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SPIRE/ESA/N/0038.10

ASTRO(98)6
Annex 1, rev. 2
Paris, 5 May 1998

EUROPEAN SPACE AGENCY

ASTRONOMY WORKING GROUP

FIRST Science Evaluation Committee (FSEC)

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	Dr. T.J.-L. Courvoisier	ISDC, Versoix, Switzerland
	Dr. E. Kreysa	M-P-I. für Radioastronomie, Bonn, Germany
	Dr. J. Lequeux	Observatoire de Paris, France
	Dr. K. Menten	M-P-I. für Radioastronomie, Bonn, Germany
Secretary:	Dr. S. Volonte	ESA, HQ, Paris
ESTEC Support:	Dr. G. Pilbratt	Project Scientist
	Mr. F. Felici	Project Manager (acting)

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Report and Recommendations of the Far-Infrared and Submillimetre Telescope (FIRST) Science Evaluation Committee (FSEC) to the Astronomy Working Group

Executive Summary:

Astronomers have long sought access to one of the least explored regions of the electromagnetic spectrum -- the far-infrared and submillimetre domain. This is the spectral window on the universe through which we expect to gain insight on:

- the formation and evolution of distant, dust-shrouded galaxies at red shifts up to $z = 5$ --- a time when the universe had only reached less than one tenth its present age;
- the merging of galaxies and the eruption of star bursts;
- the development of active galactic nuclei;
- the earliest stages of star formation;
- the dynamics of proto-planetary disks around young stars;
- the chemical composition of the interstellar medium, stellar and planetary atmospheres, and cometary outflows;
- and perhaps the underlying chemical processes that led to the formation of life.

The Far-Infrared and Submillimetre Telescope, FIRST, one of ESA's cornerstone missions, was envisioned to not only open this new electromagnetic domain to astronomical observations; it was also conceived to follow up in greater depths on selected new findings and provide new astrophysical insight.

An Announcement of Opportunity for scientific instruments to be included on FIRST resulted in the submission, in mid-February 1998, of three separate proposals designed to provide the telescope with a complement of instruments that would jointly meet the mission's objectives. To evaluate these proposals, ESA established a FIRST Science Evaluation Committee, FSEC.

The FSEC met on four occasions between March 5 and April 17, and had wide-ranging, informative discussions with the principal investigators of the three science instrument teams, the FIRST project staff and the project scientist at ESTEC, and Dr. Sergio Volonte of ESA Headquarters. From these meetings, a number of conclusions and recommendations emerged.

o The FSEC unanimously agrees that a spectacularly exciting, astronomically rewarding FIRST mission is technically feasible. However, several challenges lie ahead, that must quickly be resolved for the FIRST mission to go forward on schedule for launch in late 2005 or 2006. In particular:

o Funding for the science instruments needs to be rapidly formalized and realistic funding schedules defined, in order for mission planning to go forward in an orderly, cost-effective fashion. The complement of science instruments cannot be finally and fully defined until these funding issues are resolved.

o The FSEC expresses satisfaction that the three science instrument teams look forward to working harmoniously to provide the astronomical community with the required range of spectral and imaging capabilities to meet the mission's main scientific objectives. However, unlike the ISO mission, whose planning was facilitated by knowledge previously gained in the IRAS mission, FIRST is entering virgin territory. The instruments must be capable of both exploring the sky in this new wavelength regime, and following up with more detailed, astrophysically informative observations. These dual functions call for complementary technical designs that need to be carefully screened to define the most cost-effective mission. The FSEC recommends that the FIRST Science Team, once selected, be asked, at the earliest opportunity, to organize a workshop or series of workshops to define a mission profile that secures the most cost-effective balance between survey and detailed observations. From this effort a broad observing strategy should emerge that later could define a central observing programme and serve as a guide to calls for observing proposals.

o The FIRST instruments will gather data at a rate up to a factor of 100 higher than can be transmitted to the ground with the foreseen telemetry system. The instrument scientists and ESA engineers will have to define, as soon as feasible, the most cost-effective distribution of resources between software efforts at onboard data handling and potentially feasible increases in telemetry transmission rates. If no increases or, as currently anticipated, only modest increases in the telemetry transmission rates are possible, the data will have to be processed and compressed onboard by a factor of up to 100, before they are telemetered back to Earth. This scale of compression is mission critical. Its feasibility needs to be demonstrated at earliest opportunity. The instrument teams will have to devote far more effort to onboard software development and testing than has been required on previous missions.

o The astronomical interest of FIRST and the large international teams of scientists the mission has attracted, will require tight management structures to secure effective oversight. ESA should quickly define these structures in consultation with the instrument teams, and preferably also with organizations that have previously dealt successfully with missions of comparable complexity and similarly large data handling requirements.

o FIRST will have great potential for adding scientific insight into the findings of the planned Planck mission. The FSEC recommends that ESA keep the complementarities offered by these two missions in mind, as planning for both missions proceeds.

o In view of funding uncertainties and a wide range of detector / receiver developments planned by the instrument teams, the FSEC lists a set of "minimum-acceptable-capabilities" for the FIRST payload; these capabilities are absolutely essential if FIRST is to fulfill its astronomical objectives. While the instrument teams should be encouraged to exceed these minimum requirements, the importance of providing this list is to emphasize that the mission will fall short of meeting its prime objectives if the payload fails to attain any one of the listed capabilities.

