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The SPIRIT and SPECS Far-Infrared/Submillimeter Interferometry Missions

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Abstract: Space-based far IR/submillimeter (FIR/SMM) interferometry is needed to answer fundamental cosmological questions concerning the development of structure in the Universe and could also be used to probe nearby objects such as protostars, young planetary systems, and debris disks in unprecedented detail. We describe concepts for the *Space Infrared Interferometric Telescope* (SPIRIT) and the *Submillimeter Probe of the Evolution of Cosmic Structure* (SPECS). Both are imaging and spectral Michelson interferometers operating in the wavelength range ∼40–500 μm. The individual light-collecting mirrors are comparable in size and temperature to the HII/L2 primary mirror. SPIRIT, which could be launched in a decade, is built on a deployable boom and has a maximum baseline of ∼30–50 m, providing arcsecond resolution in the far-IR. SPECS uses formation flying to attain baseline lengths up to ∼ 1 km, and thus angular resolution comparable to that of the Hubble Space Telescope (HST), the Next Generation Space Telescope (NGST), and the Atacama Large Millimeter Array (ALMA). SPIRIT and SPECS would provide access to many important cooling and diagnostic spectral lines and to the bulk of the thermal emission from dust, and make observations complementary to those obtained with ALMA and NGST.

1. THE SCIENCE POTENTIAL OF FIR/SMM INTERFEROMETRY

About half of the luminosity and 98% of the photons released since the Big Bang are emitted in the far-infrared. Evidence for this can be found both in the spectra of individual galaxies (see, e.g. Trentham et al. 1999) and in the cosmic FIR/SMM background found by COBE (Hauser et al. 1998; Fixsen et al. 1998; Dwek et al. 1998). Based on their JCMT/SCUBA observations and referring to this background, Cowie & Barger (1999) conclude that "it is created by a population of ultraluminous (or near ultraluminous) infrared galaxies ... the bulk of [them found in the redshift interval] z =1–3".

Sensitive, high-resolution observations of FIR/SMM emission can be used to measure the physical conditions in remote galaxies, Active Galactic Nuclei, protostars, and planetary debris disks. Familiar mechanisms give rise to this emission, and it is only minimally affected by

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extinction. Heated interstellar dust glows in the wavelength interval 40–200 μm, a spectral region that also contains many important interstellar cooling and diagnostic lines. For example, the [C II] 158 μm line, the brightest line in the spectrum of the Milky Way, can be used to estimate the amount of star forming activity in a distant galaxy. A plethora of H_2O and CO lines serve as coolants and bear valuable information about the conditions in collapsing, star-forming molecular clouds (Harwit et al. 1998; Neufeld 1998). Rest frame mid-IR neon line emission can be used to distinguish thermal from nonthermal emissions (Voit 1992). Spectral patterns of bright lines can be used to measure redshifts and the kinematics of gas within distant galaxies, yielding rotation curves in some cases and information about the dynamics of mergers, interactions, and galaxy formation in others. H II regions and supernova remnants are characterized by warm dust continuum emission and are bright, discrete IR sources. By studying these signposts of massive star formation in a large sample of galaxies we can expect to gain new insights into the star formation process.

A variety of science goals are uniquely enabled by FIR/SMM interferometry. Among the most compelling of these goals is the aim to understand the formation and development of structure in the Universe (Mather et al. 2000). With FIR/SMM interferometers we could measure the cosmic history of energy release, nucleosynthesis, and dust formation and study the feedback effects of Population III stars on those that came later. We could probe the physical conditions in collapsing molecular cloud cores to better understand the star and planet formation processes.

To learn how galaxies form and evolve it is essential but not sufficient to measure UV/visible starlight redshifted toward the near-IR. Most of the sources that comprise the FIR/SMM background are extremely faint in the optical and near-infrared (Cowie & Barger 1999). Dust obscures our view of the Universe at these shorter wavelengths, often frustrating attempts to measure star formation rates accurately or peer into the centers of galaxies or star forming regions. Studies of Active Galactic Nuclei, for example, have thus far been hampered by our inability to see into the dust-obscured galactic nuclear region.

Limited by available technology, the huge science potential of the FIR/SMM has remained largely unexploited. At these wavelengths, diffraction limited optics have poor angular resolution and sensitive instruments quickly reach the confusion limit. However, thanks to the anticipated availability of sensitive new detectors and the fact that far IR photons are plentiful, it is now practical to consider building a spatial and spectral interferometer constructed from movable cryogenic mirrors comparable in size to the mirror proposed for HII/L2 (Nakagawa et al. 1998).

