SPECS

The Kilometer-baseline Far-IR Interferometer in NASA's Space Science Roadmap

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\textbf{Industrial Partners:}
Ball Aerospace, Boeing, Lockheed Martin, Northrop Grumman
Outline

• Context: community planning and study status
• Science goals
• Mission requirements
• Mission concepts for SPIRIT and SPECS
• Tethered formation flying, a key enabling technology
The Path Leading to SPECS

In Europe, two white papers submitted for Cosmic Vision planning also call for far-infrared/submillimeter space interferometry.
Missions to be discussed

Submillimeter Probe of the Evolution of Cosmic Structure

Space Infrared Interferometric Telescope

Missions:
- COBE
- IRAS
- ISO
- Spitzer
- SOFIA
- Herschel
- SPICA
- "now"
- SPECS
- SPIRIT

Timeline:
- 2010
- 2020
Mission Study Status

• The Infrared Era has begun
  • Spitzer now
  • Herschel soon
  • international community and public interest
  • new information from Spitzer available for mission planning

• Key elements of the Community Plan are being implemented
  • SAFIR and SPECS Vision Mission studies underway
  • SPIRIT “Origins Probe” study underway
  • Opportunities to report to NASA’s Astronomy and Physics Roadmap Committees coming in December and January
  • Reasonable progress on all technology frontiers
The Importance of High Angular Resolution
The Importance of High Angular Resolution

T Tauri star, disk, outflow

$\varepsilon$ Eri debris disk

40, 60, 100 $\mu$m

2.4 arcmin

200, 400, 600 $\mu$m

$t \sim 10^5 - 10^6$ yr

100 AU
The Importance of High Angular Resolution

- Proto-galaxy at z ~ 5
- YSO disk at 140 pc
- Debris disk at 30 pc
- Proto-galaxy at z ~ 5
The Importance of High Angular Resolution

![Graph showing the importance of high angular resolution with various observations at different wavelengths and angular resolutions.]

- Proto-galaxy at $z \sim 5$
- YSO disk at 140 pc
- Debris disk at 30 pc
- SOFIA
- JWST
- Spitzer
- Herschel
- SAFIR
- SPIRIT
- SPECS
- ALMA

SP003
Sensitivity Requirements: Distant and Local

To see an L* galaxy at high z, need better than 1 µJy sensitivity. Protogalaxies might have been ~100x fainter.

To image debris disk dust emission on a 1 AU scale, need ~1 µJy sensitivity.
Why Interferometry?

An interferometer is a good design choice when angular resolution rather than sensitivity drives the aperture size requirement.

**Spatial resolution:**

\[ \Delta \theta = 10 \text{ mas} \left( \frac{\lambda}{100 \mu m} \right) \left( \frac{b_{\text{max}}}{1 \text{ km}} \right)^{-1} \]

for maximum baseline \( b_{\text{max}} \) at wavelength \( \lambda \). (For comparison, a diffraction limited 10 m telescope provides 2.5 arcsec resolution at 100 \( \mu \text{m} \).)

**Spectral line sensitivity for an unresolved (point) source:**

\[ \text{MDLF} \sim 7 \times 10^{-22} \text{ W/m}^2 \left\{ \text{FBW} \ I_v, bg \text{(MJy/sr)} / [n(n-1)(\tau_{\text{sys}}/0.1)] \right\}^{1/2} (D/4m)^{-2} (t/10^5s)^{-1/2} \]

for \( n = 3 \) mirrors of diameter \( D \) in integration time \( t \), where \( \tau_{\text{sys}} \) is the system efficiency and \( \text{FBW} \), the fractional bandwidth, could be ~0.7.

In the far-IR/sub-mm, a total light collecting area comparable to that of JWST provides ample sensitivity, but an effective aperture diameter \( b_{\text{max}} \) of ~30 - 50 m is needed to overcome extragalactic source confusion into the sub-mm, 1 km to provide HST (or JWST) class angular resolution.
Far-IR Diagnostic Potential

Spectroscopy is vital to our ability to answer the important science questions.

For extragalactic problems we might be satisfied to measure the integrated line intensity. R ~ 1000 would be okay.

However, for star formation research we are interested in resolving lines. For this we desire R > 10^5.

<table>
<thead>
<tr>
<th>Typical Spectral Lines</th>
<th>Derived Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>H recombination lines</td>
<td>Age, IMF, starburst luminosity</td>
</tr>
<tr>
<td>Dust features</td>
<td>Starburst luminosity</td>
</tr>
</tbody>
</table>

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<tr>
<th>Active Galactic Nuclei (AGN)</th>
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<tbody>
<tr>
<td>Broad H recombination lines</td>
</tr>
<tr>
<td>Dust features</td>
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</tbody>
</table>

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<tr>
<th>Interstellar Medium (ISM)</th>
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<tbody>
<tr>
<td>All Ne lines, H recombination</td>
</tr>
<tr>
<td>AGN Narrow Line Region (NLR)</td>
</tr>
<tr>
<td>[NeV]14/[NeIII]15</td>
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<table>
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<tr>
<th>Photon Dominated Regions, Shocks</th>
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<tr>
<th>Molecular Clouds, Protostars, and Disks</th>
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<tbody>
<tr>
<td>Rotational and rovibrational lines of H&lt;sub&gt;2&lt;/sub&gt;O, CO, and small hydrides</td>
</tr>
</tbody>
</table>

