The Future of Far-Infrared Astrophysics: Complementary Space Missions and Terrestrial Observatories

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Abstract

The NRAO is considering its long-term role in far-infrared (FIR) astrophysics. ALMA and JVLA are huge heterodyne interferometers able to image faint sources with high sensitivity, fidelity, angular resolution, and spectral resolution. However, the atmosphere blocks $z = 0$ spectral lines of many terrestrial molecules above $\nu \sim 300$ GHz and most continuum above $\nu \sim 1$ THz. Small direct-detection interferometers in orbits near L2 are very sensitive but have limited spatial and spectral resolution. Larger heterodyne interferometers in near-Earth orbits have higher spatial and spectral resolution but suffer from quantum noise and small bandwidth.

Perhaps no single instrument can provide the frequency coverage, sensitivity, angular resolution, and spectral resolution needed, for example, to image water molecules inside the "frost line" of nearby circumstellar disks. Future FIR astrophysics may be best served by maximizing the complementary strengths of space missions and terrestrial observatories.

Science Goals

1) Evolution of Galaxies from Early Times to the Present
2) The Obscured Universe: Dust-Shrouded AGN tori and the Formation of Stars and Planets
3) The Chemical Evolution of the Universe — The Origins of Biogenic Molecules

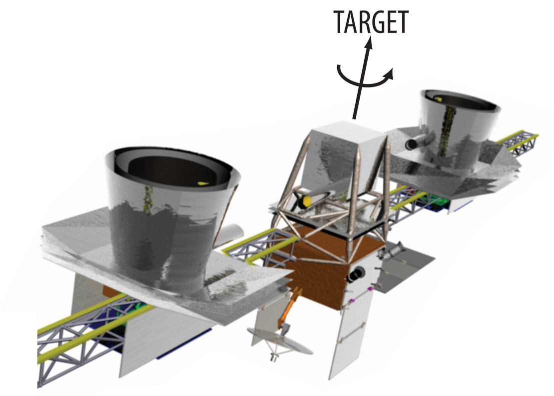
(Harwit et al. 2009, Leisawitz et al. 2009)

Technical Requirements

1) Angular resolution $\theta \sim \lambda/D_{max} \sim 0.1$ arcsec FWHM at $\lambda > 150$ μm (for source transparency)
2) Spectral resolution $R \sim 3 \times 10^5$ (velocity $\Delta v \sim 1$ km s^{-1} for Galactic sources), and $R \sim 3000$ ($\Delta v \sim 100$ km s^{-1} for distant galaxies)
3) Instantaneous bandwidth $\Delta\nu / \nu > 1/300$ ($\Delta v > 1000$ km s^{-1}) for galaxies
4) Sensitivity $S \sim 10$ μJy / beam in 24 hours

Direct-Detection Interferometer Near L2 (SPIRIT)

☑ Superior background-limited sensitivity S ~ 10 μJy / beam in 24 hours in L2 orbits despite very small collecting area $A \sim 1$ m^2
☑ Instantaneous bandwidth $\Delta\nu / \nu >> 1/300$ ($\Delta v >> 1000$ km s^{-1})



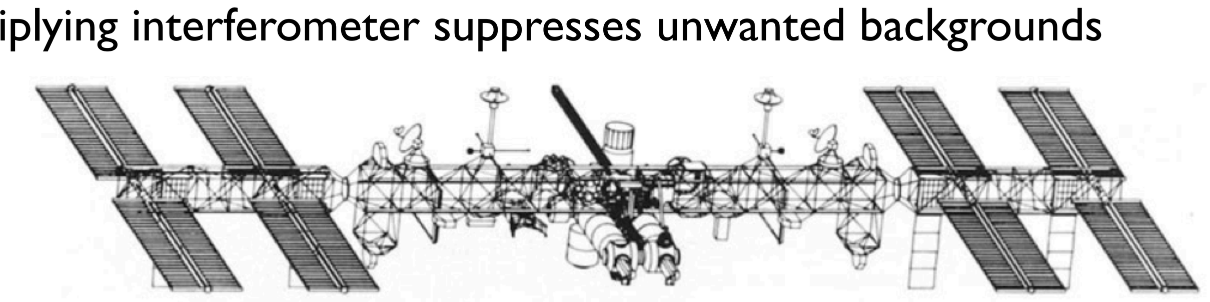
SPIRIT

☒ Angular resolution $\theta > 0.9$ arcsec ($\lambda > 150$ μm, $D_{max} = 36$ m)
☒ Spectral resolution $R \sim 3000$ with double-Fourier spectrometer
☒ Limited imaging dynamic range from $N = 2$ telescopes
☒ Adding interferometer affected by unwanted backgrounds
☒ Needs large single telescope to fill $D_{min} = 7$ m hole in (u,v) plane

Heterodyne Interferometer in Near-Earth Orbit (ESPRIT, HISAT)

