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Submillimeter Interferometry in Space

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Abstract. Radiation from the gaseous disk of a galaxy like the Milky Way principally occurs via fine structure transitions of carbon, oxygen, and nitrogen, all of which occur at submillimeter wavelengths at which the earth's atmosphere is opaque. Indeed, more than ten percent of all the energy radiated by the stars and gas in the Milky Way comes out in the 1900 GHz line of once ionized carbon! This line can only be observed from space, and it can only be observed with arcsecond angular resolution with a space-based interferometer. The international space station Freedom provides a stable platform, with the right dimension, for the necessary submillimeter interferometer.

1. Introduction

The submillimeter spectral regime, 1 mm (300 GHz) to 100 μm (3 THz), is well known to contain the resonant fine-structure transitions of the most abundant "heavy" elements—carbon, oxygen, and nitrogen—as well as important rotational signatures of light molecular species. Virtually all these lines cannot be studied from ground-based observatories because the earth's atmosphere, even on the best high altitude sites, is opaque at the wavelengths of interest. A nice illustration of the richness of the submillimeter spectral region showing the principal molecular and atomic lines superposed on the thermal dust continuum of a 30 K interstellar cloud is given by Phillips and Keene (1992) and reproduced here as Figure 1.

The important point to note here is the simplicity of the species that have their spectral emission at these submillimeter frequencies: they are all simple diatomics, diatomic ions, and a few simple molecular ions. The chemistry of all these species, and hence the interpretation of their emission vis-á-vis the physics of the emitting region, is straightforward. Certainly this is so in contrast to the study of heavy molecules at millimeter and centimeter wavelengths.

All of the lines shown in Figure 1, as well as the dust continuum emission, carry information that is complementary to that which can be learned from longer wavelength spectroscopy. However, the atomic fine-structure lines carry unique information; it is these lines that will be the focus of submillimeter interferometry in space.

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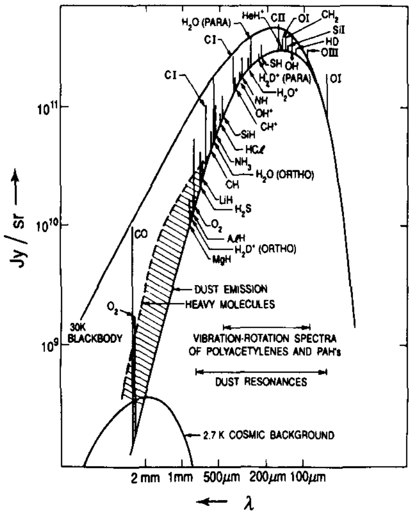

Figure 1. An illustration of the principal spectral lines expected at submillimeter wavelengths shown superposed on the dust continuum emission (after Phillips and Keene 1992).

2. Role of Submillimeter Interferometry in Space

In the next few years the submillimeter region of the spectrum will be explored with very coarse angular resolution with both free-flying spacecraft (SMIM, FIRST, and SIRTF) and with observing facilities in aircraft (SOFIA). These single aperture space and near-space telescope facilities will allow us to understand the astrochemical relationship of the submillimeter spectral lines to the longer wavelength spectral regime at a common, arcminute, angular resolution. The space submillimeter interferometer will follow the single aperture missions at a time in which we can anticipate that the fundamental submillimeter astrochemistry will have been done.

The space submillimeter interferometer is indispensable for high angular resolution astrophysics. Specifically this is the study of protostars, protoplanetary systems, and galactic nuclei. We wish to study bright spectral lines in compact sources in order to understand their kinematics and evolution. The brightest spectral lines from regions of stellar and planetary formation are all unique targets of the space submillimeter interferometer; they are given in Table 1.

The angular resolution that can be achieved by all interferometers with baseline lengths from 5 to 50 meters is given in Table 2. The resolution shown here is computed for a frequency $f = 1$ THz; the resolution is proportional to $1/f$.