Here we describe concepts for two space missions: the *Space Infrared Interferometric Telescope* (SPIRIT) and the *Submillimeter Probe of the Evolution of Cosmic Structure* (SPECS). A major goal for SPIRIT is to resolve the cosmic infrared background into discrete sources and make the spectroscopic measurements needed to characterize them. The primary goal of SPECS is to provide a definitive observational basis for understanding the history of and the processes that drive the development of complex structure from the homogeneous early universe.

2. THE SPIRIT AND SPECS CONCEPTS

Table 1 summarizes the desired measurement capabilities and defining characteristics of SPIRIT and SPECS. The main difference between the two instruments is in the maximum baseline length. SPIRIT will be built on a deployable boom, limiting its length to about 30–50 m, whereas SPECS will use formation flying to reach 1 km baselines. Both interferometers will densely sample the $u-v$ plane to provide high quality images, and both will provide sufficiently high spectral resolving power to enable the detection of galactic emission lines. The spectral range is optimum to address the scientific objectives outlined above, and will be complementary to that of the NGST at shorter wavelengths and the ALMA at longer wavelengths.

Table 1: Characteristics and capabilities of SPIRIT and SPECS.

Parameter	SPIRIT	SPECS
Wavelength range	40–500 μm	40–500 μm
Spectral resolution	up to 10^4	up to 10^4
Maximum baseline, b_{max}	up to ~30 m	up to 1 km
Number of collecting mirrors	2	3
Mirror diameter	3 m	4 m
Angular resolution, λ/b_{max}	$2.1''$ for 300 μm, 30 m	$0.06''$ for 300 μm, 1 km
Field of view	$3.4'$	$3.4'$
Resolution elements	100×100 at 300 μm	$3,400 \times 3,400$ at 300 μm
Typical exposure time	3×10^4 s	3×10^5 s
Typical sensitivity, νS_ν (1σ)		
At $\lambda/\Delta\lambda = 1,000$	2–5 $\times 10^{-18}$ W m^{-2}	0.5–2 $\times 10^{-18}$ W m^{-2}
At $\lambda/\Delta\lambda = 3$ (SED mode)	0.3–2 $\times 10^{-19}$ W m^{-2}	0.3–1 $\times 10^{-19}$ W m^{-2}

SPIRIT and SPECS are Michelson spatial and spectral interferometers. Thousands of primary beams will be observed in parallel using array detectors, providing the desired wide field of view. To achieve the best possible sensitivity from their location at the Sun-Earth L2 point, SPIRIT and SPECS will use cryogenic mirrors and next-generation detectors that approach fundamental quantum noise limits.

During an observation the flat mirrors used as siderostats will be moved around to completely cover the $u-v$ plane. The SPECS mirrors could be tethered together and spun in a spiral pattern, alleviating the need for an enormous amount of thruster propellant. Likewise, the SPIRIT boom will spin to vary the baseline orientation. Spectral information is obtained by scanning the delay line to measure the fringe visibility as a function of optical path length at each mirror position.

The following technologies are critical to the success of SPIRIT and SPECS (Leisawitz et al. 2000; Shao et al. 2000) and require further development: sensitive far IR detector arrays; lightweight, cryogenic optical systems; formation flying; active coolers; long-stroke, cryogenic Michelson interferometers; and wide-field mosaic imaging. Some of the enabling technology developments will be driven by other needs and can be adapted or inherited. For example, NGST requires lightweight, deployable optics, ASTRO-F uses mechanical coolers, and the Terrestrial Planet Finder uses formation flying. Excellent progress is being made on the detector frontier, and far-IR photon counting detectors are on the horizon (Moseley 2000; Schoelkopf 2000; Bock 2000). A laboratory instrument called the Wide-field Imaging Interferometry Testbed, now under development, is designed to demonstrate wide- field mosaic imaging and enable performance optimization through instrument design and data processing (Leisawitz 1999; Feinberg 2000).

Figure 1 compares the sensitivity of SPIRIT and SPECS with that of the planned IR missions SIRTF and FIRST, the near-IR sensitivity of NGST, and the submillimeter sensitivity of ALMA. Both broadband ($R = \lambda/\Delta\lambda = 3$) and $R = 1,000$ sensitivity curves are shown for SPIRIT and SPECS (heavy solid curves), but only broadband values are shown for the other instruments. HII/L2 would be comparable in sensitivity to NGST in the mid-IR and, although confusion-limited at longer wavelengths, would provide sensitivity comparable to that of SIRTF at wavelengths extending out to 200 μm (Nakagawa et al. 1998). The exposure times for complete aperture synthesis with SPIRIT and SPECS (see Table 1) are somewhat longer than the 1×10^4 s assumed for the other instruments. The interferometers do not run up against the confusion limit and can go significantly deeper. Four galactic spectra are also shown in Figure 1 for comparison. One (dashed line) represents the Milky Way at a redshift $z = 1$. Typical ultraluminous IR galaxy spectra at $z = 1$, 2, and 5 are shown with thin solid lines. Small vertical arrows mark the location of the [C II] 158μm line. Figure 1 shows that SPIRIT and SPECS will detect galaxies of these types. SPECS will resolve them.

