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NASA's far-IR/submillimeter roadmap missions: SAFIR and SPECS

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Abstract

The Single Aperture Far-Infrared (SAFIR) Telescope, a 10 m class, background-limited observatory, and the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), a kilometer maximum baseline far-IR/submillimeter (FIR/SMM) interferometer, were recently added to the NASA space science roadmap. We briefly describe the process that led to this adoption, explain the need for high angular resolution and sensitivity in the FIR/SMM, describe the two roadmap missions, and discuss associated practical considerations, including the new technology requirements and the potential opportunity for international collaboration.

Keywords: Single Aperture Far-Infrared Telescope (SAFIR); Submillimeter Probe of the Evolution of Cosmic Structure (SPECS); NASA's far-IR/submillimeter roadmap missions; Interferometry; Imaging

1. Introduction

The FIR/SMM roadmap described here is the culmination of a democratic and highly effective process. The US National Academy of Science's Astronomy and Astrophysics Survey Committee, chaired by Drs. Christopher McKee and Joseph Taylor, solicited community input and made recommendations in the "Decadal Report", *Astronomy and Astrophysics in the New Millennium.* The Decadal Report included SAFIR among its highest priority major new initiatives, and recommended investment by NASA in the technology that would enable a far-IR interferometry mission after SAFIR. With advice from its Space Science Advisory Committee (SScAC), NASA's Office of Space Science adopted these recommendations. In particular, the *Roadmap for the Office of Space Science Origins Theme* and the roadmap for the Structure and Evolution of the Universe (SEU) theme, *Beyond Einstein: From the Big Bang to Black Holes*, both include SAFIR and a far-IR interferometer.

Although the missions described in this paper cover a limited spectral range, it should be understood that NASA's FIR/SMM roadmap missions do not constitute a separable package; rather, they are key components of a bigger, science-oriented program. As suggested above, NASA organizes its missions according to science themes. These themes seek to answer compelling scientific questions with the best possible tools. As it happens, vast improvements in resolution and sensitivity in the FIR/SMM are needed to answer several fundamental "Origins" and "SEU" questions.

It is beyond the scope of the roadmap documents to describe *how* NASA will ready itself to launch SAFIR and SPECS, and many practical issues will have to be addressed. For example, how do the top-level science objectives flow down into required measurement capabilities, engineering requirements, and requirements for new technology? What are the advantages and disadvantages of alternative mission designs? How will new technologies be validated? In March 2002, NASA sponsored the Second Workshop on New Concepts for Far-Infrared and Submillimeter Space Astronomy. The workshop participants crafted a *Community Plan for Far-IR/Submillimeter Space Astronomy*, which will be published in the workshop proceedings. SAFIR and SPECS form the backbone of the *Community Plan*, but

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the *Plan* also addresses the practical issues and recommends a coordinated technology development program and pathfinder missions. What is the difference between a pathfinder mission and a roadmap mission? A "roadmap mission" is too expensive to fit into a traditional NASA mission line (e.g., MIDEX, New Millennium, or Discovery) and serves a purpose that is deemed by the scientific community to be imperative and worth the greater cost. The James Webb Space Telescope (JWST, formerly NGST) is a roadmap mission, as is the Terrestrial Planet Finder (TPF). The pathfinder missions to which we refer would fit into an existing or new mission line and be much less expensive than SAFIR or SPECS.

This paper is organized as follows. Section 2 introduces some of the science questions that will require new measurement capabilities in the FIR/SMM, and particularly drive us toward missions that provide vastly improved angular resolution and sensitivity. The roadmap missions, SAFIR and SPECS, are described in Section 3, and some of the practical issues addressed in the *Community Plan for Far-IR/Submillimeter Space Astronomy* are discussed in Section 4. Some concluding thoughts are given at the end.

