SPIRE

A Bolometer Instrument for FIRST

A Proposal to the European Space Agency in response to the ESA Call For Proposals

Executive Summary

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Introduction

We propose to build a submillimetre instrument for FIRST using bolometric detectors and covering the 200-670 µm spectral range. The instrument, SPIRE (Spectral and Photometric Imaging REceiver) , has been designed and optimised for two of the most important scientific goals of FIRST - galaxy and star formation - and for science which can only be done from space. As well as addressing the key themes of FIRST, SPIRE can provide a powerful tool to the scientific community for many astrophysical research projects ranging from our own solar system to the energetic nuclei of active galaxies.

SPIRE covers the still poorly known wavelength region between 200 and 700 µm. Observations in this range are especially important for determining the history of star formation in galaxies and the early stages of star formation in the interstellar medium. The instrument incorporates a three-band submillimetre camera designed for sensitive deep surveys with the largest possible field of view, and a Fourier Transform Spectrometer (FTS) which can measure the complete 200-670-µm range with adequate spectral resolution for the main scientific goals. The SPIRE design exploits proven and reliable techniques and recent advances in cryogenic and submillimetre instrument technology. Its development and manufacture will involve technical challenges in the areas of thermal/mechanical engineering, optical design and on-board data processing. SPIRE has been studied and developed by a consortium of European and US institutes and scientists with wide experience in far infrared and submillimetre astronomy and in the manufacture, operation and scientific use of space instruments.

The scientific aims of SPIRE

SPIRE is designed primarily to exploit FIRST's capabilities in addressing two of the most prominent questions of modern astrophysics:

how and when did galaxies form? - the investigation of the statistics and physics of galaxy and structure formation at high redshift;

how do stars form? - the study of the earliest phases of star formation, when the protostar is still coupled to the interstellar medium.

These investigations require the ability to carry out large area deep photometric imaging surveys at far-infrared and submillimetre wavelengths, and to follow up these systematic survey observations with spectroscopy of selected sources. SPIRE will exploit the unique advantages of FIRST, which cannot be matched by any other facilities: its large-aperture, cold, low-emissivity telescope; the complete lack of atmospheric emission giving access to the poorly explored 200-700 μm range, and the large amount of high quality observing time. Because of these advantages, SPIRE will have unmatched sensitivity for deep photometry and moderate-resolution spectroscopy.

Galaxies emit a large fraction (30% to nearly 100%) of their energy in the far infrared due to re-processing of stellar UV radiation by interstellar dust. The far infrared peak is redshifted into the SPIRE wavelength domain for galaxies with redshift larger than ~ 1. The bolometric luminosity of a galaxy cannot be determined without an accurate measurement of the Spectral Energy Distribution (SED) in the far infrared. The study of the early phases of galaxy evolution at high redshift requires an instrument which can detect the galaxies which emit in the far infrared and submillimetre and determine their SEDs to derive their bolometric luminosity. This can be achieved by a large imaging survey in three bands, followed by low-resolution spectroscopic observations of a sub-sample of the detected objects selected according to photometric criteria.

Stars form through the fragmentation and collapse of dense cloud cores in the interstellar medium. The very first stages of cloud collapse are still very poorly known. A global understanding of these phases is crucial, as they must eventually govern the origin of the stellar initial mass function (IMF). Sensitive observations at high spatial resolution in the far infrared and submillimetre region are needed to make complete surveys of protostellar clumps to determine their bolometric luminosity and mass functions. SPIRE will also, for the first time, enable astronomers to observe at high spatial resolution the physical and chemical conditions prevailing in the cold phases of the interstellar medium to study the behaviour of the interstellar gas and dust prior to and during star formation. SPIRE will have uniquely high sensitivity to very cold dust emission, making it the ideal instrument to study the material that is ejected in copious quantities from evolved stars, enriching the interstellar medium with heavy elements. It is now known that large amounts of mass - as yet undetected - are lost before the white dwarf stage. Our understanding of stellar evolution, and of the enrichment of galaxies in heavy elements and dust, will be incomplete until these earlier mass loss phases are characterised and understood.

These studies of star formation from the ISM and the interaction of forming and evolved stars with the ISM are also, of course, related to the investigation of galaxy formation and evolution, which occur through just these processes.

These high priority programmes require high-sensitivity continuum imaging in several bands to detect and make a first selection of interesting objects, and a low-resolution spectroscopic mode to obtain a detailed SED of selected objects. Many of these objects will be faint compared to the sky background, and accurate subtraction of the background must be performed. These scientific requirements have been important in the change from a grating spectrometer previously proposed for this instrument to an imaging FTS. The grating has the disadvantage of fixed spectral resolution, which is unsuitable for the faintest objects detected in the photometric surveys, and does naturally lend itself to providing an imaging capability.

Although SPIRE has been optimised for the two main scientific programmes, it will offer the astronomical community unique observing capabilities to tackle many other astrophysical problems:

giant planets, comets, the galactic interstellar medium, nearby galaxies, ultraluminous infrared galaxies, and active galactic nuclei. Its capabilities will remain unchallenged by the ground based and the airborne observatories which are planned to come into operation over the next decade.