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Planning the FIRST Mission

ESA's cornerstone mission, the Far-Infrared and Submillimetre Telescope, FIRST, was conceived to provide astronomers access to one of the least explored domains of the electromagnetic spectrum --- the far-infrared and submillimetre domain. The rich lode of astronomical information gathered by ESA's Infrared Space Observatory, ISO, between November 1995 and April 1998, and recent ground-based submillimetre observations, have strongly hinted that further revelations on fundamental astrophysical processes are to be expected at FIRST wavelengths. FIRST will extend the survey work begun by IRAS in the 1980s and the observatory work of ISO of the 1990s into the submillimetre band, to culminate the first sweeping quest for astrophysical insights to be gained from far-infrared / submillimetre astronomical observations.

ESA's call for proposals for scientific instruments to be included in the FIRST mission resulted, in mid-February 1998, in the submission of three, mutually complementing, non-competitive proposals. To judge the extent to which the proposed instruments would meet the mission's objectives and to make appropriate recommendations, ESA then established a FIRST Science Evaluation Committee, FSEC, to provide an independent assessment.

The FSEC met at ESTEC on March 5 and 17 and on April 6 and 17 to examine the three proposals. In their work FSEC members were aided by Dr. Sergio Volonte from ESA Headquarters and by members of the FIRST project and the project scientist at ESTEC. The FSEC had detailed exchanges with the proposals' principal investigators, meeting with them in person on March 17, receiving subsequent clarifying inputs in writing, and having a second detailed discussion by telephone during the final session on April 17. Throughout, the FIRST staff at ESTEC made itself available to answer questions on technical and managerial matters, and Dr. Volonte provided insight on budgetary and programmatic issues, and procedural matters.

Proposed Science Instruments

Three different instruments have been proposed for FIRST, each comprising several distinct parts. Together they span the spectral range from roughly 80 to 670 μm, to map the sky and conduct photometric and spectroscopic observations. The detection techniques available in this spectral range emphasize different instrumental approaches relying, respectively, on photoconductive, bolometric, and heterodyne components, each with its particular advantages and limitations.

PACS --- The Photoconductive Array Camera & Spectrometer

The proposed PACS instrument consists of a photometer and a spectrometer. The photometer comprises two arrays --- a 25 x 16 pixel, short wavelength (80 to 130 μm) Ge:Ga array, and a similar, 25 x 16 pixel long-wavelength (130 to 210 μm) stressed Ge:Ga array. These arrays, respectively, cover concentric, overlapping, rectangular fields of view, with dimensions 85" x 55" and 170" x 110". Radiation entering the photometer is divided by a dichroic beam-splitter that separates the short- and long-wavelength flux, and concentrates the two beams onto distinct detector arrays. Individual pixels in these arrays, respectively, resolve 3.4" x 3.4" and 6.8" x 6.8" patches on the sky. The PACS team expects the sensitivity (5σ, 1 hour) of the individual pixels to be 3.5 to 5 mJy. This is 5 times better than ISO and ten times better than the expected performance on the airborne observatory SOFIA.

The spectrometer covers the same spectral region with a grating instrument. It incorporates an image slicer that divides a 47" x 47" field of view on the sky into 25 segments, each subtending 9.4" x 9.4", and aligns them along a 1 x 25 element spectrometer entrance slit. Again, a dichroic divides the beam and acts as an order sorter for the grating. The grating further disperses the radiation which falls onto the respective 16 x 25 arrays, to simultaneously measure the radiation in 16 contiguous spectral elements for each pixel array. The spectral resolving power is ~1750, corresponding to a velocity resolution of 175 km s^{-1}. The team expects the sensitivity (5σ, 1 hour) per spectral resolution element to reach 2.5 x 10^{-18} W m^{-2}.

SPIRE --- The Spectral and Photometric Imaging Receiver

The proposed SPIRE instrument offers two capabilities. It will make use of bolometer arrays to map 4' x 4' fields of view on the sky over the 200 to 670 μm spectral range, in three broad spectral bands centred on 250, 350 and 500 μm. Its diffraction-limited spatial resolution will be, respectively 18, 25, and 36 arc seconds. Its limiting sensitivity (5σ, 1 hour) for such maps will be 7 to 10 mJy. For point sources the limiting sensitivity will be ~ 3 mJy. The lower mapping sensitivity is due to the requirement of a fully sampled map. This facility will offer important astronomical capabilities, with the promise of deep analyses of distant, early galaxies, as well as Galactic star-forming regions. Virtually every aspect of astronomy may be affected by what we will find in this sparsely explored region of the electromagnetic spectrum.

The proposed instrument also carries a Martin-Puplett interferometric spectrometer to provide a spectral resolving power R ~ 20 to 1000 at 250 μm, and ~ 8 to 400 at 600 μm. While the resolving power is low, the instrument's 2' x 2' field of view will be covered by bolometer arrays that offer the same spatial resolution as in the mapping mode. Galactic regions and nearby extragalactic sources could therefore be rapidly mapped at low resolution. This capability is meant to complement the higher spectral resolution obtained with the heterodyne receivers which, however, will not be able to provide the advantage of rapid mapping, since only a single receiver will be available in each heterodyne band for each of the two orthogonal states of polarization.