2. Science drivers

The NASA FIR/SMM roadmap was shaped by compelling scientific questions whose answers lie beyond the reach of the observatories that will be operating by 2010. One might argue that new FIR/SMM telescopes are needed because half of the light in the Universe (aside from the cosmic microwave background) appears in this spectral range. Specifically, we are referring to the range between the longest wavelength accessible to the JWST, ~25 μm, and the shortest wavelength continuously accessible to the Atacama Large Millimeter Array (ALMA) through the atmosphere, ~800 μm. Alternatively, one might note that 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, and argue that it is important to maintain a balance of measurement capabilities across the electromagnetic spectrum. The Space Infrared Telescope Facility (SIRTF), the Stratospheric Observatory for Infrared Astronomy SOFIA, and the Herschel Space Observatory will still leave IR astronomy far behind X-ray, UV, optical, millimeter, and radio astronomy in resolution and sensitivity. While these claims are true, only one fact really matters: information vital to the attainment of some of the community's highest priority scientific objectives is uniquely available in the FIR/SMM.

What are these scientific objectives, and what measurement capabilities will be needed to achieve them? It is not necessary to predict accurately what questions the astronomical community will most fervently seek to answer two decades from now in order to plan roadmap missions; an educated guess will suffice. The next generation of astronomers will be asking questions like these:

- When and how did the very first stars form in primordial, metal-free gas clouds? Were these clouds clumped in protogalactic structures or more loosely organized?
- What was the element synthesis history of the Universe, and how did dust build up over time, irreversibly altering the star formation process and enabling life to exist?
- How do stars and planetary systems form, and what factors determine the products of cloud collapse (e.g., a binary star or a solar system like ours) and the stellar initial mass function?
- What did the Hubble Space Telescope (HST) and JWST miss because objects were hidden behind a veil of dust? What are the sources that give rise to the cosmic infrared background found by the Cosmic Background Explorer (COBE), and how are they distributed?

The gas clouds that collapsed to form the first stars must have given up the bulk of their potential energy through the most readily excited H_2 lines, namely those at the rest wavelengths 17 and 28 μm (Haiman et al., 1996). Recent results from the Wilkinson Microwave Anisotropy Probe suggest that reionization occurred when the Universe was only about 200 million years old, with corresponding redshift in the range 11–30 (95% confidence interval; Kogut et al., 2003). Thus, the H_2 cooling lines should appear in the wavelength interval 200–870 μm. Astrophysical background photon noise is at a minimum in this spectral range, the foreground optical depth is modest (Kogut et al., 2003), and a pair of lines would likely be seen. However, the lines would be very weak. If the collapsing clouds were concentrated in unresolved objects as massive as a small galaxy ($10^{10} M_{\odot}$), the line strengths would be approximately 10^{-23}–10^{-24} W m^{-2} (Leisawitz et al., 2003b). A large-aperture, background-limited telescope equipped with a moderate resolution spectrometer ($\lambda/\Delta\lambda \sim 3000$) that operates over a wide spectral range would be capable of making these observations.

Spectral line measurements in the FTR/SMM could be used to measure the element synthesis history of the Universe without the compromising effect of a large and uncertain correction for foreground dust extinction. As illustrated by Rieke et al. (2003, see Figs. 2 and 3), mid-IR neon fine structure lines can be used to discriminate between sources whose emission is dominated by star formation and those dominated by Active Galactic Nuclei (AGN). Once the excitation conditions are understood, the far-IR fine structure lines of carbon,

nitrogen, and oxygen can be used as tracers of elemental abundances. One of these lines, the C+ line at 158 μm, is the single brightest feature in the spectrum of a normal galaxy, typically accounting for 0.1–1% of the bolometric luminosity (Stacey et al., 1991). The lines need not be resolved to make these measurements, and galactic line widths are of the order of 100 km s^{-1}. To see the most interesting lines over a wide redshift range, complete coverage of the FIR/SMM region is needed. ALMA, with its enormous collecting area, will make complementary observations at millimeter wavelengths (e.g., the 158 μm line in sources at $z > 5$). A typical far-IR line intensity for a galaxy like the Milky Way at a redshift $z = 5$ is about 10^{-22} W m^{-2} (Leisawitz et al., 2003b). To detect the thermal dust continuum emission from such a galaxy, we would need broad band sensitivity of the order of 1 μJy. Although spectral template fitting could be used to interpret the envisioned spectroscopic and spectrophotometric observations, it is highly desirable to limit the number of sources per beam to a few. Accordingly, the required angular resolution is about 1 arcsec (Blain, 2000). Observatories that provide these measurement capabilities in the FIR/SMM would also be able to characterize the sources that have no optical counterparts and definitively resolve the cosmic IR background.