☑ Angular resolution $\theta \sim 0.1$ arcsec at $\lambda \sim 150$ μm ($D_{max} = 300$ m)
☑ Spectral resolution $R \sim 3 \times 10^5$
☑ Can operate with uncooled telescopes in near-Earth orbits
☑ Good imaging dynamic range from $N > 2$ telescopes
☑ Multiplying interferometer suppresses unwanted backgrounds

HISAT



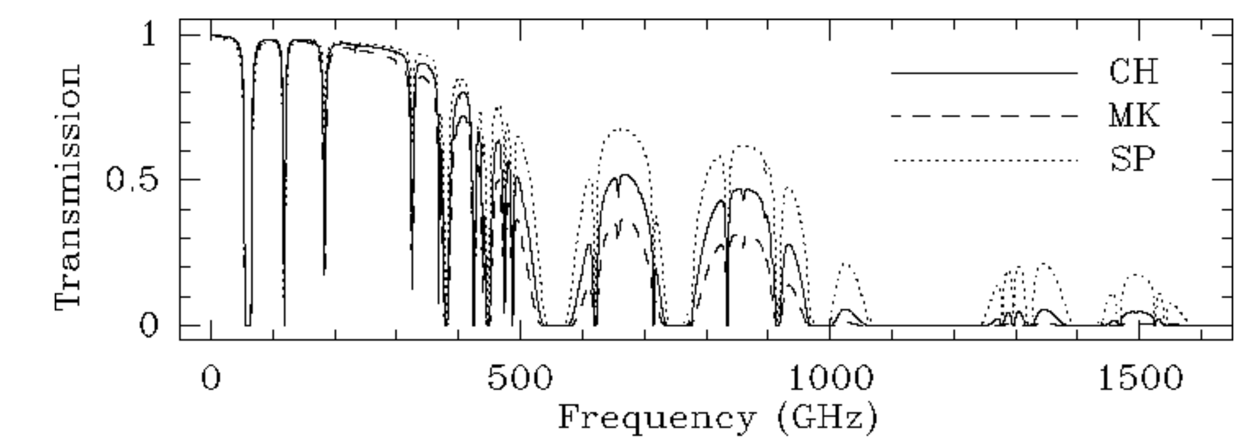
☒ Sensitivity limited by quantum noise $T_{sys} > h\nu/k \sim 50$ K × (ν/THz) and by small collecting area
☒ Instantaneous bandwidth $\Delta\nu/\nu < 1/300$ when $\nu > 1$ THz
☒ Good imaging dynamic range from $N > 2$ telescopes
☒ Needs large single telescope to fill $D_{min} = 7$ m hole in (u,v) plane

References:

Brown, R. et al. 1990, HISAT, in *Observatories in Earth Orbit and Beyond*, Y. Kondo (ed), p. 509
Harwit, M., et al. 2009, *Far-Infrared/Submillimeter Astronomy from Space: Tracking an Evolving Universe and the Emergence of Life* — A White Paper and Set of Recommendations for The Astronomy & Astrophysics Decadal Survey of 2010 http://www.ipac.caltech.edu/DecadalSurvey/farir.html
Leisawitz, D. et al. 2009, *The Space Infrared Interferometric Telescope (SPIRIT): A Far-IR Observatory for High-resolution Imaging and Spectroscopy* http://astrophysics.gsfc.nasa.gov/cosmology/spirit/
Wild, W. et al. 2005, ESPRIT, in *18th International Symposium o fSpace Terahertz Technology*, 244

Terrestrial Heterodyne Interferometers (ALMA, JVLA)

☑ Angular resolution $\theta < 0.1$ arcsec FWHM at all $\lambda < 1$ cm
☑ Spectral resolution R ~ 3×10^5
☑ Instantaneous bandwidth $\Delta\nu / \nu > 1/300$ ($\Delta v > 1000$ km s^{-1})
☑ Sensitivity S ~ 10 μJy / beam (5σ) in 24 hours from $A \sim 10^4$ m^2
☑ Superior imaging dynamic range from $N >> 1$ telescopes



☒ Maximum continuum frequency $\nu \sim 850$ GHz ($\lambda \sim 350$ μm)
☒ 50% atmospheric opacity at 850 GHz costs ~ 4X in sensitivity
☒ Few z = 0 lines of atmospheric molecules (e.g., 557 GHz H_2O line)
☒ Good observing weather only ~ 10% of the time at 850 GHz

Conclusions

No single interferometer seems to meet all of the technical requirements of the science goals: resolving protoplanetary disks, imaging faint emission from dusty galaxies, resolving narrow spectral lines from Galactic sources, and covering wide spectral lines from distant galaxies. Small direct-detection interferometers near L2 have the sensitivity and spectral resolution needed to study galaxy evolution. Somewhat larger heterodyne interferometers in near-Earth orbits have the angular and spectral resolution required for spectroscopy of Galactic sources and nearby galaxies. Terrestrial heterodyne interferometers can make sensitive high-resolution dust continuum images at the longer wavelengths $\lambda > 350$ μm where even compact sources are transparent, plus line and continuum observations of high-redshift galaxies.

New space missions and new or upgraded terrestrial interferometers should be planned cooperatively to maximize their complementary strengths for the best science.