HIFI --- The Heterodyne Instrument for FIRST

The proposed HIFI instrument will provide receivers to cover the spectral range from 480 to 2700 GHz, in three broad bands 480 - 1250, 1410 - 1910, and 2400 - 2700 GHz. The spectral resolution offered by the proposal ranges from roughly R ~ 10^3 to 10^7. This range of resolving powers is made possible through the use of two types of mixers, a low-resolution acousto-optic spectrometer, AOS, that provides a frequency resolution of 1 MHz, corresponding to a resolving power of R ~ 5 x 10^5 at 480 MHz, and higher at all higher frequencies, and a digital autocorrelator spectrometer (ACS) or Chirp Transform Spectrometer (CTS) at higher resolving powers. The HIFI receivers will provide unparalleled opportunities to observe interstellar and circumstellar chemical processes, particularly in observing chemical species such as H_2O, O_2, and many minor interstellar constituents which telluric absorption will make inaccessible to the airborne observatory SOFIA.

General Background Remarks

1. The FIRST Mission's Role in Astronomy

The FIRST mission differs in one essential respect from ESA's prior successful infrared mission, ISO. The Infrared Space Observatory was able to capitalize on the all-sky survey that had been previously conducted by the IRAS satellite over the 12 to 100 μm spectral range. This survey identified many new sources that ISO could investigate to obtain new astrophysical insight. When FIRST is launched, no comprehensive survey of the submillimetre domain equivalent to the IRAS mission will have been flown. The Serendipity Survey on ISO will have mapped a small portion of the sky at 200 μm; SIRTF will have conducted some photometric work at submillimetre wavelengths; and the Japanese IRIS mission will have conducted a survey of the sky at 200 μm; but results from these last two missions will be available only just before FIRST flies. Planning for FIRST is therefore more difficult than it was for ISO. This difficulty is reflected in the complement of instruments that has been proposed. It represents a balance of capabilities, some of which concentrate on survey efforts, while others are provided to analyse the results of the surveys in substantially greater detail. Two examples typify the issue:

a. In the instruments' mapping capabilities, one asks whether FIRST should concentrate on obtaining a preliminary set of maps of large areas of the sky or more refined maps of smaller regions. The two aims call for different sampling schemes, respectively efficient sampling and full sampling of a field of view. Full sampling requires observations with roughly a dozen pixels covering the Airy disk of a point source. Efficient sampling would require just one.

b. In spectroscopy the same question arises on whether FIRST should provide the rough spectral characteristics of sources, concentrating only on the strongest emission lines? Or should its capabilities range up to the very highest spectral resolving powers achievable? Should spectral resolving powers as high as R ~ 10^7 be pursued, when only a few special purposes for such investigations might emerge, or should a more restricted approach be adopted to cover the generally useful range of R < 3 x 10^5?

Clear choices are imperative if realistic budgetary constraints are to be met. While the FSEC makes unambiguous recommendations on some of these points, it also realizes that other issues will require wider debate. Accordingly, the FSEC recommends that the FIRST Science Team, once selected, be asked, at the earliest opportunity, to organize a workshop or series of workshops to define a mission profile that secures the most cost-effective balance between exploratory and detailed observations. From this effort a broad observing strategy should emerge that later could define a central observing programme and serve as a guide to calls for observing proposals.

2. Complementarity of FIRST and Other Observatories

The FSEC has stressed the unique capabilities the FIRST mission will offer. But it is also important to recognize the ways in which FIRST and other observatories will complement each others' strengths.

o NASA's Submillimeter Wave Astronomy Satellite, SWAS, and the Swedish/international Odin mission, both presently scheduled for launch in 1999, will search for submillimetre emission in a number of specific spectral lines, including emission from $H_2{}^{16}O$ at 556.9 GHz, $H_2{}^{18}O$ at 547.5 GHz, and O_2 at 487.3 GHz.

o NASA's SIRTF, to be launched in late 2001, will cover the wavelength range from 3.5 to 185μm, roughly the range that was covered by ISO, but with far larger and more sensitive arrays than were available on ISO. This will permit unparalleled, deep mapping of faint, distant and low-surface-brightness sources.

o The Japanese ASTRO-F / IRIS mission, currently scheduled for launch in 2003 will survey approximately 80% of the sky in four bands ranging from 50 to 200 μm.

The dramatic advances to be expected from FIRST will, therefore, not stand in isolation, but be enriched by the findings of these other missions. However, FIRST will operate at wavelengths beyond the 200 μm limit of ISO, SIRTF and IRIS, and will have an aperture a factor of 4 to 6 times larger than ISO, SIRTF, IRIS, Odin or SWAS.