The far-IR is rich with information about star, disk and planet formation because protostars emit predominantly in this spectral range, and the radiation can escape from the inherently dusty stellar birth sites. Spectral lines contain particularly valuable information about the cooling, collapse, and chemistry of molecular cloud cores and protostars. However, the interpretation of line intensities and profiles is model-dependent; ultimately, high angular resolution is needed to break model degeneracy and definitively characterize the source. 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 milli-arcsec. Thus, future astrophysicists will need high spatial (~10 milli-arcsec) and spectral ($\lambda/\Delta\lambda > 10^5$) 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). These observations will not require extraordinary sensitivity.

In summary, future FIR/SMM space observatories should have the sensitivity needed to reach back in time to the formation epoch of the first luminous objects, the angular resolution needed to image proto-planetary systems and distinguish the emissions of individual galaxies, and the spectral resolution needed to probe the physical conditions and measure the flows of interstellar gas in young galaxies, nascent stars, and the dust-enshrouded nuclei of galaxies that harbor massive black holes.

3. The roadmap missions

3.1. First step: SAFIR

The Single Aperture Far-IR (SAFIR) Telescope (Yorke et al., 2003) will be operated like HST for a wide user community with a launch by the middle of the JWST lifetime in 2015. SAFIR will be astrophysical background limited over a wavelength range from about 15 to 600 μm, and could be diffraction limited at around 40 μm. With a 10 m aperture it would have 150 times the collecting area and an order of magnitude greater angular resolution at a given wavelength than SIRTF. The angular resolution will be about 2.5 arcsec × (λ/100 μm). Thus, SAFIR will provide our first deep view of the sky at far-IR wavelengths that does not suffer severely from extragalactic source confusion. SAFIR instruments will provide imaging and spectroscopic capabilities with maximum spectral resolution $\lambda/\Delta\lambda \sim 10^6$. SAFIR will enable detailed studies of the individual sources that give rise to the cosmic IR background. A 10^{-22} W m^{-2} spectral line will be detectable in about an hour.

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 $Hz^{-1/2}$ (Amato et al., 2003).

Three alternative mission designs are being studied. One is based on the JWST design for maximum heritage and fidelity; the second design uses stretched membrane mirrors (Dragovan, 2003) to reduce mass; and the third design has the same total aperture as a 10 m diameter circle, but uses a non-circular primary mirror to improve angular resolution.

According to the Decadal Report, "[f]or studies of both star-forming regions in our galaxy and dusty galaxies at high redshifts, SAFIR will be essential in tying together information that [JWST] will obtain on these systems at shorter wavelengths and that ALMA will obtain at longer wavelengths".

3.2. Second step: SPECS

The Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) is a spatial and spectral ("double Fourier"; Mariotti and Ridgway, 1988) interferometer with a 1 km maximum baseline that will operate over the wavelength range ~40–800 μm. SPECS will provide angular resolution comparable to that of the HST in the

far-IR, ~10 milli-arcsec $\times(\lambda/100\ \mu m)$, improving on the SAFIR resolution by two orders of magnitude. The spectral resolution, $\lambda/\Delta\lambda$, will be about 10^4. SPECS could be ready to launch by 2025, around the end of the SAFIR operational lifetime.

SPECS would employ the same detector, mirror, and cooler technologies as SAFIR. 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. The interferometer mirrors would be smaller than the SAFIR mirror and could be monolithic. SPECS could use three 4 m diameter mirrors as light collectors, as in the original concept (Mather et al., 1999; Leisawitz et al., 2000), but alternative design concepts will be studied.

Three additional technologies will be needed to enable long-baseline imaging interferometry. A long-stroke cryogenic delay line is required for spectroscopy and wide-field imaging (Swain et al., 2001). The light collecting mirrors will be mounted on separate spacecraft to provide access to km-baselines, and the spacecraft formation will have to be highly reconfigurable to enable *u–v* plane filling and provide good image quality. Tethers could be used to do the work that would otherwise have to be done with thrusters, providing coarse position control and a huge saving in propellant mass (Farley and Quinn, 2001). Third, we will have to develop the technique of wide field mosaic imaging for optical/IR interferometers (Leisawitz et al., 2003c).

