengths in the 30 – 50 m range.

Originally, two SPIRIT architectures were considered, one in which a single pair of mirrors moved radially along the boom while the boom rotated to provide *u*-*v* plane coverage, and another in which mirrors spaced densely along the boom were sampled pairwise by articulating secondary mirrors held on a perpendicular boom while the main boom rotated. Variations on both of the initial SPIRIT architecture concepts were evaluated during a week-long study in the Instrument Synthesis and Analysis Laboratory (ISAL) at NASA's Goddard Space Flight Center. A variation on the radially translating collectors theme was adopted, the variation being that the siderostats were replaced by afocal telescopes, and this design concept was explored further during a second week in the ISAL. A much deeper engineering study will begin in August 2004.

Thermal analysis conducted during the SPIRIT ISAL studies, and later extended during an independent cryo-optical system design study at Goddard, led to a thermal model optimized for a 2 m diameter afocal telescope on a warm (unshielded) boom in a halo orbit around the Sun-Earth L2 point. The telescope is cooled to 4K by a three-stage cryocooler. The number of Sun shades and shields, the angle between shade layers, and the number and temperatures of cooling stages were optimized to provide the required mirror temperature with a minimum of input power to the cryocoolers. Coolers currently under development by the awardees of NASA contracts under the Advanced Cryocooler Technology Development Program are capable of providing the cooling and will require, in our estimation, less than 500 W of input power to cool a 2 m diameter mirror. The SPECS thermal design, while not yet developed, could be very similar to the SPIRIT design.

5. CONCLUSIONS

Information needed to answer some of the most compelling astrophysical questions – questions so profound that non-scientists yearn to know the answers – is uniquely available in the FIR/SMM spectral region. To extract this information, the astronomical community will need access to telescopes with measurement capabilities in the FIR/SMM that exceed those of the current and next-generation missions *Spitzer*, SOFIA, *Herschel* and SPICA by orders of magnitude in angular resolution and sensitivity. The interferometers SPIRIT and SPECS will provide capabilities complementary to and comparable with those of JWST and ALMA in the neighboring spectral regions. SPIRIT, a candidate Origins Probe mission, could be launched in about a decade. SPECS is envisioned by the community as a successor to SAFIR, and it will ultimately provide resolution in the far-IR matching that of the Hubble Space Telescope at visible wavelengths. Like other major missions in NASA's space science roadmap (e.g., JWST, LISA, and TPF-I), SPECS may represent an opportunity for international collaboration.

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