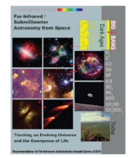
The Space Infrared Interferometric Telescope (SPIRIT): A Far-IR Observatory for High-resolution Imaging and Spectroscopy

D. Leisawitz (NASA/GSFC) and the SPIRIT Mission Study Team

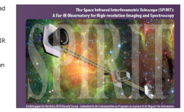
The NASA Astrophysics Roadmap calls for a far-IR interferometer – the "FIR Surveyor" – to deliver "crucial science" in the Formative Era (2020s), where it would serve as "a logical starting point" and "a training ground" for more ambitious shorter-wavelength interferometers in the Visionary Era (2030s and beyond). A "Probe-class" far-IR interferometer is well within NASA's technical and fiscal means and motivated by some of the most compelling questions posed in the Decadal survey.

SPIRIT is a two-telescope Michelson interferometer operating over the far-infrared wavelength range 25 to 400 μm and offering a powerful combination of spectroscopy ($\lambda/\Delta\lambda \sim 3000$) and sub-arcsecond angular resolution imaging (integral field spectroscopy) in every arcminute-sized field observed. With angular resolution two orders of magnitude better than that of the *Spitzer Space Telescope*, and with comparable sensitivity, SPIRIT will revolutionize our understanding of the formation of planetary systems, map debris disk structure to find otherwise-undetectable planets, and make profound contributions to our understanding of the formation and evolution of galaxies.

SPIRIT has two afocal, off-axis telescopes with 1 m diameter primary mirrors. Its single scientific instrument serves a dual purpose: it combines the telescope beams and provides variable optical delay for Fourier transform spectroscopy, a technique now approaching TRL 6 (see companion poster on Wide-field Spatio-spectral Interferometry). The SPIRIT telescopes are moveable across the length of a rotating 36 m long structure and are thus capable of densely sampling the *u-v* plane for high-quality imaging. Cryocoolers similar to the one developed for JWST are used to cool the optics to 4 K, cold baffles reject stray thermal radiation, and next-generation detectors cooled to ~50 mK will enable measurements limited by astrophysical background photon noise. Metrology tolerances are coarser than those in interferometers or segmented mirror telescopes designed to operate at shorter wavelengths; alignment and pathlength control are well within reach of current technical capability, leaving only subsystem details to be proven in a flight-like environment. Two balloon-borne far-IR interferometers - BETTII and FITE - will fly in the next couple of years.



The SPIRIT study was sponsored by NASA under the Origins Science Mission Concept study program. SPIRIT was recommended in the 2009 far-IR "Community Plan," which was submitted to the 2010 Decadal Survey, as was a SPIRIT mission concept white paper.



SPIRIT Mission Study Team

Science Team

Amy Barger (Univ. Wisconsin)
Dominic Benford (GSFC)
Andrew Blain (Caltech)
John Carpenter (Caltech)
Jackie Fischer (NRL)
Jonathan Gardner (GSFC)
Martin Harwit (Cornell)
Lynne Hillenbrand (Caltech)
Alan Kogut (GSFC)
Marc Kuchner (Princeton)
Dave Leisawitz (GSFC), PI
Amy Mainzer (JPL)
John Mather (GSFC)
Lee Mundy (Univ. Maryland)
Stephen Rinehart (GSFC)
Robert Silverberg (GSFC)
Gordon Stacey (Cornell)
Johannes Staguhn (SSAI)

Engineering Team
(at GSFC unless noted otherwise)

Dave DiPietro, Mission Systems Engineer
Jim Kellogg, Instrument Systems Engineer
Tupper Hyde, Instrument Architect
Kate Hartman, Project Formulation Manager

Charles Baker, Thermal
Dominic Benford, Detectors
Rob Boyle, Cryocoolers
Richard Broderick, Power
Jason Budinoff, Mechanisms
Richard Caverly, Propulsion
Phil Chen, Contamination
Steve Cooley, Flight Dynamics
Christine Cottingham, Thermal
Julie Crooke, Optics I&T
Mike DiPirro, Cryogenics
Michael Femiano, GN&C
Art Ferrer, C&DH
Lou Hallock, Flight Software
Kenny Harris, Structure
Drew Jones, Mechanical Drawings
Bill Lawson, PRICE H Cost Lead
Javier Lecha, Mechanism Electronics
Maria Lecha, Communications
Jim Mannion, Cost Advisor
Tony Martino, Metrology
Paul Mason, Controls
Gibran McDonald, Cost Lead
Rick Mills, Electrical Systems
Stan Ollendorf, Sr.Eng. Consultant
Joe Pellicciotti, Mechanical
Dave Quinn, Flight Dynamics
Kirk Rhee, Integration and Test
Stephen Rinehart, Instr. Scientist
Tim Sauerwine, Instrument I&T
Terry Smith, Instrument Electronics
Phil Stahl (MSFC), Optics Consultant
Steve Tompkins, Operations
June Tveekrem, Stray Light
Sheila Wall, Mechanical Analysis
Mark Wilson, Optical Design