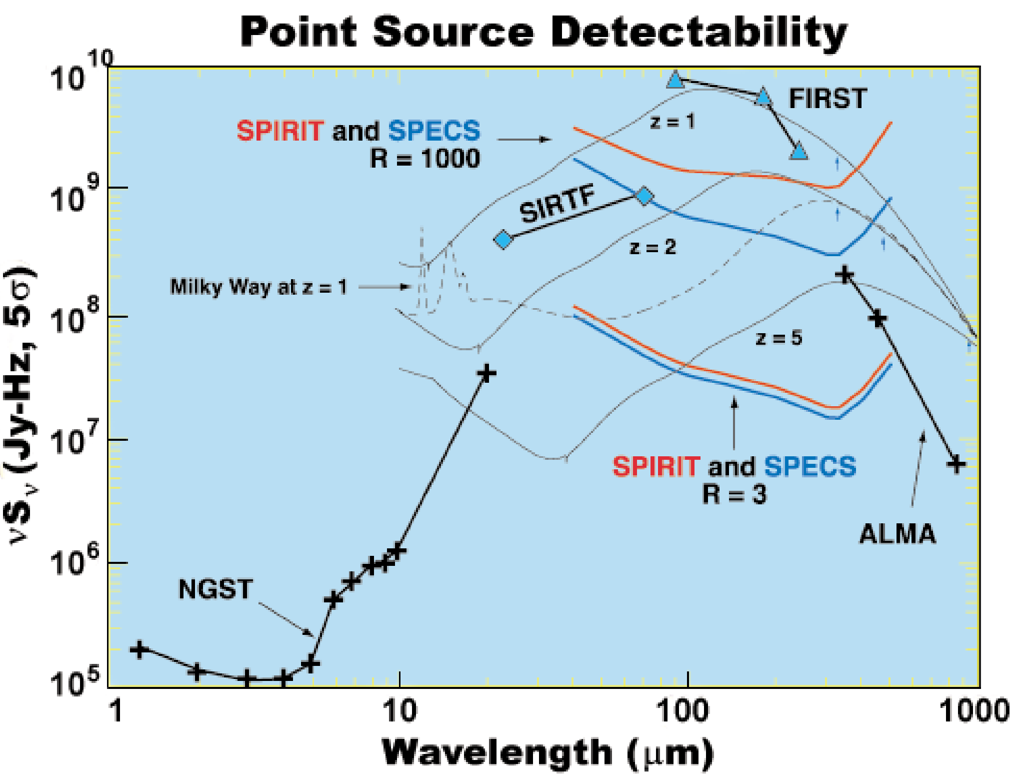

Fig. 1: SPIRIT and SPECS will have sensitivity comparable to that of NGST and ALMA over a spectral range that bridges the gap between them. The FIR/SMM interferometers will be able to measure cooling and diagnostic lines in the spectra of high-z galaxies.

3. SUMMARY

Space-based far IR/submillimeter imaging and spectral interferometry is needed to answer fundamental cosmological questions concerning the development of structure in the Universe and could also be used to probe nearby objects such as protoplanetary disks and star forming regions in unprecedented detail. The SPIRIT and SPECS interferometers would be complementary in their capabilities and objectives to NGST and ALMA. In particular, they would provide access to a large number of important cooling and diagnostic spectral lines from ions, atoms, and molecules, and to the bulk of the thermal emission from dust. Together, NGST, SPECS and ALMA would provide virtually continuous spectral coverage at tens of milliarcsecond resolution from visible to millimeter wavelengths. SPIRIT would demonstrate the technologies needed to build SPECS and, for the first time, provide the angular resolution and sensitivity needed to resolve the cosmic infrared background.

In light of recent technology developments, especially the possibility of background-limited photon counting detectors in the far-infrared, it is now practical to consider building these instruments. In the US, the National Academy of Sciences has recommended that a concerted effort be made to develop the technologies required to enable space-based far-infrared interferometry in the coming decade in order to enable the deployment of a far-IR interferometer in the decade beginning in 2010 (McKee & Taylor 2000). SPIRIT and SPECS are large projects which, if past trends persist, will likely afford opportunities for international collaboration.

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