Since such arcsecond angular resolution is (1) precisely what is needed to study protostellar and protoplanetary regions and galactic nuclei; (2) precisely what is needed for comparison with ground based radio and millimeter-wave interferometers; (3) precisely what is needed for comparison with the best near

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Table 1. Unique Target of Space Submillimeter Interferometry

Dust Continuum of Compact Objects		
Fine Structure Lines		
	CI	492, 809 GHz
	OI	2060, 4745 GHz
	SiI	2312, 4378 GHz
	NII	1470, 2460 GHz
	CII	1901 GHz
Diagnostic Molecules		
	CO, O_2, NH_3, H_2O	

Table 2. Interferometer Angular Resolution

Interferometer Baseline (meters)	Resolution at 1 THz (arcseconds)
5	6.2
10	3.1
20	1.5
30	1.0
50	0.6

infrared angular resolution achievable from the ground and in space (SIRTF); and (4) precisely the resolution available from an interferometer mounted on the boom truss of Space Station Freedom, it is natural to consider exactly this instrument. In 1989 the NRAO proposed such a facility, the High Resolution Imaging Spectroscopy at Terahertz Frequencies (HISAT) mission, to NASA for the space station. The HISAT concept, a two-element interferometer, is shown in Figure 2.

3. Spatial Frequency Coverage of a Space Station Interferometer

For the specific case of Space Station Freedom, the transverse boom is oriented perpendicular to the vector $\mathbf{r}$ and perpendicular to the velocity vector $\dot{\mathbf{r}}$; this means that the baseline vector vector $\mathbf{b}$ lies in the direction of the angular momentum vector $\mathbf{L} = \mathbf{r} \times \dot{\mathbf{r}}$. In terms of the Keplerian orbital elements

$$\mathbf{L} = L \begin{pmatrix} \sin i \sin \Omega \\ -\sin i \cos \Omega \\ \cos i \end{pmatrix}$$

where $L^2 = GMa(1-e^2)$. This defines the direction of the interferometer baseline vector in terms of the geocentric orbital elements.

For a celestial source at right ascension α and declination δ, the unit vector in the direction of the source, in geocentric coordinates, is

$$\mathbf{s}(\alpha, \delta) = \begin{pmatrix} \cos \delta \cos \alpha \\ \cos \delta \sin \alpha \\ \sin \delta \end{pmatrix}$$

Now express the coordinates of the baseline vector (u, v, w) in a new coordinate system in which the w-axis points in the $\mathbf{s}(\alpha, \delta)$ direction and in which the common plane of the u- and v-axis is perpendicular to $\mathbf{s}(\alpha, \delta)$:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = |\mathbf{b}| \begin{pmatrix} -\sin i \cos(\Omega - \alpha) \\ -\sin \delta \sin i \sin(\Omega - \alpha) + \cos \delta \cos i \\ \cos \delta \sin i \sin(\Omega - \alpha) + \sin \delta \cos i \end{pmatrix}$$

Points in the (u, v)-plane are traced out by the baseline vector as the orbital plane processes in longitude.

For Space Station Freedom the rate of regression of the nodes is 7°of longitude per day. Over a full internodel period, $360/7 \sim 50$ days, the baseline vector traces out a closed elliptical curve in the (u,v)-plane. Its equation is

$$u^2 + \frac{(v - |\mathbf{b}| \cos \delta \cos i)^2}{\sin^2 \delta} = |\mathbf{b}|^2 \sin^2 i$$

An example of the (u, v)-coverage is shown in Figure 3 with data taken over the full internodel period. Such a two element interferometer will be a very useful instrument. A three-element interferometer fixed on the space station is a more than adequate imaging instrument.