Two other facilities will have comparable size or larger apertures than FIRST.

o The telescope on the airborne observatory SOFIA will have an aperture of 2.5 m --- not quite as large as that of FIRST. It will be able to cover the entire spectral range from the near infrared to the submillimetre, except in portions of the spectrum where the atmosphere is opaque, notably at virtually all wavelengths at which Galactic water vapour or molecular oxygen might be studied at zero red shift. Studies of low-surface-brightness objects, like some galaxies, will also be difficult through the terrestrial atmosphere. FIRST and SOFIA, therefore, can complement each other in observations on bright sources. FIRST, however, will have unique potential for studies of faint objects, the H_2O and O_2 content of astronomical sources, and particularly for survey work.

o The NGST will have a much larger, ~ 6 to 8m aperture, and is currently expected to operate out to near infrared wavelengths, but not beyond. Observations carried out by FIRST and the NGST will complement each other, but not overlap. Both will conduct searches for early epoch star formation in galaxies, though looking for different signatures of the process.

The complementing capabilities of FIRST, the NGST, and the large submillimetre interferometer arrays, will be particularly fruitful.

o Large (sub)millimetre interferometer array(s) will become available at about the time FIRST is launched (the European LSA, the American MMA, the Japanese LMSA, or combinations of these). They will be eminently suited for deep searches of red-shifted dust continuum emission from very distant (proto)galaxies almost independently of their red shift, and will measure their spectral energy distributions for red shifts greater than ~ 5. The multi-element detectors onboard FIRST, and the spacecraft's placement above the atmosphere, more than compensate for the interferometer's much larger collecting area. FIRST, therefore, will achieve comparable or even higher detection efficiencies in large field surveys for such sources. The interferometer arrays, in turn, will facilitate high spatial resolution imaging of objects discovered in these surveys. Red shifts will be obtained with both instruments or with the NGST. Thus the FIRST mission, the large (sub)millimeter arrays, and the NGST, are perfectly complementary instruments for galaxy formation in the early universe, as well as for studies of star formation.

3. FIRST and Planck

ESA is contemplating several scenarios for launching the FIRST and Planck missions, which will provide the astronomical community with unimaginably rich insights. These two missions should not be viewed in isolation. Three possibilities are currently under consideration. A merged scenario, consisting of FIRST and Planck mounted on a single spacecraft, would interleave the Planck survey with FIRST observations; launch on a common carrier would permit FIRST and Planck to operate independently in orbit; a last option would provide for two independent missions, Planck being launched as a SOYUZ mission, while FIRST was placed into orbit on an Ariane 5. In considering these options an important scientific consideration should be kept firmly in mind. The findings of Planck will convey new information on the distribution of radiation emitted at a time when the Universe was only a few hundred thousand years old, and its red shift was z ~ 1500. These results will provide new perspectives on the origin and early structure of the Universe. But foreground sources are likely to confuse the task of uniquely interpreting the Planck observations. Some of the detectors and receivers on FIRST will be operating in the same spectral range covered by Planck, and will provide an opportunity to follow up Planck's survey with finer-resolution maps of interesting features, analyzing them with potentially higher spectral resolving power. This will help to separate foreground emission from Galactic and extragalactic sources, from the genuine cosmic background radiation that Planck seeks to analyze. In addition, FIRST and Planck will complement each other in providing spectral energy distribution (SED) functions spanning the far-infrared, submillimetre, and millimetre wavelength ranges, for both Galactic and extragalactic sources. The synergy offered by launching the Planck and FIRST missions within roughly the same time frame needs to be recognized and should, if at all possible be made a goal of both missions.

Specific Findings and Recommendations

1. Funding Issues

At the time of writing, eighteen to twenty months remain before the three scientific instruments on FIRST must be fully defined if the telescope is to be launched, as currently proposed, in late 2005. Mission definition is a first step toward launch. It aims at a clear understanding of weight limitations, electrical power, and cryogenic cooling budgets, telescope and spacecraft pointing requirements, potentially conflicting demands of the various instruments, interfaces between spacecraft and instruments, and many other basic factors.

Most of the PI teams have proposed extensive refinements to detector / receiver technology to permit them to include the most sensitive detector arrays or receivers in their payloads. However, some of the teams are finding that the funding required for detector / receiver development will not be available for many months, possibly for a year or two. Such a delay would have serious impact.

The FSEC critically reviewed the three science instruments in the light of current funding pressures, and identified for each instrument those capabilities that were felt to be of primary scientific importance. These considerations are reflected in our specific recommendations on the individual instrument proposals.

Budgetary constraints clearly impose serious restrictions on technical development efforts. The FSEC shares the concerns repeatedly expressed by the PIs that the FIRST mission will not fulfil its science objectives if curtailed beyond a reasonable point. We strongly feel that FIRST is an excellent mission, with absolutely unique scientific potential. While the PI teams are making every attempt to achieve whatever cost reductions they can, it is also important that concerted efforts continue to provide appropriate levels of funding to assure that the mission will realize its essential objectives. Early funding is urgently required to support the science instrument teams' critically important development work. The FSEC also shares concerns voiced by the instrument PIs, regarding the funding of the Instrument Control Centres, ICCs. We recommend that ESA investigate whether it could find the means to contribute to the support of the ICCs.

Because agreement on funding has not yet been reached, a fully optimized payload design cannot be finalized. The FSEC is convinced that serious work on the mission should not start before adequate funding is certain. Nor does the FSEC feel that realistic launch dates can be scheduled unless the funding stream not only is assured, but is ramped up sufficiently early to secure a timely launch. Delays in funding threaten unnecessary cost overruns, and should be avoided to stay within budget. Funding and funding schedules are likely to remain the most critical issues standing in the way of assured success.