<sup>1</sup> Rest wavelengths in µm, but redshifted at high z
<sup>2</sup> Spectral Energy Distribution
<sup>3</sup> Ionization parameter
<sup>4</sup> Initial Mass Function
**Science Goals**

- Characterize the epoch of first generation star formation
- Probe the luminosity evolution and physical conditions in galaxies since the epoch at which they formed
- Observe the chemical and dynamical processes that lead to the formation of stars
- Image the dusty disks around newly formed stars to study temperature, density, grain size distribution and chemical fractionation to learn how planetary systems form

**Measurement Capabilities**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Requirement</th>
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<tbody>
<tr>
<td><strong>Far-IR and Submillimeter Imaging and Spectroscopy</strong></td>
<td></td>
</tr>
<tr>
<td>Spectral Range</td>
<td>40 - 600 µm required</td>
</tr>
<tr>
<td></td>
<td>30 - 800 µm desirable</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>0.05 (λ / 250 µm) arcsec</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>λ/Δλ = 1000 for galaxies and 10^4 for protostars</td>
</tr>
<tr>
<td>Field of View</td>
<td>1′ required, &gt;1.5′ desired</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1 µJy for continuum and 10^{-22} Wm^{-2} for spectral lines in 10^2 sec</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>10^3 - 10^4</td>
</tr>
<tr>
<td>Observations</td>
<td>At least one target a day</td>
</tr>
</tbody>
</table>

**Engineering Implications**

- 2 or 3 light collectors plus Michelson beam combiner and spectrometer
- 3 - 10 m diameter collector mirrors
- 4 K optics
- 0.5 µm mirror surface
- Metrology to ~1 µm
- sub-arcsecond relative pointing
- Detectors
  - NEP < 10^{-20} W Hz^{-1/2}
  - 50 x 50 pixel array
- Orientation
  - Able to view at least +/-20° from ecliptic
- Active and passive cooling
- 0.1 K coolers
- Mechanical coolers
- 4K cooling loops
- Deployable multi-layer sunshields

**Key Technologies**

- **Formation flying**
  - Tethers in spin-stabilized formation
  - Inertial referencing for phasing, guiding
- **Optics and interferometry**
  - Lightweight 4K optics (3 - 10 m)
  - Wide-field imaging interferometry
  - Cryogenic delay line

**From analysis of the science team’s Design Reference Mission (“use cases”)**
SPIRIT Mission Concept

SPIRIT could fly in the next decade as an Origins Probe

Collector telescopes move radially and boom spins to provide u-v coverage

All optics cooled to 4K
SPECS Mission Concept

Fully extended array

Tether configuration developed by Farley and Quinn (2001)
SPECS Mission Concept

Partially contracted array

2-collector systems and off-axis afocal telescopes are under study
SPECS Simple Concept

Linear array

Tether instead of the SPIRIT boom
Technology Requirements

SAFIR
- Deployable mirror with active surface control
- Large format detector arrays with fast, low-power readout and ultra-high sensitivity
- Deployable multi-layer Sun shields
- Lightweight mirrors with surface accuracy ~1 μm
- Advanced active/passive cooling systems

SPECS
- Long-stroke cryogenic delay line
- Wide-field imaging interferometry
- Low-vibration deployable structures
- Highly reconfigurable formation flying

- Stable boom and metrology in common with SIM
- Wide-field double Fourier technique in common with TPF-I/Darwin
Highly Reconfigurable Arrays

• “Highly reconfigurable” for dense $u$-$v$ plane coverage
• Rotating deployable boom with light collectors on trolleys - works for $b_{\text{max}}$ up to $\sim$50 m
• Formation flying works for $b_{\text{max}}$ up to $\sim$200 m (too much thruster propellant or too few images per mission if $b_{\text{max}}$ bigger)
• Formation flying with tethers works for $b_{\text{max}}$ up to $\sim$1 km
  • Quinn et al. study suggests viability, addresses requirements, alternative architectures, re-pointing; tools developed to facilitate further analysis
  • Lorenzini et al. have analyzed tether dynamics
  • Sell et al. adapting SPHEREs to test tethers, could lead to air table demo and first space demo
• Need inexpensive long-baseline space demo scalable to SPECS
Formation Flying with Tethers

• Propellant mass prohibitively large for a highly-reconfigurable, km-baseline array (essential for good image quality)

• Tethers have many advantages:
  – light weight
  – passive stability
  – ease of reconfiguration
  – easier metrology and spacecraft relative bearing
  – planar spin-stabilized tethered configuration can have many shapes

• Centrifugal forces in the spin plane provide tether tension and shape stability

• High angular momentum due to spin provides stable pointing to target and low sensitivity to external torques

• For heliocentric and L2 halo orbits cm-level stability of tethered units is provided by spin-stability with no need for thruster control during station-keeping

• Tether oscillations, excited by maneuvers, can be damped out in minutes (long baselines) or seconds (short baselines)

• With damping, tethered formation naturally converges to rigid flat spin configuration

• Tether noise spectrum is at low frequency (periods from a fraction of a second to a minute)
Summary

• SPIRIT and SPECS satisfy critical needs of NASA’s space science program (e.g., characterize exo-zodi debris disks) and address compelling scientific questions (How did we wind up on a watery rock orbiting the Sun in the disk of a spiral galaxy?)

• Broad support exists for far-IR/sub-mm space interferometry in the international scientific community

• SPIRIT could fly next decade as an “Origins Probe” (SPECS will come later)

• Formation flying with tethers is an enabling technology for space-based long-baseline imaging interferometry