Advisory Review Panel

Gary Melnick (SAO), Chair
Dave Miller (MIT)
Harvey Moseley (GSFC)
Gene Serabyn (JPL)
Mike Shao (JPL)
Wes Traub (SAO)
Steve Unwin (JPL)
Ned Wright (UCLA)

Additional Contributors to the Decadal Survey white paper:
Peter Ade (U. Cardif, UK), Ben Braam (TNO, The Netherlands), Martin Caldwell (RAL, UK), John Carr (NRL), Peter Day (JPL), Drake Deming (GSFC), Nick Elias (U. Heidelberg, Germany), Mike Fich (U. Waterloo, Canada), Paul Goldsmith (JPL), Jane Greaves (U. St. Andrews), Frank Helmich (SRON, The Netherlands), George Helou (IPAC, Caltech), Rob Ivison (ATC, UK), Hannah Jang-Condell (UMD), Claudia Knez (UMD), Bill Langer (JPL), Carey Lisse (JHU/APL), Rick Lyon (GSFC), Hiroshi Matsuo (NAO, Japan), Aki Roberge (GSFC), Hiroshi Shibai (Nagoya U., Japan), Ken Stewart (NRL), Alycia Weinberger (Carnegie DTM), Mike Weiss (GSFC), and David Wilner (SAO)

SCIENTIFIC OBJECTIVES FROM THE DECADAL SURVEY

- Discover how the conditions for planet habitability arise during the planet formation process. (Follow the water!)
- Find and characterize exoplanets by imaging and measuring the structures in protoplanetary and debris disks, and by looking for changes on orbital timescales.
- Study the formation, merger history, and star formation history of galaxies. (How did a hot, smooth universe give rise to the Milky Way?)

MEASUREMENT REQUIREMENTS

Table 1: SPIRIT Measurement Requirements

Wavelength range	25 – 400 μm
Instantaneous FoV	1 arcmin
Angular Resolution	0.3 (λ/100 μm) arcsec
Spectral Resolution	3000
Point Source Sensitivity (5σ, 24 hours)	Spectral line: 10^{-19} W m^{-2} Continuum: 10 μJy
Science Time per Field	24 hours
Field of Regard	40° band centered on ecliptic

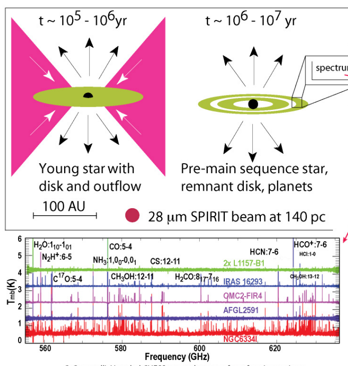


Figure 1. SPIRIT will map the distribution of gas and dust in young and developing planetary systems to test theoretical models and elucidate the planet formation process. SPIRIT will trace the distribution of water in its gaseous and solid states and teach us how our planet acquired its life-enabling oceans.

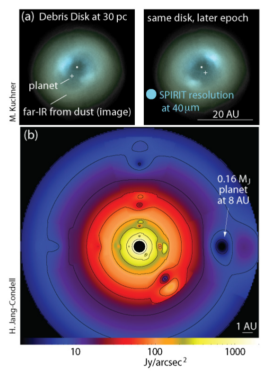


Figure 2. With angular resolution a hundred-fold better than that of *Spitzer*, SPIRIT will image a large statistical sample of debris disks (a) and protoplanetary systems (b), enabling new discoveries of exoplanets and proto-planets and a great improvement in our understanding of the factors that influence the development of planetary systems.

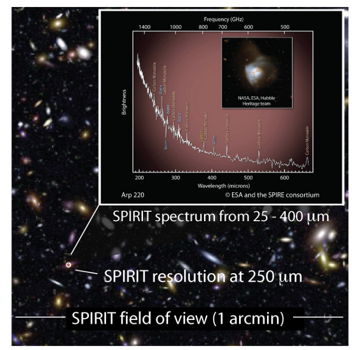


Figure 3. For the first time, SPIRIT will isolate the rest frame far-IR emissions of individual non-local extragalactic objects in the important z < 3 redshift range. Major interstellar cooling and diagnostic spectral lines and features will be accessible to SPIRIT, complementing the measurement capabilities of JWST and ALMA.

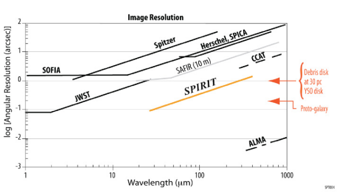


Figure 4. SPIRIT will deliver one hundred times better angular resolution than Spitzer, and resolution comparable to that of JWST, but at ten times longer wavelengths, where protoplanetary disks, debris disks, and some galaxies emit most of their light.

