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The Far Infrared Spectroscopic Explorer (FIRSPEX)

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Abstract— **The Far InfraRed Spectroscopic EXplorer (FIRSPEX) is a novel concept for an astronomy satellite mission that will revolutionise our understanding of the properties of the Interstellar Medium (ISM) and star formation through velocity resolved spectroscopic observations at multi-terahertz frequencies. FIRSPEX comprises a fully cryogenic (~4K) heterodyne payload and a ~1.2 m primary antenna to scan the sky in a number of discreet spectroscopic channels delivering 3-dimensional spectral information. The spectral range selected contains important molecular, atomic and ionic species; the majority of which cannot be observed from the ground.**

FIRSPEX is UK led with additional contributions from partners throughout Europe. FIRSPEX opens up a relatively unexplored parameter space that will produce an enormously significant scientific legacy by focusing on the properties of the multi-phase ISM, the assembly of molecular clouds in our Galaxy and the onset of star formation topics which are fundamental to our understanding of galaxy evolution.

INTRODUCTION

The far-infrared (FIR) to submillimetre (submm) window is one of the least-studied regions of the electromagnetic spectrum. Yet, this wavelength range is absolutely crucial to our understanding of star formation and stellar evolution in the Universe. These complex physical processes leave their imprint on the Interstellar medium (ISM) of our Galaxy and that of external galaxies. By studying the phase structure of the ISM we can begin to unravel the processes that control the heating and cooling of the clouds that regulate star formation. FIR/submm spectroscopy is essential to answer these questions since this regime contains important cooling lines of the different phases of the ISM. The fine-structure line of singly ionised carbon [CII] at 158μm is the most important cooling line of the neutral ISM. FIRAS/COBE maps showed that this is the strongest cooling line in the ISM at about 0.3% of the continuum infrared emission (Fixsen et al. 1999). Other important atomic fine-structure lines include the atomic oxygen lines [OI] at 63 and 145 μm, and the atomic carbon [CI] lines at 370 and 609 μm.

The FIR/submm window also contains a number of atomic fine-structure lines that trace ionized gas, such as the singly ionized nitrogen [NII] 205μm. Finally, it contains a large number of high- J molecular rotational transitions. The mid- to high-J transitions, which are either difficult to observe or completely inaccessible from the ground, have a large span in critical densities, making them excellent tracers of the physical conditions of gas over a wide range in temperatures and densities. The Herschel Space Observatory (Pilbratt et al. 2010) highlighted the immense potential of far-infrared spectroscopy in understanding the complex physics of the ISM. While the superb imaging capabilities of Herschel resulted in panoramic views of the Galactic Plane that provided a full census of the dust reservoir available (e.g. Molinari et al. 2010), there is a distinct lack of similar information for the gaseous component of the ISM. Only then, will be able to establish the gas-to-dust ratio and how this affects star formation in our own Galaxy and in external galaxies. But Herschel spectroscopic observations that allow us to probe the gas phase structure of the ISM were limited to less than 1% of the whole sky. Our mission concept, the Far-Infrared Spectroscopic Explorer (FIRSPEX) comes to fill this gap: FIRSPEX will carry out large area surveys in four discreet spectral channels centered on key FIR lines: [CI] 370 μm (809 GHz), [NII] 205μm (1460 GHz), [CII] 158μm (1900 GHz), and [OI] 63μm (4700 GHz). The choice of the spectral bands has been motivated by the need to study the dynamics of the multi-phase ISM in the Universe. In what follows we present the FIRSPEX scientific drivers and give an overview of the payload and it capabilities.

FIRSPEX SCIENCE DRIVERS

Observations in the four FIRSPEX bands have been designed to serve three intertwined science themes. Firstly, a fully sampled velocity resolved map of the Galactic Plane (~3600 sq. deg) targets the physical and dynamical properties of the ISM in our Galaxy. Secondly, pointed observations of a volume-limited sample of nearby galaxies will establish the role of environment on the ISM, and how the properties of the ISM affect star formation. Thirdly, a deep blind FIR spectroscopic survey (~400 sq. deg.) will probe the physics of distant galaxies and establish the properties of the gas and how it impacts on galaxy evolution from ``cosmic noon'' to the galaxies we see today.