SPECS will be able to resolve individual high-*z* objects, protostars, and planetary debris disks to address the questions raised in Section 2. A single SPECS observation of a patch of dark sky will be equivalent to the Hubble Deep Field, but a spectrum will be available for every pixel.

According to the Decadal Report, "[a] rational coordinated program for space optical and infrared astronomy would build on the experience gained with [JWST] to construct SAFIR, and then ultimately, in the decade 2010 to 2020, build on the SAFIR, TPF, and [Space Interferometry Mission (SIM)] experience to assemble a space-based, far-infrared interferometer".

4. Building the road

In 2002, NASA sponsored a workshop on New Concepts for Far-Infrared and Submillimeter Space Astronomy and convened an Infrared, Submillimeter, and Millimeter Detector Working Group, chaired by Erick Young. The *Community Plan for Far-IR/Submillimeter Space Astronomy* gives the consensus view of the workshop participants. It recommends a coordinated technology program to respond to the technology challenges noted in the previous section. New detector technology is critical for both SAFIR and SPECS. The state of the art and options for future development are discussed in the detector working group report *Detector Needs for Long Wavelength Astrophysics*.

Some of the new technology can be tested in laboratories on the ground, and other technologies will be used in space on missions that fly before SAFIR. For example, Constellation-X needs superconducting detectors and cryo-coolers. The Laser Interferometer Space Antennna (LISA), like SPECS, requires formation flying. LISA and Constellation-X are the two Great Observatories in the recently approved *Beyond Einstein* program. Some of the interferometry technologies are shared with planned NASA "Origins" 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.

The flight worthiness of a third class of technologies needed for SAFIR and SPECS will be proven first on less expensive missions, such as those in NASA's New Millennium line. For example, large aperture mirror cooling technology, which poses new thermal engineering and cryocooler challenges and is virtually impossible to test satisfactorily on the ground, can be demonstrated relatively inexpensively in space. Likewise, tethered formation flying and control can be demonstrated with inexpensive nanosats (Miller et al., 2000).

It is important to consider the possibility of building a small FIR/SMM imaging interferometer as a science and technology pathfinder for SPECS (Leisawitz et al., 2000; Leisawitz et al., 2003a). Most of the major engineering issues could be resolved and validated on a less expensive mission that would still be capable of producing breakthrough science. An interferometer on a boom with a maximum baseline length in the 30–50 m range would provide sub-arcsecond resolution and beat extragalactic source confusion at wavelengths greater than 200 μm, where SAFIR will still have this problem. We call the pathfinder mission SPIRIT, for Space Infrared Interferometric Telescope. According to the *Community Plan*, "[i]f the cost of SPIRIT is much less than that of a 'roadmap mission' like SPECS, as preliminary studies indicate, then SPIRIT should precede SPECS". Further studies will be conducted to develop viable design solutions for SPIRIT and estimate the cost of this mission.

The *Community Plan* also recognizes that the science return from SAFIR may be greatly enhanced if SAFIR is preceded by a FIR/SMM all-sky survey mission, which could be conducted with a 2 m class cryogenic telescope. Such a mission would find the rare but important objects that act as signposts to the early universe, and would undoubtedly uncover many interesting sources that have no optical counterparts.

5. Concluding remarks

In response to recommendations made by the US National Academy of Science's Astronomy and Astrophysics Survey Committee, which stated the community's priorities in the Decadal Report *Astronomy and Astrophysics in the New Millennium*, NASA has added the SAFIR and SPECS missions to its space science roadmap.

SAFIR and SPECS, like the NASA "roadmap missions" JWST, LISA, and TPF, may represent opportunities for international collaboration. 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 international astronomical community will need access to telescopes with measurement capabilities in the FIR/SMM that exceed those of the next-generation missions SIRTF, SOFIA, Herschel and SPICA by orders of magnitude in angular resolution and sensitivity. SAFIR and SPECS will provide capabilities complementary to and comparable with those of JWST and ALMA in the neighboring spectral regions.

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