HIGH-RESOLUTION IMAGING SPECTROSCOPY AT TERAHERTZ FREQUENCIES

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Abstract. HISAT, a multi-element heterodyne interferometer attached to Space Station Freedom, will provide spectroscopic images with unprecedented detail of those submillimeter lines of C, O and C^+ which are critical diagnostics of UV excitation in the Galaxy. With the arcsecond angular resolution achievable from the space station, HISAT will reveal:

– The distribution of sources of ultraviolet radiation in the Galaxy;
– The effective temperature of the UV radiation as a function of galactocentric radius;
– The chemical and isotopic enhancement of atomic carbon and oxygen with galactic radius;
– The propagation of UV radiation in molecular clouds and its stimulative, or inhibitive, effect on star formation;
– The density structure, clumpiness or fragmentation, of molecular clouds throughout the Galaxy. HISAT has been selected by NASA for a concept-phase study.

1. Overview

The goal of this mission is to determine the origin and propagation of ultraviolet (UV) radiation in the Galaxy by studying the excitation of atomic carbon and oxygen at submillimeter wavelengths. Obscured by the Galactic disk, UV radiation from most of the Galaxy is invisible at the earth. However, we can infer its presence from its effect on interstellar material. We intend to obtain spectroscopic images at high angular resolution of those submillimeter lines of C, O and C^+ to which the Galactic disk is transparent and which are critical diagnostics of UV excitation.

Near the Sun, 8.5 kpc from the center of the Galaxy, the energy density of UV radiation, at wavelengths $91 < \lambda < 300$ nm, is nearly equal to that of visible light or infrared (IR) radiation. But the influence of the UV radiation on the interstellar medium is disproportionately large: the UV ionizes all elements with ionization potentials less than one Rydberg, and it heats the gas via collisions between the resultant photoelectrons and the atomic and ionic gas. Further, because the UV radiation has its origin in early-type stars, it serves to delineate regions of active star formation. We can study such regions in the solar neighborhood with UV detectors stationed above the atmosphere. However, the UV opacity of the Galactic disk is large, and therefore we cannot directly observe UV light that arises at distances greater than a few hundred parsecs from the Sun: we have little knowledge of the UV energy density, its origin, propagation and effect throughout most of the Galaxy.

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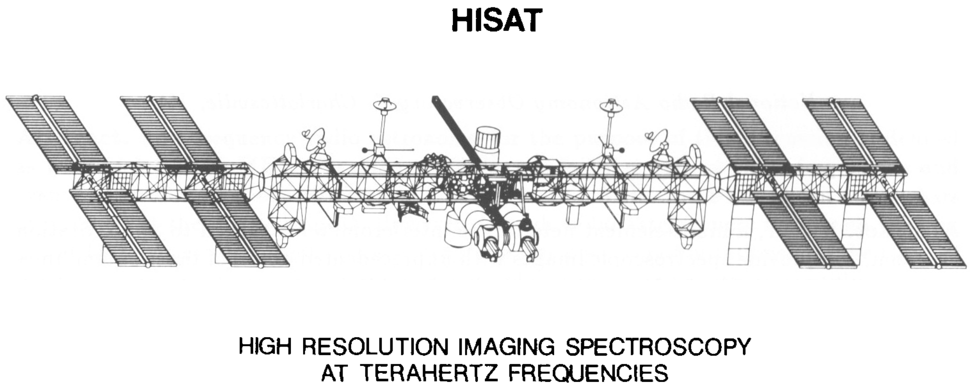

Fig. 1. HISAT, shown in its simplest form as a two-element interferometer, mounted on the upper truss of Space Station Freedom.

We intend to bridge these gaps in our understanding by use of spectroscopic observations from an imaging interferometer attached to Space Station Freedom. We will investigate secondary effects of the UV radiation in enough detail to permit us to infer the nature of the UV emission and its propagation throughout the Galaxy. The unique capabilities of the space station provide an ideal environment for operation of an interferometer that will provide images with arcsecond angular resolution of the crucial submillimeter lines of C, O and C^+.

Below we describe a Space Station Attached Payload that allows us to achieve this objective. The plan is evolutionary: as technology matures and is incorporated into the instrument the scientific yield increases. At all phases the instrument yields unique scientific insight complementary to that provided by the premier orbiting instruments, HST and SIRTF, with which it will be contemporary.

2. Galactic UV Radiation in Perspective

Understanding of the origin and propagation of UV radiation in the Galaxy must be based on observations of the effects of that radiation on its surroundings. The observed effects, in turn, provide us with insight into the extent of nucleosynthesis in the Galaxy, the galactic abundance gradient, interstellar chemistry, and the structure of molecular clouds which presage star formation.

2.1. The Distribution of Galactic UV Radiation

The single unmistakable manifestation of a stellar source of UV radiation is a region of atomic hydrogen ionized by the radiation $\lambda < 91$ nm of the hot star. From observations of their radio and IR emission such HII regions are found throughout the Galaxy, preferentially in the Galactic plane and preferentially interior to the solar circle.