A. *FIRSPEX deep Galactic Plane Survey*

How do molecular clouds form?

Theoretical studies (Goldbaum et al 2011) have suggested that molecular clouds are formed by large-scale accretion of new material onto existing dense clouds. This scenario is consistent with recent Herschel observations that suggest the global filamentary structure of molecular clouds is created by large scale flows of atomic material at earlier times (e.g. Molinari 2010, Peretto 2012). Nonetheless, mass accretion has not been convincingly demonstrated observationally. As the accreted material undergoes a transition from atomic hydrogen to low-density molecular hydrogen and finally denser molecular gas, also visible in CO, we need to disentangle the various phases of the ISM to probe molecular cloud formation. Resolving the velocities of the different components that determine the accretion time scales is a pre-requisite to our understanding of star-formation on galactic scales. Without the ability to separate the different ISM phases proper assessment of the atomic hydrogen emission is impossible.

What fraction of the baryonic matter is in CO dark clouds?

High spectral resolution observations of C+ will enable us to quantify the fraction of CO-dark gas, which is likely to contain a significant fraction of the baryonic matter in the Galaxy, but is invisible in most other tracers. By comparing the phase distribution with the known distribution of energetic sources in the Galaxy we can quantify the effects of the Galactic metallicity gradient and measure the global trapping efficiency of the ISM for the different heating sources.

What heats the ISM?

Radiative feedback from young stellar sources is one of the main heating sources for the Galactic ISM. FIRSPEX observations of the two main cooling lines of the ISM [CII] and [OI] will provide an complete census of the UV heating of the Galactic ISM from UV radiation in terms of photon-dominated regions (PDRs). This allows to globally access the impact of stellar feedback on the evolution of the ISM structure and it allows us to ``calibrate" the contribution to the different phases to the integrated [OI], [NII], and [CII] emission observed in other galaxies.

To provide answers to these fundamental question requires surveys with reasonable angular resolution (< 1') together with large spatial coverage, with the velocity resolution to detect the predicted velocity shifts of less than or equal to 1 km/s. The FIRSPEX Galactic plane survey (Fig.1) will unravel the physics controlling the evolution of these structures and their role in the process of star formation.

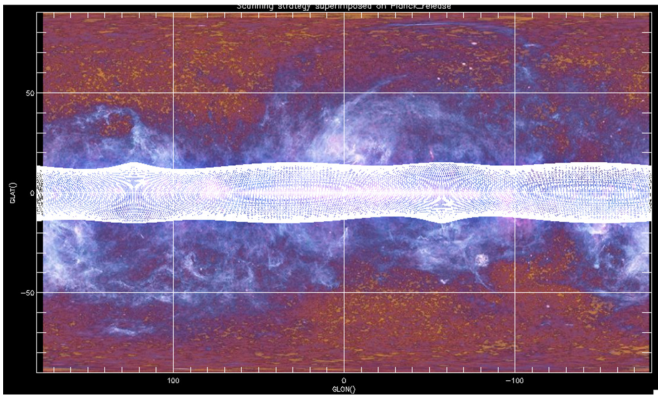

Fig. 1: The planned FIRSPEX Galactic Plane Survey superimposed on Planck all sky map (credit: ESA/HFI/LFI).

B. *FIRSPEX Observations of Nearby Galaxies*

Some of the fundamental science questions in the study of local galaxies are: ***What regulates star formation in galaxies? How does the ISM vary with environment?*** These questions have important cosmological implications and, as such, it is imperative to answer them in the local Universe, to be able also to understand the distant Universe. We can answer these questions with a detailed study of the gas components and properties in external galaxies of different types (starburst, ellipticals, mergers etc). These properties seem to be quite different from those seen in galactic star forming regions and this may impact the extragalactic star formation efficiencies and rates (e.g. Magdis et al. 2012). It is now well established that massive galaxies show large variations in the physical and chemical properties of their star forming gas, which in turn regulates the evolution of galaxies. Existing atomic and molecular data, for at least the nearest galaxies, show a chemical diversity and complexity that cannot be explained by a one-component, steady-state chemical model, and indicates how relative abundances between atoms and molecules may be able to provide insights into the physical distribution of the gas and the energetics of these galaxies.