The FIRST instruments will generate extremely large data streams. These will call for funding levels for data handling substantially higher than on previous far-infrared missions. They will also entail funding for software development far earlier in the mission. As a consequence, the instrument teams will need to define at the earliest opportunity, and then rigorously keep track of, the most cost-effective distribution of available funds, in each phase of the schedule, to meet both their instruments' ultimate software and hardware requirements.

2. Telemetry and Onboard Data Processing

The large detector arrays and/or spectral bandwidths incorporated into the three instruments will provide data rates up to two orders of magnitude higher than the nominal time-averaged downlink rate of 50 kilobits per second, described in the Announcement of Opportunity for FIRST. This necessitates an extensive degree of onboard data processing. It is, however, not obvious at this point that a fully automated process can achieve the required level of data compression without excessive loss of information that could jeopardize the mission.

On ISO all data were transmitted to the ground and processed there. The difficulties encountered by the ISO data handling teams in establishing automated pipelines to yield reliable data are a measure of the depth to which detectors will have to be characterized before flight, and the sophistication and computing power that will have to be incorporated into onboard data processing. While full sampling of small portions of data streams will be possible to verify proper onboard data handling, the bulk of the data will have to be downlinked after all disturbances and glitches have been recognized and removed. The FSEC appreciates the various economic and complex technical considerations that have led to the baselined telemetry budget, but is also concerned that the present situation may jeopardize the full exploitation of the unique scientific data gathered by the FIRST instruments. The Committee, therefore, strongly recommends that the project give urgent consideration to all possible means of increasing the telemetry transmission rate on FIRST. The FIRST project should work closely with the instrument teams in assessing quantitatively the scientific gains of any potential increase in telemetry bandwidth.

The software aspects of the FIRST mission need to be addressed very early. It is important that the hardware and software development progress harmoniously to optimise the science output from the mission at minimum cost. Developing data analysis software, means encoding of knowledge of the instruments into a set of software tools. The translation process is delicate. On previous projects, instrument builders have often considered software development secondary to hardware design and construction, especially in the early years of mission preparation. This has led to difficulties closer to the time of launch. To avoid this problem, the FIRST project has rightly insisted that the instrument teams clearly identify funding and manpower requirements for the Instrument Control Centres, ICC, which will be in charge of pre-operations developments, operations support, and post-operations archiving. The instrument teams have had to clearly identify resources for ICC operations, as distinct from instrument development, but even within instrument development, strict separation and monitoring of resources for software, as distinct from hardware, will be essential. Monitoring these separate resources throughout development of the science instruments will have to remain a high priority.

With the FIRST data analysis system split between a FIRST Science Centre and three ICC's, as is currently foreseen, the management structure, as conceived, must allow the four centres to share experience, avoid duplication of effort, and develop a common systematic approach. The development of the FIRST Integrated Network Data Archive System FINDAS will, similarly, have to be made globally compatible with all other elements of the mission. A number of structures are foreseen to address these problems, including a Ground Segment Advisory Group (GSAG), a FIRST Science Centre (FSC) a Mission Operations Centre (MOC), and a Commonality Working Group (CWG). The purpose of the CWG, which has already met once, is to eliminate duplication of efforts, by developing common systematic approaches for the different instrument teams, and an overall system which is homogeneous and coherent.

Large scientific software systems, such as the one to be developed for FIRST need to be able to evolve. This is most often not compatible with industrial developments, particularly when based on rigidly specified fixed term contracts. Care will, therefore, be needed in developing industrial participation. The process may be facilitated by incorporating packages that have already been developed for ISO, XMM and possibly other missions. Some software and data handling packages that could be beneficial to both Planck and FIRST may also be developed in common.

The FIRST Project appears to be well aware of all these issues but, for the FIRST mission to succeed, the degree of discipline that the science teams and Project will have to impose on themselves will clearly be very high. The central role that software developments will play in all aspects of this mission cannot be overemphasised.

3. Findings and Recommendations on Individual Instruments

i. PACS

The PACS instrument, in many ways provides the best-understood technology on FIRST, since ISO already flew instrumentation using the same kind of Ge:Ga detectors. The highly significant advances offered by FIRST will be a roughly six-fold increase in diffraction-limited spatial resolution and a ~36-fold increase in light gathering power for point sources, both due to the nearly six-fold increase in telescope aperture from 60 cm to 3.5 m. Additional advantages accrue from a ~ 40 to 100-fold increase in mapping speed provided by the 16 x 25 arrays --- far larger than the 3 x 3, 100 μm and 2 x 2, 200 μm arrays in the ISO photometer.

Ways of dealing with cosmic ray bombardment will require particular attention. The Ge:Ga detector elements have cross sections comparable to the largest detectors flown on ISO. The radiation environment in L2 is expected to be similar to the environment ISO experienced at apogee. This means that a cosmic ray hit may be expected roughly every 10 seconds on each detector element in each array if PACS detectors have approximately the same size as those on ISO. On ISO, recovery times of 2 to 3 seconds were typical after a cosmic ray hit, and some types of hits caused responsivity changes that lasted as long as 30 seconds. Thermal emission from the FIRST optics will illuminate the PACS detectors with a higher infrared background flux than experienced on ISO. This is expected to reduce the severity of detector memory effects, but a complete analysis of how the detectors will behave is still pending.