Each of these HII regions is a copious source of UV emission longward of 91 nm, with energies of 10^{36} to 10^{38} ergs s^{-1}, which freely escapes the region of ionized hydrogen and is absorbed by gas and dust in its vicinity. We can study its effects and infer its properties by observing spectral lines of the most abundant elements, O, C and C^{+}. As noted below, these observations need to be made from a space platform.

2.2. Temperature of the UV Sources

The effective blackbody temperature of stellar sources of UV radiation can be computed accurately using numerical models of stellar atmospheres. The emergent stellar intensity, at all wavelengths, depends in these models on the chemical abundance adopted for the star. As the abundance of heavy elements (O, C, N, Ne, Si, S, Fe, Mg) increases relative to the solar values, the effective temperature of the exciting star decreases, as does the average energy of the nebular photoelectrons, and hence the heating rate in the HII region is lowered. The temperature of the HII region excited by such a star is lower than it would be if the excitation were by a similar star having solar abundances.

Present indications are that nebulae near the Galactic center are systematically cooler. Whether this temperature gradient represents an increase in heavy element abundance in the UV source that excites the HII region or an increase in the abundances in the nebular gas – or both – awaits the [CI], [OI] and [CII] observations noted below.

2.3. Chemical and Isotopic Enrichment in Interstellar Clouds

Galactic abundance gradients play an important role in discriminating between nucleosynthesis models involving primary and secondary species. Primary elements, C and O, have H or He as their direct progenitors, whereas secondary species, such as ^{13}C and ^{17}O, are products of subsequent nucleosynthesis processes. The ratio of the abundances of any two primary elements, for example the ratio C/O, should thus be a constant, whereas the abundance of a secondary element should increase as the abundance of its primary progenitor, e.g., $^{13}C/C$. Thus these two ratios together provide a complete picture of the efficacy of nucleosynthesis as a function of position in the Galaxy. The space station interferometric images of [OI], [CI] and [^{13}CI] obtained in this mission will directly address these questions.

2.4. Propagation of Ultraviolet Radiation in Molecular Clouds and Its Effect on Star Formation

The stellar UV radiation longward of the Lyman limit, $\lambda > 91$ nm, which freely escapes the HII region and is absorbed by the gas and dust in molecular material found near early-type stars, provides an ionization rate high enough to stimulate cloud fragmentation and gravitational collapse of the fragments, and it will cat-

TABLE I
Spectral Lines to be Observed

	Species	Transition	Frequency (GHz)
Phase I	[CI]	$^3P_1 - {^3P_0}$	492.1612
		$^3P_2 - {^3P_1}$	809.3432
Phase II	[CII]	$^2P_{3/2} - {^2P_{1/2}}$	1900.54
	[OI]	$^3P_0 - {^3P_1}$	2060.06

alyze a rapid phase of massive star formation. This, too, is subject to observational verification once observations at high angular resolution are possible.

3. Concept of the Investigation

3.1. Spectral Lines to be Observed

The propagation of UV radiation through interstellar molecular clouds has as its principal effects the dissociation of H_2 and CO, the ionization of atomic carbon and the heating of dust grains. HISAT will image these products: the (forbidden) ground-state fine-structure lines of neutral atomic carbon, CI, in Phase I and the lines of ionized carbon, CII, and neutral oxygen, OI, in Phase II. The second phase of the investigation is paced by development of low-noise receivers for frequencies above 1 THz. (See Table I.)

Note that the isotopic spectral line of ^{13}C will appear in the same spectra as the [CI] and [CII] main lines and will also be imaged.

In Phase I, simultaneous measurement of both transitions of CI is important: the two lines together provide a complete characterization of the 3-level ground-state of atomic carbon and hence of the physical conditions in the region of excitation.

3.2. Targets to be Observed

Observations will be made of a large sample of molecular clouds found near Galactic HII regions. Since a primary goal of the mission is to investigate Galactic abundance gradients and spatial inhomogeneity of Galactic chemical abundances, the targets are distributed throughout the Galactic disk.

3.3. Angular Resolution to be Achieved

HISAT will image the fine-scale spatial structure, filamentation, clumping and granularity in molecular clouds. A gravitational condensation of stellar mass – a protostar – has a size of 0.1 pc. In the inner Galaxy, 8 kpc from the Sun, this corresponds to 2″. HISAT provides this resolution (see Table II).

TABLE II
Interferometer Resolution (arcseconds)

	Species Transition Frequency			
B (meters)	492 GHz	809 GHz	1900 GHz	2060 GHz
5	12.6	7.7	3.3	3.0
10	6.3	3.8	1.6	1.5
15	4.2	2.6	1.1	1.0
20	3.1	1.9	0.81	0.75
30	2.1	1.3	0.54	0.50
40	1.6	0.96	0.41	0.38
50	1.3	0.76	0.33	0.30

4. High-Fidelity Imaging on Space Station Freedom

The fidelity of an interferometric image is directly related to the completeness with which the interferometer samples the range of spatial frequencies represented by the parent aperture which the interferometer "synthesizes". Ground-based interferometers, such as the VLA, fill in the aperture-synthesis plane by tracking a source in hour-angle: rotation of the earth gradually changes the vector orientation and separation of each pair of antennas. A similar technique can be exploited by HISAT on the space station.