FIRSPEX offers the unique opportunity to obtain velocity resolved maps of the major cooling lines of the ISM in galaxies. High spectral resolution is needed to disentangle the contributions of the various ISM phases along the same line of sight, such observarions will shed unprecedented light on the interplay of the ISM phases and their specific role in the cycle of matter inside galaxies as well as in their evolution.

C. *Probing the ISM of Distant Galaxies with FIRSPEX*

FIR fine structure (FS) lines provide an extremely powerful tool to probe the physical conditions of star formation in galaxies. Several studies have examined their reliability as Star Formation Rate (SFR) indicators (e.g. de Looze et al. 2014, Rigopoulou et al. 2014, Magdis et al. 2014). However, there is a considerable gap in redshifts between observations of FIR FS lines in relatively nearby galaxies with Herschel and detections of FIR FS lines in distant (z>3) galaxies routinely reported by ALMA. If we are to establish the use of

FIR FS lines as SFR indicators in the very distant Universe then it is essential to trace their evolution from present day till about redshift 3. We need to understand the physics driving the emission of cooling lines at an epoch where the Universe was very energetic, the cosmic `noon'.

FIRSPEX deep `blind spectroscopic surveys' will detect galaxies based on their line emission. Using the four FIRSPEX Bands we will detect [OI], [OIII], [CII], [NII] and [NIII] in various redshifts bins between 0.3<z<3. The FIRSPEX deep fields are located in prime strategic fields with deep ancillary data in other wavelengths. Such observations will allow us to characterize the ISM of distant galaxies and how the properties of the gas affect star formation efficiencies and subsequent galaxy evolution.

FIRSPEX PAYLOAD

The two prime scientific requirements for the FIRSPEX mission are high detection sensitivity and high spectral resolving power (resolution order > 10^6) within the Terahertz frequency domain. The sensitivity requirement is satisfied with the use of advanced heterodyne receivers based upon superconducting mixer technology used in conjunction with frequency stable local oscillators (LOs) and advanced digital sampling and analysis techniques.

The FIRSPEX payload comprises four parallel receiver channels that can operate simultaneously and therefore independently sample neighbouring regions of the sky. Each receiver channel is located within the focal plane of a 1.2m diameter primary antenna, and offers angular resolution on the scale of 1 arcmin. A schematic view of the payload is shown in Fig. 2.

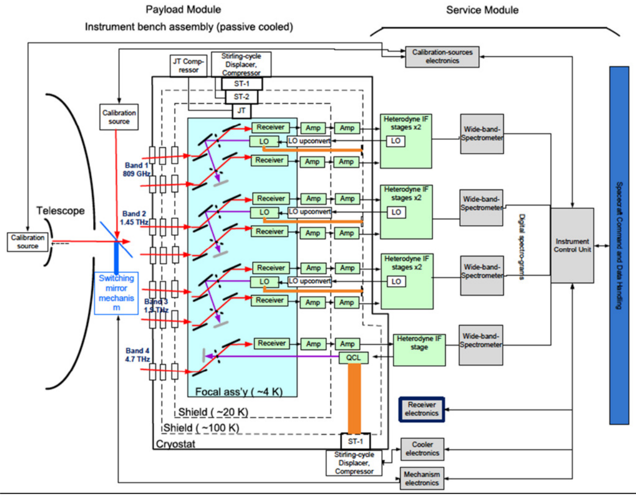

Fig.2: A schematic view of the FIRSPEX payload

In addition, each receiver channel comprises a superconducting mixer, LO chain, stages of intermediate frequency (IF) amplification followed by digital sampling and signal processing. The need for state-of-the-art sensitivity defines the use of superconducting mixers configured either as tunnel junctions or hot electron bolometers. Such technology requires cooling to a low temperature, and approaching 4K, in order to operate. Achieving such low temperatures in space is non-trivial, but has been demonstrated by various past missions e.g. Planck used active closed cycle coolers. Our baseline configuration proposes to passively cool the instrument to 50K (L2 orbit) and with active cooler technology providing sub-stages with necessary heat lift at 4K and 15K. The 4K stage cools the sensitive mixers and the 15K and 50K stages, in addition to reducing the thermal conductive and radiation load on the 4K stage, also cool vital elements of the receiver chain such as the final LO stage and IF low noise amplifiers (LNAs).