The reduction of ISO data was made difficult by the high rate of detector hits, and required months of post-launch testing on the ground to determine the best ways of removing cosmic ray glitches to retain the largest possible body of reliable data. On FIRST, experimenters will not have this luxury. The data rate will require most of the deglitching to be performed onboard the spacecraft. The experimenters will, therefore, need to gain far greater pre-flight familiarity than was required on ISO, with the different types of cosmic ray hits, detector memory effects following a hit, and algorithms permitting the recognition and optimum removal of different types of cosmic ray glitches.

ii. SPIRE

a. The bolometric arrays on SPIRE appear to the Committee to hold exceptional promise. The three broad spectral bands at 250, 350 and 500 μm in which photometry and mapping will be possible will provide a new look at a spectral range previously all but inaccessible. Any survey conducted in these spectral bands and any known sources mapped with these detectors, will provide new astronomical information. Because so little has been done in this spectral domain, the SPIRE photometers have the greatest inherent promise of providing new astronomical insights.

b. The FSEC judged the low-resolution, spectrophotometric mode on SPIRE, R ~ 20, to be particularly important for providing spatially resolved far-infrared / submillimetre spectral energy distributions (SEDs) for all types of galaxies, to elucidate their dust component and radiation mechanisms. The broad wavelength coverage on SPIRE will permit determination of these SEDs out to red shifts as high as z ~ 5 — a realm of paramount importance. At intermediate dispersion, R ~ 50 - 100, SPIRE can measure the [OI] 63μm and the C^+ 158μm emission lines, thereby determining red shifts for extremely distant, possibly protogalactic, objects. At higher resolving powers R > 1000, the HIFI instrument will provide primary spectroscopic capabilities in this wavelength regime. For this reason the Committee judges the higher resolution, R ~ 100 - 1000, capability proposed for SPIRE to be less essential than the lower resolution modes.

c. The Martin-Puplett interferometric spectrometer design is useful in that the entrance polarizer and the polarising beam-splitter both can be used over a wide spectral range — in this instance the entire range from 200 to 670 μm. No suitable beam-splitter with a correspondingly broad spectral coverage exist for a Michelson interferometric spectrometer design. However, the Martin-Puplett spectrometer throws away half the light hitting the entrance polarizer, a defect that might be avoided in other Fourier transform spectrometer designs for low-resolution spectrometry. While the FSEC has no specific suggestions, it urges the SPIRE team to re-examine whether means could be found to avoid rejection of half the incident flux.

d. The FSEC similarly asks the SPIRE team to reconsider whether a low spectral resolution capability could be effectively built into the SPIRE photometer, streamlining the instrument by replacing the currently proposed, completely independent SPIRE spectrometer.

iii. Issues Concerning both PACS and SPIRE

a. In both the SPIRE and PACS focal plane arrays, two different schemes for coupling detectors to radiation may be considered: antenna-coupling and absorber-coupling. Both options can be used in order to achieve the diffraction limit at a given telescope, either by making the individual elements of the array large and fully efficient for point source detection, or small for instantaneous full sampling of the focal plane. The antenna coupling is most attractive for fully efficient detectors, because of the difficulty of machining a large number of very small antennas. The antenna-coupled, fully efficient array will also be less vulnerable to stray light, because of the intrinsic angular response of the antennas. However, such systems necessarily undersample the focal plane. Therefore, some strategy for scanning for the missing samples will be necessary. One can alternatively consider the new possibility of bolometers that cover the focal plane completely. With highly efficient absorbers, Nyquist coupling is an attractive possibility, though the signal and the background will be lower for the Nyquist sampled array. This may require detectors with lower NEPs, and these might be achievable only by lowering operating temperatures.

b. The relative merits of fully efficient vs. fully sampled arrays are far from settled, and should be further explored by both the PACS and SPIRE teams. For example, if the total number of detectors were limited, fully efficient detectors could cover a larger instantaneous field of view, though providing somewhat lower-fidelity mapping.

iv. HIFI

a. The currently proposed heterodyne bands will not cover the entire spectral range from 480 to 2700 GHz (111 to 625 μm) in one contiguous domain. As currently conceived, gaps will remain from 1250 to 1410 and 1910 to 2400 GHz (214 to 240 μm and 125 to 157 μm). The FSEC asked the HIFI team to elucidate the astronomical consequences of these two spectral gaps. Their response indicates that the only serious losses will be an inability to search for the important interstellar features due to the [OI] fine-structure line at 146 μm, and the HeH^+ line at 149 μm. The expected faint HeH^+ feature would have particularly benefited from the high resolving powers offered by heterodyne spectroscopy. The FSEC, however, considers this loss acceptable in view of the possibility that PACS or SOFIA might succeed in adequately studying the 149 μm line and definitely will be capable of observing the 146 μm line. The FSEC also recognises that substantial development efforts would be required to develop heterodyne capabilities to cover these spectral gaps.