The SPIRE instrument

SPIRE comprises an imaging photometer and an imaging Fourier Transform Spectrometer. The photometer has a 4-arcminute field of view (the maximum possible given the constraints of the FIRST focal plane layout). Three imaging arrays of bolometric detectors provide broad-band photometry ($\lambda/\Delta\lambda \approx 3$) in wavelength bands centred on 250, 350 and 500 μm. The instrument does not use a filter wheel: the whole field of view is observed simultaneously in all bands through the use of fixed dichroic beam-splitters. Sky chopping is provided by a chopping mirror within the instrument (this is the only mechanism within the photometer). A internal thermal calibration source is available to provide a repeatable calibration signal for the detectors. The Fourier transform spectrometer uses the Martin Puplett polarising design, which has two input and two output ports. One input port covers a 2-arcminute field of view on the sky and the other is fed by an on-board calibration source. Two bolometer arrays are located at the output ports, one covering 200-300 μm and the other 300-670 μm. The FTS will be operated in continuous scan mode, with the path difference between the two arms of the interferometer being changed by a constant speed mirror drive mechanism. The spectral resolution of the FTS is determined by the maximum optical path difference for a scan, and will be adjustable between 0.04 and 2 cm^{-1} (which corresponds to ($\lambda/\Delta\lambda \approx 20$ - 1000 at 350 μm wavelength). The photometer and spectrometer are not designed to operate simultaneously.

The change of the spectrometer design from a grating to an FTS has allowed the operating temperature of the detectors to be relaxed to 0.3 K because the photon noise limited NEP is higher for the FTS, whose detectors observe broad-band, than for grating or Fabry Perot spectrometers in which they observe in narrow-band mode.. This change has allowed a ^{3}He sorption cooler to be adopted for SPIRE - a considerable simplification over the previously base-lined dilution cooler. The SPIRE ^{3}He cooler is similar in its essential features to the one successfully flown on the IRTS satellite. It is a self-contained unit with simple electrical and mechanical interfaces to the spacecraft. It is designed specifically for the requirements of SPIRE and FIRST. The 0.3-K hold time is in excess of 46 hours, and the fridge can be recycled in 2 hours, with an average heat-load on the helium tank of only a few mW.

The photometer and spectrometer share some common input optics, and use the same refrigerator for the detector arrays, but otherwise occupy separate compartments within the focal plane unit. Each contains optical elements at 2 K and 4 K. The optical designs of both parts of the instrument will be carefully optimised for maximum stray light rejection and minimum aberrations.

The base-line detectors for both are bolometer arrays providing full instantaneous sampling of the telescope point spread function. The array sizes for the photometer are 32 x 32 (250 μm), 24 x 24 (350 μm) and 16 x 16 (500 μm). For the spectrometer, the 200-300 μm band uses a 16 x 16 array and the 300-670 μm band uses a 12 x 12 array. Several different kinds of detector array and associated cold multiplexer are currently under development within the SPIRE consortium (which includes the world's leading bolometer groups), and the best has yet to be selected. A proven fall-back option, incorporating the technique of feed-horn arrays (as used by the successful SCUBA instrument on the JCMT telescope) is available should there be any major difficulties with the planar bolometer array technology.

The large numbers of pixels in both the spectrometer and photometer requires a significant amount of on-board signal processing to accommodate the available telemetry rate. A specialised signal processing unit will carry out data de-spiking and signal averaging (of both photometric frames and spectrometer interferograms) prior to transmission of the data to the ground.

Building SPIRE will require considerable technical ingenuity. Three areas have been identified in which the development of the instrument will present technical challenges:

(i) thermal mechanical engineering: the support of significant masses at low temperatures with stringent alignment tolerances and vibration specifications, but conforming to the very strict thermal budgets allocated to the FIRST focal plane instruments;
(ii) stray light control: the elimination of spurious thermal background radiation from the instrument enclosure, as this could degrade the sensitivity of the detectors or lead to systematic errors in the instrument calibration;
(iii) the development and proof of planar detector arrays in time for flight, and the solution to the problem of the heavy on-board data processing which they will require.

Addressing all of these issues requires particular expertise which is available within the SPIRE consortium.

The SPIRE consortium

SPIRE will be built by an international consortium from the UK, France, Italy, USA, Spain and Sweden. The consortium includes individuals and institutes with world-leading expertise in far infrared and submillimetre instrumentation, and astronomy, and with a wealth of experience in previous cryogenic space missions including IRAS, COBE and ISO. The SPIRE institutes and their main roles in the project are summarised in the table below.