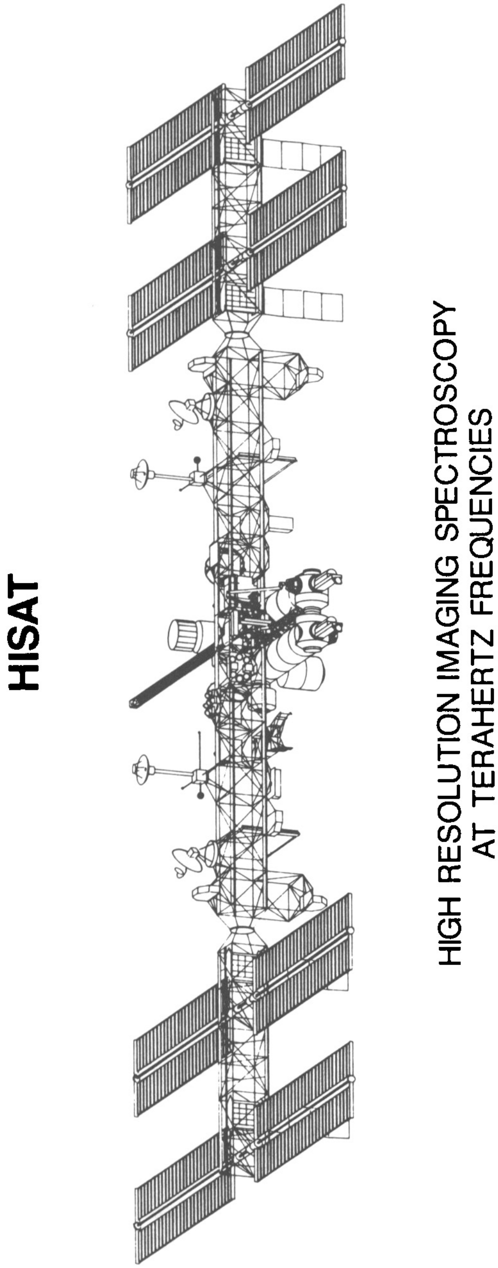

Figure 2. A specific illustration of a two-element submillimeter interferometer mounted on top of the main truss boom of Space Station Freedom.

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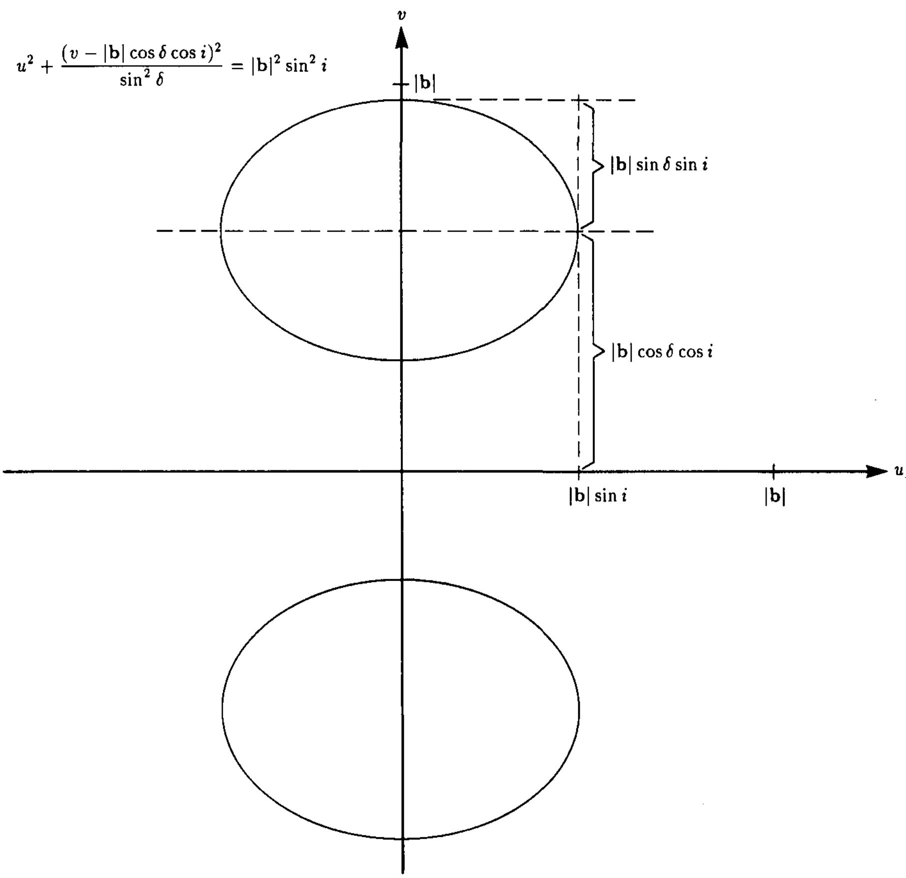

Figure 3. The (u, v)-coverage of a two-element space station interferometer. In this example $\delta = 45°$ and $i = 28.5°$.

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At the present time NASA has "deselected" the NRAO HISAT proposal while it reassess the scientific role it sees for the space station. However, given the unique role that a space submillimeter interferometer will play in unraveling the details of the formation of stars and planets, and given the unique perspective that high angular resolution observations of the submillimeter fine-structure lines (Table 1) play in conveying exactly the scientific information that is sought, we look forward to a renaissance of science-based thought for the space station that will lead to an exceptionally capable astronomical facility in the future.

References

Phillips, T. G. and Keene, J. 1992 Proc. IEEE, **80**, 1662