b. The HIFI team has proposed spectral resolving powers as high as $R \sim 10^7$ corresponding to a velocity resolution of 30 m s^{-1}. The FSEC is not convinced that there are many pressing astronomical investigations that would call for such high resolving powers. Resolving powers of the order of 3×10^5 to 10^6, or ~ 1 to 0.3 km s^{-1}, should be adequate for most purposes. An acousto-optic spectrometer (AOS) can provide adequate frequency resolution for most observations. The AOS provides a frequency resolution of 1.5 MHz which, from the lowest to the highest HIFI frequencies, corresponds to resolving powers of a few times 10^5 to a few times 10^6. This resolution might be somewhat coarse for resolving spectral lines from such sources as comets, very narrow lines from cold dark clouds with widths < 0.5 km s^{-1} or the cores of some absorption features in interstellar clouds or planetary atmospheres. However, inclusion of a high-resolution spectrometer, the digital Autocorrelation Spectrometer, ACS, or the Chirp Transform Spectrometer, CTS, in addition to the AOS, will meet all astronomical requirements and also provide an important backup option using a different technology.

c. The HIFI team has requested an improvement of the FIRST pointing requirements by a factor of three. Compliance with this request would significantly increase the cost of the mission. The FSEC, therefore urges the HIFI team to propose a design compatible with the present pointing requirements.

v. Issues Affecting all three Proposals

The FIRST Project has identified technical problems at one level or another with each of the three proposed instruments. Weight limitations have been exceeded. Excessive cooling requirements have been proposed. Certain electronic requirements would be difficult if not impossible to meet. These are serious concerns. Because the FSEC believes that each of the proposed instruments will still be undergoing modifications as funding levels become formalised, we do not itemise these problems here. However, the FSEC is convinced that, as these modifications are implemented, the instrument teams will need to carefully conform to the FIRST Project's requirements to assure that the Project, as well as the entire mission, will stay within their designated cost envelopes.

As already discussed, onboard data reduction remains one of the pressing issues that will need to be resolved by all three instrument teams. The FSEC recommends that the three instrument teams provide, at the earliest opportunity, convincingly detailed plans for onboard data processing. These are likely to affect many other decisions including the level of software funding required for this effort.

vi. Delivery Schedules

Adherence to schedules is an important issue. At the time of writing, the FIRST Project reports that PACS is compliant with scheduled dates specified in the Announcement of Opportunity, though with a 6-month verbal relaxation. SPIRE is reported to be compliant with all the dates. For HIFI, the FIRST Project reports that the qualification model is 6 months behind schedule. The FSEC urges the HIFI team to advance this date to validate the design at the earliest possible opportunity.

4. A Minimum-Acceptable-Capability Payload

With two purposes in mind, the FSEC identified a minimum-acceptable-capability payload:

o A potential shortage of funds has suggested reductions in mission capabilities. The FSEC intended to indicate a point beyond which such reductions would seriously undermine the astronomical rationale for conducting the mission.

o Such a payload identifies essential instrumental components that must not be neglected in an attempt to develop new technologies that would provide more sensitive detectors and receivers.

The minimum-acceptable-capability payload comprises the three instruments that have been proposed, but with the following characteristics:

i. PACS

a. The photometer comprises the two wavelength channels proposed by the PACS team and retains the proposed sensitivity and the proposed number of pixel arrays, however, reducing the array sizes to an acceptable 4 x 16 pixels in place of the nominal 25 x 16 pixel arrays.

b. The spectrometer also retains its two wavelength channels and its sensitivity figures, but again reduces array sizes to 4 x 16 pixels. A spectral resolving power reduction to R = 1000 is acceptable.

Rationale: Stacks of linear, stressed 1 x 16 Ge:Ga arrays to form rectangular stressed arrays have been demonstrated. The minimum-acceptable PACS instrument with 4 x 16 arrays would be capable of all the proposed observations on point sources, and would suffer only from a 25/4 = 6.25-fold reduction in mapping speed, while reducing both hardware and data-handling costs. With the smaller arrays the need for an image slicer also disappears. The indicated spectral resolving power, R = 1000, is the minimum acceptable for extragalactic work.

ii. SPIRE

a. The three photometry bands specified in the proposal, 250, 350, and 550 μm are retained at their cited sensitivities, but with the SPIRE team's proposed fall-back array --- a fully-efficient array covering a 4' x 4' field of view.

b. The spectrometer covers the entire proposed wavelength range, but at a reduced spectral resolving power of R = 100.

c. Separate photometer and spectrometer instruments are not a scientific requirement.

Rationale: A fully efficient coupling to the sky provides for undiminished sensitivity for point sources, though making the construction of maps more difficult with a telescope having limited pointing capabilities. At the cited spectral resolving power the strongest fine-structure lines in highly red shifted galaxies will be detectable, permitting identification and red-shift measurement of these interesting sources. Higher spectral resolving power will be available through HIFI and, in some wavelength ranges, with SOFIA. With the lowered resolving power, it might be possible to construct a single instrument that satisfactorily combines photometric and spectrometric capabilities, though this would have to be studied. At the cited minimum resolving power, many of the crucially important water vapour lines not observable from SOFIA can also be clearly identified.

iii. HIFI

a. The proposed frequency bands 1 to 6, covering the 480 to 2700 GHz frequency range are included at the state-of-the-art performance (SOAP) sensitivities cited in the proposal.

b. A minimum 4 GHz bandwidth is required.

c. A minimum 1km/sec velocity resolution is essential.

