A Probe-Class Opportunity for Far-IR Space Astrophysics

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1 Motivation

The far-IR waveband (broadly 30–1000 μm) accesses a rich and wide-ranging scientific landscape, yet remains a technical frontier for which rapid scientific advances are still possible at sub-flagship cost. While there is great astrophysical promise, the world has not yet brought together the two key elements required for sensitive far-IR measurements: an actively-cooled space telescope operating near the temperature of the microwave background (e.g.$\sim$4 K), and sensitive, large-format far-IR detector arrays. NASA is now poised to integrate these building on system-level experience with Spitzer, Herschel, and Planck, and augmented with detector development progress and new low-cost telescope technology. This possibility has produced great excitement in the far-IR community, as evidenced with our well-attended workshop in June 2015 focusing on a flagship-class 'Far-IR Surveyor.'[2]

Here we emphasize that because the far-IR is so fertile and as yet relatively unexplored, large advances are possible with a mission that is smaller in scope than the d$\geq$5-meter Surveyor under consideration for the Decadal. The far-IR is particularly compelling for sensitive wideband spectroscopy, which overcomes source confusion and provides redshifts and unique astrophysical diagnostics of the inner workings of dusty galaxies and star- and planet-forming sites. While the probe outlined below will not offer the ultimate point-source sensitivity or speed of the Surveyor (required for individual early-Universe objects), it will nevertheless obtain spectra of thousands of objects, both targeted (e.g. JWST, WFIRST follow-up) and in blind surveys. Sources range from dusty galaxies to heavily enshrouded young stars and protoplanetary disks in our own Galaxy. Far-IR spectra will directly address several key goals of modern astrophysics:

- Directly chart the history of cosmic star formation, supermassive black hole growth, and baryons in the cosmic web by studying gas-phase cooling lines through the epochs of peak stellar and black-hole mass growth.
- Conduct a census of gas mass and conditions in protoplanetary disks throughout their evolutionary sequence.
- Measure clustering and total emission of faint galaxies below the individual detection threshold using tomographic intensity mapping of the far-IR emission lines, particularly for the faint Epoch of Reionization galaxy populations.
- Probe the cycling of matter and energy in the Milky Way and nearby galaxies with sensitive spectral probes of the energetics of the atomic and molecular ISM.

We emphasize for the last two programs, surface brightness sensitivity is paramount, and is readily provided by a modest-aperture telescope.

2 A Strawman Far-IR Astrophysics Probe

In the left panel of Figure 1 we show discovery potential (plotted as survey time – lower is better) for spectroscopic measurements from space. Orders of magnitude improvement are possible relative to the Herschel instruments; much of this derives from cooling the telescope and using optimized instrumentation with background-limited detectors. Telescope area, a typical driver of mass and cost, is only one aspect of these potential gains. As a point design, we consider a 2.5-meter cryogenic telescope with moderate-resolution (R$\sim$500) wideband spectrometers covering 50–500 μm with $\sim$20,000 detectors. We also include SPICA, a 2.5-meter telescope being proposed Europe and Japan, and emphasize that even if SPICA proceeds, the probe considered here offers improved instrumentation (5–10$\times$ format increase and 2–3$\times$ per-pixel sensitivity increase) which would make it substantially more sensitive that SPICA for 3-D spectral surveys. We now consider the basic parameters of a far-IR astrophysics probe (summary in Table 1).

Mission Design. A key requirement is telescope temperature—while a non-cooled telescope may be useful for heterodyne spectroscopy, a telescope which is actively cooled to a few degrees K is vital for the broad range of far-IR astrophysics under discussion. This common requirement for all future far-IR missions drives important architecture elements, regardless of mission size. A far-IR mission requires a careful thermal design integrating passive (radiative) cooling, and active cooling provided by closed-cycle ^{4}He and ^{3}He cryocoolers such as those available from Sumitomo or US vendors. It also requires a thermally-friendly orbit such as sun-earth L2 or earth-trailing; models indicate that cryogenic systems of any size indicate are not viable in low-earth orbit. Fortunately, it seems that reaching L2 is now viable for a 2–3 ton probe with a commercial launcher (e.g. SpaceX Falcon-9).

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[2]https://conference.ipac.caltech.edu/firsurveyor/page/documents

