V. SAFIR – Uniqueness of Proposed Approach

Science Objectives

Our approach to a background limited single-aperture space observatory has been described carefully in the section on observatory architecture. Many implementations were considered, and the baseline design was selected as a strawman. Nevertheless, there are other approaches to the main science goals of SAFIR that can be considered. We believe that while these approaches can attack some of the same problems, they either do so in a way that is complementary to SAFIR, or in a way that is perhaps less costly, but much less productive. We address the scientific uniqueness of SAFIR with respect to the key science objectives listed earlier.

- Probe the earliest epochs of metal enrichment and see the galaxy-forming universe before metals. Understand the origin of dust in the universe.

A cosmic background-limited far infrared telescope has the sensitivity to look for the pure rotational lines of molecular hydrogen at rest wavelengths of 28 μm and 12.2 μm. These are likely to be the main coolant lines of cosmic gas before the first stars form and seed the universe with metals. For galaxy-sized clumps of pure hydrogen gas at z=10-15, the large primary aperture of SAFIR is a requirement. For the earliest generations of dust in the universe, after the first episodes of star formation, thermal emission peaks in the submillimeter will reveal the first generation of dust. Again, a cosmic background-limited telescope with the collecting aperture of SAFIR is required to see dusty galaxies at large redshifts with luminosities like that of our own galaxy. While low frequency radio interferometers (e.g. SKA) will search for primordial 21 cm emission from hydrogen atoms, that does not distinguish warm material of forming galaxies.

- Resolve the far infrared cosmic background - trace formation and evolution of starforming and active galaxies since the dawn of the universe, and measure the history of star formation.

The history of star formation in the universe tells the story of nuclear enrichment and mixing. Star formation is invariably associated with clouds of dust and gas that can strongly obscure ultraviolet, optical, and even near infrared emission. Far infrared signatures of reradiated starlight from massive stars associated with star formation allows a relatively clear view into star forming regions, and spectroscopy with SAFIR will allow accurate determination of redshifts and distance scales for them. While ALMA will offer high sensitivity at long wavelengths, and greatly suppressed confusion limits, the opportunity with SAFIR to have large format arrays in the focal plane allows much more efficient surveying for relatively luminous sources. Half the energy in the universe comes out in the greater bandpass that is targeted by SAFIR.

- Explore the connection between embedded nuclear black holes and their host galaxies. Understand the relationship of active nuclei to galaxy formation.

Many nuclear black holes in galaxies are heavily obscured by dust, which is relatively transparent only at very long wavelengths, and hard X-rays. While the accretion process, which drives the luminosity that heats the inner regions of these galaxies, can be explored through X-ray line emission in the hot gas, the total luminosity is more precisely determined in the far IR. These wavelengths provide a metric for the luminosity through thermalization by the refractory dust, which cannot survive at temperatures that would show thermal peaks at shorter wavelengths. Far infrared fine structure lines offer excitation diagnostics that allow luminosity from star formation to be distinguished from that produced by accretion.

- Track the chemistry of life. Follow prebiotic molecules, ices, and minerals from clouds to nascent solar systems.

Spectral features of biogenic-relevant molecules and ices are largely confined to the infrared part of the spectrum. While ground-based submillimeter telescopes can be used for many of these features, the unrestricted spectral coverage of SAFIR provides a much more complete picture, and the far higher spectral sensitivity of SAFIR allows probes of lower density scenarios.

- Identify young solar systems from debris disk structure and map the birth of planetary systems from deep within obscuring envelopes. Assess their bombardment habitability.

Resonance structures in debris disks will be detectable by a range of observatories. Large optical telescopes will be sensitive to scattered light from dense regions near the central star. Submillimeter interferometers will also be sensitive to inner solar system structure, and will be effective at resolving the finest detail. SAFIR will probe these disks effectively on a larger scale, larger than the primary beam of ALMA, for example, and with greater sensitivity to low level emission. This will be of value for nearby stars being surveyed by TPF.

Complementarity of Interferometers and Single Aperture Telescopes

It is important to understand the complementarity of infrared interferometers with single aperture telescopes, as both designs are represented in future mission concepts. The Decadal Report *Astronomy and Astrophysics in the New Millennium* recommended a "rational coordinated program for space optical and infrared astronomy [that] would build on the experience gained with NGST 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." The Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), a kilometer-maximum baseline far-infrared interferometer with more challenging technical requirements, would build on SAFIR to more clearly exhibit structure in galaxies and protostars, and to more completely define evolutionary processes. In other words, SAFIR and SPECS fulfill complementary roles and will provide information vital to the attainment of major Universe Division scientific objectives. Concurrently with the SAFIR study, NASA also undertook a study of SPECS under the Vision Mission program. Throughout the study period, technical information was exchanged between the two study teams to maximize progress on both fronts.

The *Community Plan for Far-IR/Submillimeter Space Astronomy* addresses practical issues associated with implementing the Decadal Report recommendations and gives the consensus view of the infrared astronomical community. The *Community Plan* recognizes the need for a structurally-connected far-IR interferometer as a rational step toward the more ambitious SPECS mission, which requires formation flying. NASA selected the 1 m x 36 m baseline SPIRIT for study as such a candidate Origins Probe mission.

SAFIR, SPIRIT, and SPECS share not only scientific synergy, but also a host of technical challenges. Most significantly, all three observatories require arrays of similarly sensitive direct detectors with efficient readout electronics; they require 4 K optics and achieve this with a combination of multi-layered sun shades, powerful and efficient cryocoolers, and sub-scale engineering tests to validate the thermal models that will be used to predict in-space performance; and they require mechanisms that operate at cryogenic temperatures and generate very modest parasitic heat loads.

The far-IR missions SAFIR, SPIRIT and SPECS provide measurement capabilities which complement those of JWST and the Atacama Large Millimeter Array (ALMA). Key questions that motivate NASA's Universe Division, such as "How do planetary systems form?" and "What is the history and fate of the Universe?" can only be answered with the full suite of observatories that embrace large collecting area as well as high spatial resolution. Collectively these telescopes will provide sensitive high angular resolution imaging and spectroscopic observations in the optical-to-millimeter spectral range, and they will see nearly all of the energy generated in the Universe since the decoupling of radiation from matter. To help explain the importance of high-angular resolution far-IR measurements in the era of ALMA, we note that the rich spectrum of H_2O emission lines is uniquely available in the far-IR, and that the spectral energy distributions of merging galaxies, protostars and protoplanetary disks, and exozodiacal debris disks all peak in the far-IR. Thus, for example, while ALMA will see the cold dust in debris disks, SAFIR, SPIRIT and SPECS will be needed to image the bulk of the emission.