EXPLORATORY SUBMM SPACE RADIO-INTERFEROMETRIC TELESCOPE (ESPRIT)

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Abstract
Angular resolution in the far-infrared (FIR) wavelength regime is still very limited although the FIR range has become of prime importance for astrophysics. Investigations of the star- and planet formation process occurring in interstellar clouds, and on the lifecycle of gas and dust in general require, besides high angular resolution, also high spectral resolution. To combine both characteristics, we propose a heterodyne aperture-synthesis mission concept, ESPRIT, to operate in a wavelength regime that is neither accessible from the ground by ALMA (Atacama Large Millimeter Array), nor with JWST (James Webb Space Telescope).

Keywords: FarInfrared, Submillimeter, Interferometry, Space Instrumentation, Space mission, Star Formation, Spectroscopy.

1. INTRODUCTION

The study of star and planet formation is one of the prime topics in modern astrophysics. Important questions include the physical conditions for star-formation to occur, the evolution of circum-stellar disks, the decoupling of dusty proto-planetary regions from the gas, and the chemistry that leads to the pre-biotic conditions of early Earth-like planets. In addition, we also would like to know what role star-formation, and in particular starbursts, play in external galaxies and how this interacts with the general interstellar medium.

As the FIR wavelength range holds the most important spectral signatures of the material (atoms, ions, molecules) involved, a FIR space mission is required. The low extinction at these long wavelengths allows unique observations of details of the star formation process, in particular during its early phases, when these regions are completely obscured by the surrounding dust. The Earth atmosphere severely limits the possibility to observe at THz frequencies from ground-based observatories. ALMA will cover the atmospheric windows at very high angular resolution up to about 1 THz (the limit for observations even from high-altitude sites).

Astronomical observations above 1 THz need to be done from space. However, all past, current and planned missions have limited angular resolution. The relatively small ratios of aperture diameter to wavelength, like for example in ISO, Spitzer Space Telescope and Herschel, provide only angular resolutions of the order of 5 arcsec in the 100μm region. This does not match the 0.1 arcsec resolution which is required for these studies. In order to achieve the required angular resolution, to investigate for example the distribution of key molecules in a circum-stellar disk, application of interferometer techniques in space is the only way forward. At the same time, high spectral resolution is required to measure the chemical composition, the dynamics and other physical conditions. In particular, studies of water and other hydrides, together with the isotopic/deuterated versions, are of prime interest for the star formation process.

We will present a mission concept that combines all these capabilities and is therefore uniquely suited to address these questions: a free-flying, 6 element, far-infrared imaging interferometer using heterodyne detection. The results from ESPRIT will be highly complementary to TPF/Darwin as it will fill the gap and establish the link between formation of a planet and detection of a planet. It is also complementary to JWST-MIRI since ESPRIT will observe the evolution of these regions in the epoch prior to becoming observable in the mid IR.

2. MISSION CONCEPT

Table 1 gives the present baseline requirements for ESPRIT. The interferometer with 6 elements (15 baselines) will be in a free-flying configuration. In a preliminary trade-off between signal strength, primary beam size and practical considerations, it appears that a 3.5 to 4 meter diameter of the primary mirrors would satisfy the overall mission goals. From ground-based interferometer experience it is evident that in order to get an acceptable imaging capability one needs a minimum of 6 antenna elements. As will be argued below, a distributed correlator seems be the most practical solution for this mission. Each antenna will be equipped with a number of heterodyne receivers covering selected ranges between 0.5 and 6 THz (600µm to 50µm). Pointing requirements are proportional to the diffraction diameter and are roughly a factor of 10 more stringent than is being provided today in ESA's space missions. The 6 ESPRIT elements are expected to be put in orbit by one single launcher and the interferometer is preferably situated in the Sun-Earth L2 region.

Table 1. The main characteristics of ESPRIT

Telescope sizes : ~ 3.5 meter ; off-axis	F.O.V. /primary beam size: ~ 6" at 100 µm
Number of elements: N =6 (15 baselines)	Spatial Resolution: 0.02" at 100 µm
Frequencies: ranges in 0.5- 6 THz; (600 µm – 50 µm)	Pointing Reqts: accuracy: 0.2"; measurement: 0.1"
Projected baselines: ~ 7- 200-1000 meter	Image Dynamic range: > 100
Tsys: 1000 K; HEB mixers; QCL as LO;	Spectral Dynamic range: > 1000
IF: 4 GHz wide	Correlator: 4 sections of 1 GHz, each 128 channels
Spectral Resolution: 1 km/s at 100 µm	Free-flying configuration

3. SCIENCE GOALS

The study of the formation and evolution of stars and solar systems is now one of the main themes of astrophysics. In particular the indirect detection of more than 100 Jupiter-like extra-solar planets has enforced these studies and the development of missions. Although Spitzer and JWST will address these subjects in detail, there is a clear missing link in these studies. This concerns mainly the epoch before the objects are becoming strong IR emitters. And Herschel, although the largest space telescope planned for the FIR, will have a too modest angular resolution (ranging from 6 to 40 arcsec) for unraveling the star/planet formation process.