TECHNIQUE

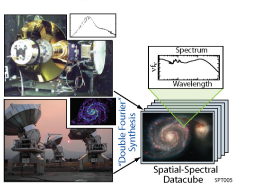


Figure 5. SPIRIT combines the capabilities of an imaging interferometer (e.g., CARMA, lower left) with those of a Fourier Transform Spectrometer (e.g., Cassini/CIRS, upper left) to produce spatial-spectral data cubes.

SPIRIT MISSION CONCEPT

Figure 6. Major components of the SPIRIT observatory are two movable afocal off-axis telescopes and a single beam-combining instrument. SPIRIT densely samples the *u-v* plane and provides high-quality images.

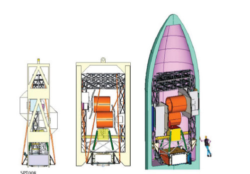


Figure 7. SPIRIT and its expendable launch support structure (left, two views), when stowed for launch, are 8.7 m tall and fit into an EELV 5 m medium-length fairing dynamic envelope.

Table 2: SPIRIT Origins Probe Design Parameters

Parameter	Value
Phase B start to launch	72 months (incl. 10 month margin)
Instrument	Michelson beam combiner, double Fourier
Telescopes	2 off-axis, afocal
Telescope diameter	1.0 m
Angular resolution[1]	0.3 (λ/100 μm) arcsec
Field of view	1 arcmin
Baseline range	"zero spacing" plus 6 m to 36 m
Optics temperature	4 K, cryocooled
ODL mechanism scan range	6.15 cm (physical)
Spectral resolution[1]	3175, 5058, 4265, and 3000 at 35, 70, 140, and 280 μm, respectively
Focal plane temperature	30 mK via CADR
Structure	Rigid truss
Sunshield location	Above boom
Uncalibrated point source visibility, V[1]	0.98, $V = (I_{max} - I_{min})/(I_{max} + I_{min})$
Typical time per field	29 hours (24 hours for science)
Point Source Sensitivity[1] (5σ, 24 hours)	Spectral line (10^{-19} W m^{-2}): 2.9, 1.7, 1.4 and 1.3 Continuum (μJy): 14, 20, 31, and 48, at 35, 70, 140, and 280 μm, respectively
Science data rate[1]	5.4 Mb/s
Propulsion system	Hydrazine (monoprop.)
ACS type, accuracy	6 rx wheels, 100 Nm/s, 5.0 arcsec
Star trackers	Two on boom
Slew rate (peak)	1 deg per min
High gain antenna type	Ka band, two-axis gimbal
Ground contacts	2.0 hr/2 days DSN, Ka band
Observatory mass (wet)	4497 kg (incl. 25% contingency)
Instrument power (EOL)	1081 W for beam combiner + 1036 W per telescope (incl. 25% contingency)
Launch vehicle and fairing	EELV with 5m diam., medium length fairing
Orbit	Sun-Earth L2 Lissajous
Mission life at L2	3 years (propellant for 5)
[1]Derived quantity	

ENABLING TECHNOLOGY

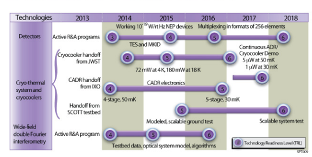


Figure 8. The technology development plan for SPIRIT builds on existing heritage and past investments to mature all the mission enabling technologies from their present state to TRL 6 in four years.

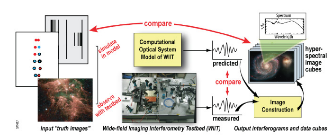
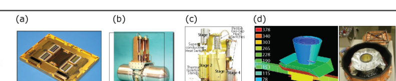


Figure 9. WIIT, a laboratory testbed functionally equivalent to SPIRIT, and a high-fidelity model of the testbed, are giving us practical experience with the wide-field spatio-spectral interferometric technique to be used on SPIRIT (see companion poster paper).

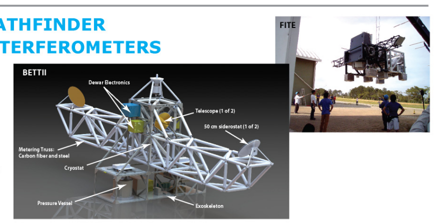
Figure 10. TES bolometers (a) or MKIDs are viable candidate detectors for SPIRIT. With straightforward modifications, the JWST cryocooler (b) and the Continuous Adiabatic Demagnetization Refrigerator (CADR; c) will reach TRL 6 for SPIRIT. Heat loads and cryocooler requirements were based on a 106-node thermal model (d, left). Subscale cryothermal testing in a LHe shroud validated the model (d, right).



BALLOON-BORNE PATHFINDER FAR-INFRARED INTERFEROMETERS

Figure 11. Japan has built and will soon fly the Far-Infrared Telescope Experiment (FITE; far right), a balloon-borne far-IR Fizeau interferometer (H. Shibai, PI).

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) is a SPIRIT prototype, a spatio-spectral Michelson interferometer. BETTII (S. Rinehart, PI) is in development with a first flight planned in 2015. See companion poster on BETTII.



http://astrophysics.gsfc.nasa.gov/cosmology/spirit/