Institute	**Role**
Caltech/JPL, Pasadena	Bolometers (option)
CEA, Grenoble	^{3}He cooler
CEA, SAp, Saclay	Bolometers (option); Instrument control and Signal Processing Electronics and related On-board S/W; ICC DAPSAS Centre
Obs. de Meudon (DESPA), Paris	Warm electronics (with SAp)
Instituto de Astrofisica de Canarias (IAC), Tenerife	Signal proc. electronics (with SAp)
Institut d'Astrphysique Spatiale, Orsay	Ground calibration support
Istituto di Fisica dello Spazio Interplanetario (IFSI), Rome	Digital Processing Unit (DPU) and related on-board S/W
Imperial College, London	EGSE; ICC DAPSAS Centre
LAS, Marseille	Optics; FTS mechanism; cold vibration
MSSL, Surrey	Structure
NASA, Goddard	Bolometers (option)
University of Padua	ICC manpower
Queen Mary and Westfield College, London	Focal plane arrays; filters, dichroics, polarisers; internal calibrator for photometer
Rutherford Appleton Laboratory, Oxfordshire	Project management; AIV and ground calib. facilities; ICC Operations Centre
Royal Observatory Edinburgh	Chopper; FTS internal calibrator; contributions to ground calibration, structure and optics design
Stockholm Observatory	Instrument simulator

In addition to their hardware-provision responsibilities, all SPIRE hardware institutes will support the development and operation of the SPIRE Instrument Control Centre (ICC).

The SPIRE Instrument Control Centre

The SPIRE consortium fully agrees with the mission operations scheme proposed in the FIRST Science Management Plan, in which the instrument consortium provides an Instrument Control Centre (ICC) which plays a major role in mission operations by ensuring that the unique expertise built up by the PI team in the course of instrument development and ground testing can be brought to bear most effectively on the task of operating the instrument most effectively in flight. The SPIRE ICC will comprise an Operations Centre, located at the Rutherford Appleton Laboratory in the UK which will be responsible for all aspects of ICC activities associated with mission operations, and will be the sole ICC interface with ESA. We have adopted an approach which will allow the de-centralised know-how of the consortium to be focused on the task of delivering the requirements of the ICC while recognising the logistical impracticalities of seconding key staff to distant or foreign locations for periods of years during mission operations. Two Data Processing and Science Analysis Software (DAPSAS) Centres will be located at SAp, Saclay and Imperial College, London with the responsibility for producing ICC data-processing software to the required standards. Both centres will draw on the expertise and effort of the main hardware providing groups. Some functions of the ICC will thus be distributed to make maximum use of the expertise developed during instrument construction and ground testing, while others will be centralised to provide a single clear interface for deliverable software within the consortium and for interaction with ESA's Mission Operations Centre (MOC) and FINDAS.

The SPIRE consortium management structure

The SPIRE PI is Dr. Matt Griffin of Queen Mary and Westfield College, London, who will carry out the role and responsibilities as given in the FIRST Science Management Plan. Dr. Laurent Vigroux of SAp, Saclay will be Co-PI, reflecting the major contribution to the project from France, and the agreement that all important project decisions will require consensus between the UK and France. The overall direction of the project shall be under the control of the SPIRE Steering Group, which shall be chaired by the PI and shall agree all major policy and strategic decisions concerning the instrument development and the international allocation of tasks. It shall comprise the PI, the Co-PI and one representative from each of the participating countries. These shall be senior figures representing the project within their own countries and before their national space agencies and shall work to ensure that the project has the necessary support from those agencies. In particular, they shall assist the PI in solving problems associated with funding and manpower resources within their countries.

The SPIRE consortium has one Co-Investigator from each institute having significant hardware and/or ICC responsibilities. This policy has been adopted to avoid having a very large number of Co-Investigators, with consequent dilution or blurring of key responsibilities in such an extensive and complex consortium. The Co-Investigators are senior scientists in their institutes and, besides contributing their expertise to the instrument development and operation, will assist the PI in solving any problems associated with work allocated to their institutes.

SPIRE project activities shall be organised by the Project Manager who shall communicate directly with local institute managers. Other key positions in the consortium include (a) two Project Scientists, whose main duties are to ensure that the scientific goals of the instrument are translated into the necessary technical specifications, and to oversee the design, construction, calibration and operation of the instrument with respect to the scientific requirements; (b) an Instrument Scientist, whose main task is to specify the detailed requirements for the instrument subsystems taking the scientific aims into account, and to oversee the ground and in-orbit calibration plans for SPIRE; (c) a Systems Engineer who will lead the SPIRE Systems Team which shall oversee the systems design and specification of the instrument, with particular emphasis on subsystem interfaces and potential problems at system level.

Prior to the Operations phase, the SPIRE ICC shall be under the control of the ICC Development Manager who shall execute the policies of the ICC Steering Group, chaired by the ICC Scientist. The ICC Development Manager shall be the formal point of contact with ESA for ICC matters. During FIRST mission operations, the Development Manager position shall be replaced by the position of ICC Operations Manager.

The SPIRE consortium funding status

The national agencies of the countries participating in SPIRE are all strongly supportive of their groups' participation and proposed roles in the consortium. Final decisions on funding levels and schedules will not be made until after the decision on how the FIRST mission is to be implemented.