The most critical and unique spectral lines for studying this process are from H_2O, H_3O^+, [OI], C^+, N^+, CH, OH, CH^+, and their isotopes including their deuterations. ESPRIT will trace the movements and spatial distribution of the ionic and molecular material and its specific components, from cold dark pre-stellar clouds through the final stages of star formation process. In particular measuring the distribution of water in the pre-stellar clouds and proto-planetary nebulae and disks is crucial, not only for its unique diagnostics but also for assessing the cloud's thermal conditions during its evolution.

Similar observations of circum-stellar material of evolved stars are most relevant for understanding the evolution of extra-solar planetary systems. In this sense the detection by SWAS of circum-stellar water vapor towards the evolved carbon-rich star IRC+10216 is very interesting [1]. The most plausible explanation for the presence of the amount of detected water vapor is evaporation of ice on Kuiper Belt type objects by the central star. ESPRIT will have sufficient sensitivity to detect in detail many of these objects.

The facility will be the high-frequency/short-wavelength complement of the ground-based ALMA, without any atmospheric attenuation and disturbance in phase and transmission. It will be a follow-up mission of ISO-LWS, SWAS, ODIN, SIRTF, ASTRO-F, Herschel-PACS and Herschel-HIFI and of MIRI on JWST. Nevertheless, with the rapid development and increase of observing capabilities of ground-based and space/airborne facilities it will be important to update the scientific case

4. FOCAL PLANE INSTRUMENTATION

The focal plane instrumentation of ESPRIT will consist of cryogenic heterodyne receivers. Two types of mixer technology will be used: from 0.5 to about 1.3 or 1.5 THz SIS mixers offer best sensitivity, and above 1.5 THz up to 6 THz HEB mixers are the best choice, although some more development, to widen their IF frequency range and increase sensitivity, would be desirable. Both types of mixer have been space qualified (up to 1.9 THz) for Herschel-HIFI [2], Table 2, and will be flown in 2007. Heterodyne detection has a number of important advantages over direct detectors, and in particular when used in a space mission.

Background and stray light suppression are particularly important for future direct detection missions where two orders of magnitude improvement in detection sensitivities is required together with a deeply cooled telescope and instrument compartment. Heterodyne detection is not seriously hindered by background radiation and there are no stringent stray light issues. For heterodyne receivers, only the mixers themselves need to be cooled (4K), together with their intermediate frequency pre-amplifier (20K). Table 3 gives the estimated cooling requirements for the ESPRIT receivers. The complete focal plane unit and the telescope itself do not require active cooling.

For SIS as well as HEB mixers a development to include the pre-amplifier into the mixer block, using MMIC techniques would simplify the instrument. A further step towards integration could come from the Superconducting Integrated Receiver. Here a planar LO, double-slot antenna and mixer are integrated onto a single chip [3].

The Local Oscillator development for Herschel-HIFI has pushed the operation of multiplier chains driven by high-power millimeter-wave sources to 2 THz. With some effort this could be extended to 3 THz [4]. Coming from the mid-IR side of the spectrum, a recent successful development of Quantum Cascade Lasers has opened up the possibility for Local Oscillators operating as high as 6 THz (=50μm). Recently, SRON in collaboration with TU Delft, The Netherlands and MIT, USA has demonstrated a heterodyne measurement using a NbN HEB as mixer and a QCL as LO, which shows a DSB receiver noise temperature of 1400 K at 2.8 THz [5]. QCL devices require well moderate low operating temperatures. Frequency tuning is achieved by controlled temperature variation. For more details on the ESPRIT frontends, see [6].