A total of four receiver channels are planned with each operating in a double sideband configuration and providing a total of 7 sampling pixels on the sky. Fig. 3 shows the receiver optics for a two receiver channel.

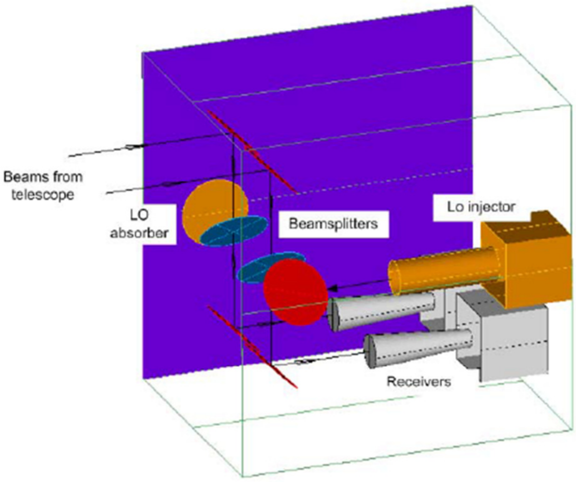

Fig. 3: Receiver optics for double pixel channel

The frequency band allocations are described within Table 1 along with estimated system sensitivities. Bands 1 through 3 use two independent mixers per frequency band giving multiple pixel sampling to compensate for the smaller beams. Coupling to the primary quasi-optical focal plane is accomplished via relay optics comprising a series of re-imaging mirrors. For Band 2, 3 and 4, conventional harmonic frequency up-convertors provide suitable sources of LO power injected into the mixer using simple beam splitter. For band 1, the LO source is provided by a quantum cascade laser (QCL) cooled to ~50K. Each mixer is followed by a cooled LNA and a further stage of room temperature amplification while the IF final output is processed by a dedicated fast Fourier Transform spectrometer (FFTS). Each receiver system is calibrated through the use of blackbody targets of known brightness temperature that are sequentially introduced into the optical path.

Table 1: FIRSPEX receiver channel frequency, species and performance designations

Designation	**Frequency (THz)**	**Primary Species**	**Secondary Species**	**No of Pixels**	**System Noise (K)**
Band 1	4.7	OI	-	2	800
Band 2	1.9	CII	^{13}C+	2	500
Band 3	1.45	NII	SH^+,SO,CF^+,H^2O+	2	350
Band 4	0.81	CI	CO(7-6)	1	180

The spacecraft (SC) design consists of a cold Payload Module (PM) that includes the telescope and instrument box. Positioned at the Lagrangian obit L2, the PM is located on the anti-sun side of a sunshade and using a multiple V-groove thermal shield arrangement as per other missions at L2 (Planck, NGCryoIRTel) is passively cooled to ~50K. The cold PM provides a low temperature starting point for the closed- cycle cooler system, with use of instrument radiators, allowing the coolers to achieve the 15K, 4K stages, The warm Service Module (SM) is located on the sun-facing side.

The proposed structural mounting scheme is shown in Fig. 4.