Of particular interest is that locus of points in the u–v plane which is traced out by the baseline vector as the orbital plane of the space station precesses in longitude. For the space station, the rate of the regression of the nodes is $\sim 7°$ of longitude per day. Over a time interval equal to the period of revolution of the nodes ($360/7 \approx 50$ days), the baseline vector $\mathbf{b}$ traces out a closed elliptical curve in the u–v plane. Its equation is $(u^2 + (v - |\mathbf{b}| \cos\delta \cos i)^2 / \sin^2\delta = |\mathbf{b}|^2 \sin^2 i)$. An example of such an ellipse, for $\delta = 45°$ and $i = 28\overset{\circ}{.}5$, is shown in Figure 2, along with a similar ellipse corresponding to $-\mathbf{b}$.

Instead of a simple 2-element interferometer, one might consider a multi-element interferometer, comprising three or more elements (the more elements, the better the u–v coverage and the better the imaging fidelity and speed). For a 3-element, 3-baseline instrument the u–v coverage would consist of three pairs of ellipses. A potentially attractive option for a space station interferometer might be a 3-element instrument comprising two fixed elements and one movable element. The movable element would be re-positioned only infrequently – probably at time intervals no shorter than the internodal period of the orbit.

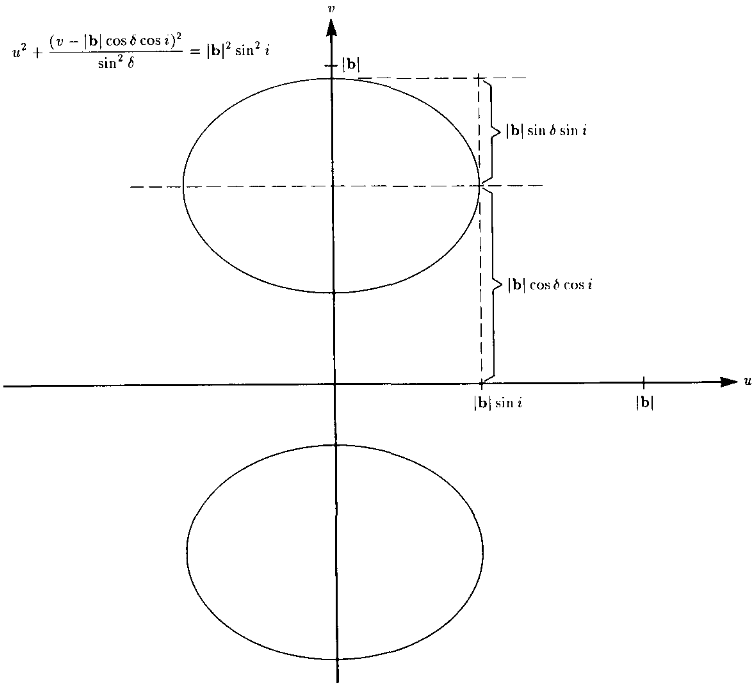

Fig. 2. The u–v coverage provided by a single-baseline (i.e., a two-element) space station interferometer. In this example, $\delta = 45°$ and $i = 28\overset{\circ}{.}5$. Over a time interval equal to the internodal period of the longitudinal precession of the satellite orbit the tip of the baseline vector traces out an ellipse in the u–v plane.

5. HISAT Instrumentation

Technical Summary:

Antennas:	2 (or more), each of 2-meter diameter; surface accuracy $\leq 10\ \mu$m r.m.s.;
Pointing:	3 arcseconds r.m.s.; servo star-tracker on each antenna;
Frequencies:	492 and 809 GHz (during Phase I), both frequencies observed simultaneously;
Receivers:	Low-noise, SIS, $T_{sys} < 1000$ K;
Correlator:	Analog/digital hybrid, with bandwidth ≥ 250 MHz;
Baselines:	5–30 meters, reconfigurable.

Technical Goals:

– The observations first require low-noise receivers which will allow us to achieve $T_{sys} < 1000$ K at 492 and 809 GHz. Our principal goal is to demonstrate the feasibility of such receivers at the Phase I frequencies;

– High-fidelity spectroscopic imaging will require data to be taken over the full internodal period of the space station orbit. The secondary goal of the concept

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study is to define a data-taking technique, given the constraints of the space station orbit, that provides for images of the highest fidelity.

Technical Evolution:

– As the technology of low-noise heterodyne receivers matures at still higher frequencies, we plan to complement the Phase I receivers with Phase II instrumentation and extend the observational program.

– An imaging interferometric array is an instrument that could grow as the space station expands, allowing for longer antenna spacings to provide even higher-resolution images. The possibility might also exist of increasing the number of antennas, thereby enhancing the sensitivity and speed of imaging. Thus although the present study is scientifically complete as outlined here it also provides a necessary first step toward a possibly larger and more general-purpose imaging array. Such an array could be used for a wide range of remote sensing problems, including planetary and extragalactic astronomy.