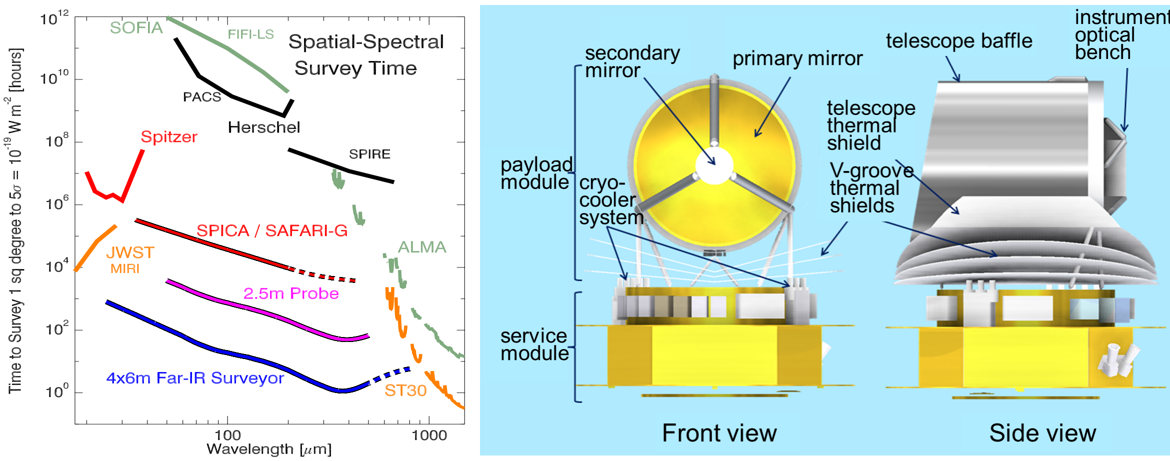

Figure 1: LEFT: Spectroscopic sensitivities plotted as spectral survey time in the far-IR and submillimeter. The Far-IR Surveyor concept has a 4×6 meter telescope, equipped with R=500 grating spectrometers with 100 beams (at each wavelength) and 1:1.5 instantaneous bandwidth. Detectors are assumed to operate with NEP = 2×10^{-20} $\mathrm{WHz}^{-1/2}$. The SPICA / SAFARI-G curve refers to the new SPICA configuration: a 2.5-meter telescope with a suite of R=300 grating spectrometer modules with 4 spatial beams, and detectors with NEP=2×10^{-19} $\mathrm{WHz}^{-1/2}$. Advances in instrumentation on a 2.5-meter facility could improve on SPICA substantially—the 2.5 meter probe assumes R=500 grating spectrometers with 15 beams per band, and detector NEP of 4×10^{-20} $\mathrm{WHz}^{-1/2}$, a sensitivity demonstrated in the lab. RIGHT: Schematic of the SPICA concept: provided as one potential example of a cryogenic 2.5-meter class mission; it uses a thermal architecture similar to Planck with passive and active cooling.

Telescope. Because the telescope manufacture and iterative figuring / cryogenic testing are the dominant terms in the system cost estimates, this is a key area to address. A promising avenue of study is novel telescope techniques optimized for a cryogenic far-IR mission. For example, a low-bandwidth active system, if has sufficiently high surface control authority at sufficiently low dissipated power could allow figure adjustment on orbit. This would greatly reduce or even eliminate much of the costly cryogenic optical testing and re-figuring that is required with a traditional telescope, and likely reduce mass. Of course, for a given architecture, minimizing the aperture offers savings in figuring and testing, and also in reduction of the cold mass, which scales though the full system. In particular, a telescope such as our probe in the 2–3 meter class avoids the need for deployable structures—the full system including the sunshades and secondary mirror could fit within a 5-meter shroud, eliminating the need for costly mechanisms.

Instrumentation. The probe will have moderate resolution grating-type dispersive spectrometers: 4–5 bands can combine to cover the full decade of wavelength range. Detectors will operate near the photon background limit, with an NEP at or below 4×10^{-10} W $\mathrm{Hz}^{-1/2}$. The baseline 20,000 pixels is conservative: frequency-domain readout techniques now being used on the ground greatly increase the format available per heat lift and per dollar, and we note that the Surveyor design includes provision in cryogenic heat loads and warm-side power for up to 500,000 pixels.

Summary, Cost. While a well-costed probe-class far-IR mission is not yet on the table, the probe outlined here is a great simplification of the 4×6-meter with deployed sunshade and secondary studied at JPL in 2008 which has evolved into the Far-IR Surveyor concept. It should therefore have a much lower cost than the Surveyor's estimated \$1.7B. We look forward to studying this, and expect that it will be within striking distance of a ∼\$1B cap. In any case, a competed opportunity would generate the most efficient solutions, and excellent science value.

Table 1: Strawman Far-IR Probe

Parameter	Ex. FIR Probe	notes
Telescope Temperature	∼ 4 K	Key sensitivity requirement
Telescope Diameter	2–3 m	Leading term in cost
Wavelength Range	50–500 μm	Complements JWST, ALMA spectroscopic capabilities, can be optimized
Telescope Surface Accuracy	1–2 μm	Could be reduced for mission targeting the long wavelengths
Instrument Temperature	50–100 mK	Key for instrument sensitivity, common for all future far-IR missions
Total Number of Detectors	$1–5\times10^4$	Comparable to the large ground-based instruments
Heat Lift at 4 K	∼50 mW	Scaled from Planck, terms from telescope mass and sub-K mass
Heat Lift at 20 K	∼0.6 W	Scaled from Planck, terms from telescope mass and # detectors
Data Rate	∼ 100 Mbit / sec	Scales with survey ambition
Orbit	Sun-earth L2 halo	Key for thermal stability
Mass estimate	<3000 kg	Scaled from 2008 Team-X 4×6 meter study
(Falcon 9 performance to L2)	3700 kg	SpaceX via Matt Abrahamson @ JPL