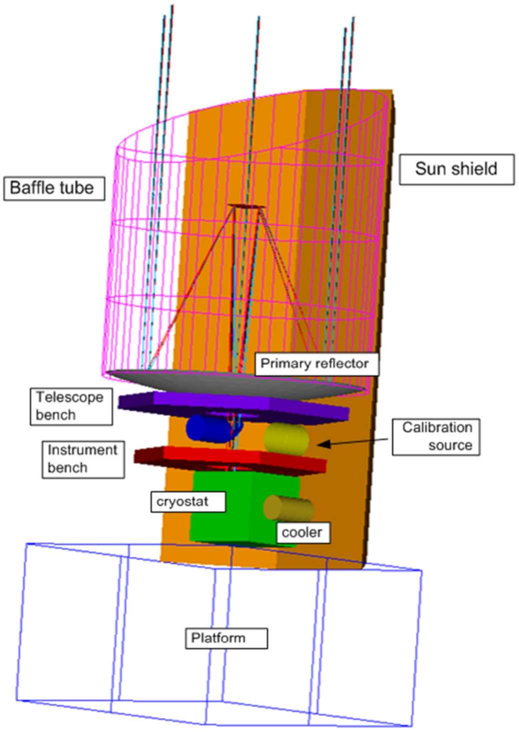

Fig.4: Outline model of the FIRSPEX payload showing the relationship between the various payload elements.

The payload harnesses, and cryo-coolers for the instrument, have to penetrate through the V-groove shields, and they make use of the progressively colder stages of the shields to achieve required cooling. The cooling scheme uses a 2-stage Stirling cryo-cooler in the shields, and following ESA's NG-CryoIRTel design, and cools to ~15K. This latter stage cools a 15K enclosure for the receiver and precools the Joule-Thompson cooler which provides heat lift at ~4K. A design driver is the need to minimise the power dissipation in the cold stages (4K and 15K), due to the limited capacity of the cryo-coolers. This is accomplished through careful thermal and harnesses design.

The receiver back-end electronics, e.g. LO generation and IF components and FFTS, is mostly located within the SM. Also located within the SM are the compressors required for the Stirling and Joule-Thompson cryo-coolers, including a gas-preparation system for the latter; the cooler and on-board calibration target and target deployment electronics, and instrument control functions. A schematic of the proposed payload structure is shown in Fig. 5.

This mission will be operated in two distinct modes. Mode 1 allows large area surveys around the galactic plane to be performed by continuously varying the SC pointing. Mode 2 extends the spatial sampling range to higher out-of-plane positions and allows for period of deep integration on extragalactic sources.

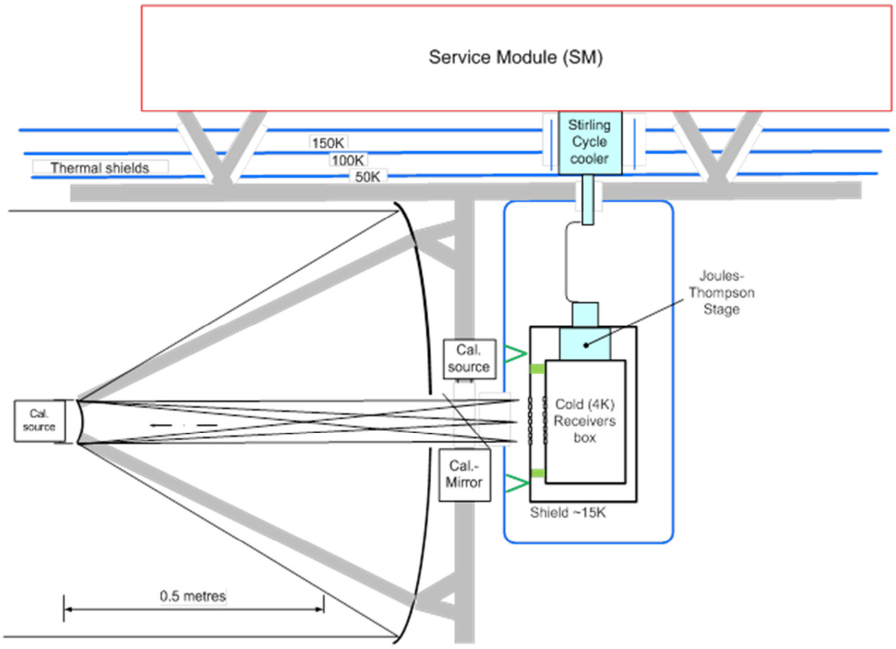

Fig. 5: A side view of the proposed FIRSPEX payload

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