Table 2. Space qualified heterodyne technology (HIFI)

	Band 1 to 5	Band 6
Mixer type	SIS	HEB
Frequency	0.48-1.25 THz	1.4 – 1.9 THz
IF	4 – 8 GHz	2.4 – 4.8 GHz
Local oscillator	Multiplier chain	Multiplier chain
Sensitivity	3 - 5 hν/k	20 hν/k
Status	Space qualified	Space qualified

Table 3. Cooling requirements for receivers

Temperature level	One receiver with 2 mixers and LO	
Between 30 K and 120 K	LO (QCL)	2.5 W
70 K	2 Amplifiers	20 mW
25 K	2 Pre-amplifiers	16 mW
4.2 K	2 Mixers	0.5 mW
	Parasitics	1 mW

With ambient temperature telescopes and instruments, and thus without expensive and complicated cryostats or demanding multiple-stage cryo-coolers, the spacecraft design can be optimized and become much simpler as is for example the case with Herschel.

5. INTERFEROMETER CONSIDERATIONS

Aperture synthesis with heterodyne techniques at FIR/Submm wavelengths implies several advantages over optical-type interferometers where direct detection is used. In heterodyne interferometers the correlation takes place after the signal has been down converted and detected. This allows simple and “endless” division of the signal and distribution to the correlators with no penalties of loss in signal-to noise ratio. The signal distribution can be done in several practical ways, using optical or microwave transmission links.

Observing at longer wavelengths and in particular with limited IF bandwidth, which is usually experienced as a limitation for instantaneous frequency coverage and continuum measurements, now makes the coherence length ($\lambda_{coh}=\lambda^2/\Delta\lambda$) of the signals very long (150m at100μm for 2 MHz channels) and eases the requirement for delay line correction. Therefore there is no need to have very precise real-time optical (=RF) path-length adjustments, compensation and control, as is the case in optical interferometers. The radio technique actually allows for a simple delay line compensation that can take place at the correlator and one needs only an accurate determination and knowledge of the position and orientation of each antenna element with respect to each other, in 3 dimensions, at all times. Estimated accuracies for the inter-distance metrology are of the order of a few microns. Compared to DARWIN the tolerances are several orders of magnitude more relaxed; from the longer wavelengths a factor 10; from higher spectral resolution, resulting in a longer coherence length, a factor 1000. With these two advantageous properties a heterodyne interferometer gets an important freedom in selecting interferometer baseline configurations.

On the other hand there are two issues that complicate aperture synthesis in space using a free-flyer configuration with heterodyne techniques.

The use of the Local Oscillator for down conversion of the signal while keeping phase information, requires a careful phase locking and referencing of all the individual Local Oscillators in order to achieve phase closure. However, this seems not to be a problem and has been demonstrated in ground-based mm-wave and IR heterodyne interferometers [7]. Such an additional adjustment is not required for optical interferometers with direct detectors.

Contrary to optical interferometers, at FIR/Submm wavelengths it is unlikely that there will be strong point sources nearby for phase calibration. Also compared to ground-based radio interferometers, the position of each antenna element is not stable, and a space interferometer calibration cannot simply be carried forward to other observations. However by careful tracking and storing of the inter-distances of the interferometer elements, a phase calibration can be valid for a long time span as there is no phase disturbing atmosphere.

In the proposed free-flying interferometer there are now basically three pieces of information that need to be communicated between the interferometer elements: the metrology results for position and orientation, the correlated signals, and the phase reference signals for the LOs. After some preliminary studies, it appears that all three can be transported using optical communication methods. With the recent development in space optical communications, ample technology appears to be available.

With these typical heterodyne characteristics this type of interferometer becomes relatively simple, in particular at FIR wavelengths as compared to the mid-IR.

6. SYSTEM CONSIDERATIONS

From the point of view of path length difference the long coherence length in heterodyne interferometers one has a large degree of freedom in positioning the elements and their movements. Therefore the free-flying interferometer with 6 elements can have a 3 dimensional configuration – although not completely arbitrarily as this would stretch the complexity of the metrology for the distance measurements between the elements. We estimate that placing the elements in two planes with each three elements is the most favored configuration.

Concerning the correlator design, the preferred approach here is to have a distributed correlator, where each element houses a correlator. This will not only provide redundancy but it could also mean that all 6 satellite elements can be identical and thus requiring only one design. Also the electrical power supply requirement, demanding for correlators, can be more evenly distributed over all satellite elements.

Concerning the fitting of all elements into one rocket fairing, a deployable boom for the support of each secondary mirror in an off-axis telescope design, could provide a very compact set of telescope-satellites. Preliminary estimates of the dimensions of an element indicate a two meter high cylinder with a 4 meter diameter.

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