Rationale: Few observing programs require velocity resolution higher than 1 km/sec. The 4 GHz bandwidth permits low-resolution spectrometry for extragalactic work, and complements the minimum capabilities of SPIRE. The channel 6 bands, though not part of the original mission requirements, will uniquely enable FIRST to resolve velocities and establish temperatures of different water vapour clouds in small fields of view along a line of sight. This will provide crucial information on the radiative cooling of molecular cloud components at temperatures below a few hundred degrees Kelvin, where H_2O cooling is expected to be dominant. No other mission currently foreseen will provide this capability.

The FSEC recognises the many important and laudable efforts the PACS, SPIRE and HIFI proposals have described to develop instrumentation with substantially higher capabilities than this minimum-acceptable-capability payload. The FSEC most emphatically welcomes any increases in instrumental performance well beyond the minimum requirements, as long as the necessary resources are available; but the committee also is convinced that primary attention must be focussed on making certain that a reliable payload with at least the cited minimum acceptable capabilities is successfully launched.

5. Managerial Issues

i. The data rate of the instruments proposed for the FIRST mission significantly exceeds that of the instruments flown on ISO. The number of moving parts in each instrument is not high, nor is the number of observing modes excessive. However, the large number of detector elements in the proposed arrays, and to a lesser extent the high bandwidths of the heterodyne receivers, will produce a continuous flow of data at far higher rates than previously encountered in any infrared or submillimetre astronomical space mission. These data rates pose severe electronic demands, and will require sophisticated onboard data processing and compression. Success in building these instruments and in servicing their data in flight will require deliberate efforts along lines not previously emphasised by the infrared / submillimetre community, as well as strong organisational oversight and clean lines of authority.

ii. The managerial aspects of handling such complexities should be discussed by ESA and the instrument teams, possibly with input from organisations that have had experience in successfully managing similarly complex projects involving comparable data rates and onboard processing. Proper management and well-suited management structures will be an essential component to assure the FIRST mission's success.

iii. The resources, particularly manpower, required for the development and operation of the three instruments are comparable to those required to build and operate a medium-sized spacecraft. The proposals convey the impression of an organisation similar to that of other projects staffed with scientists with well-defined tasks. However, it lacks definition of a formal framework and formal management rules for reaching binding decisions both within the science team and between the team and the FIRST project. The use of working groups across an unusually large number of institutes will make decisions by consensus difficult, and lengthier to reach, with possible repercussions on formal schedules. To overcome such potential problems, a set of management procedures will need to be closely defined and agreed to in the next phase.

iv. A "bottom up" schedule for each work package is not yet evident to support feasibility assessments and critical path evaluation. Such a schedule will need to be established as soon as possible at the start of the next phase. It will need to incorporate modifications that may result from funding discussions and SPC decisions.

v. An essential ingredient of proper management is certainty about available resources. The FSEC urges that firm commitments to provide the resources needed for the timely delivery of instrument hardware and software, and the instruments' respective control centres, be obtained during finalisation of instrument design. Interfaces between instruments and spacecraft will have to be agreed to at this time, and adhered to, since significant alterations could prove extremely costly.

Conclusions

The FSEC considers the FIRST mission to be of the highest astronomical promise. Issues of complexity, funding, and management need to be resolved, but the science teams and the FIRST project are both enthusiastic and highly competent. There is no doubt in our minds that this is a mission that is now technically feasible and ready to be undertaken. It is a mission that may prove as challenging as any that ESA has undertaken, but also rewarding beyond all expectations.

Submitted: April 28, 1998

Martin Harwit (Chairman)
Sergio Volonte (Secretary)
Peter D. Barthel
Thierry J.-L. Courvoisier
Ernst Kreysa
James Lequeux
Karl Menten

ASTRO(98)8
Paris, 4 May 1998

EUROPEAN SPACE AGENCY

ASTRONOMY WORKING GROUP

Recommendation on the FIRST Science Instrument Proposals

The Astronomy Working Group (AWG), at its 96th meeting held at ESA Headquarters, Paris, on 4-5 May 1998, was presented with the findings and conclusions of the ***FIRST*** *Science Evaluation Committee* and commends the committee for its excellent work. It generally agrees with the conclusions and the concerns raised, especially in the areas of mission focus (surveys vs. detailed observations), funding profile, payload critical areas and management structure. On the particularly important issue of telemetry the AWG urges the project and the PIs to work together to find a common and realistic strategy. As far as the minimum-acceptable-payload is concerned, the AWG strongly feels that this should be an absolute minimum, 'safeguard'-scenario and that the baseline plans of the instrument proposals should be fully realized. In particular, in view of the importance of the deep surveys, the AWG feels it is essential to maintain the mapping multiplex advantage of PACS/SPIRE.

D/SCI/RMB/SV/iv/2944

Paris, 8 June 1998

Dr. Matt Griffin
Physics Department
Queen Mary and Westfield College
Mile End Road
London E1 4NS
England

Dear Dr. Griffin,

It gives me great pleasure to inform you that, at its meeting on 28-29 May 1998, the Science Programme Committee (SPC) approved the inclusion of your instrument, the ***Spectral and Photometric Imaging REceiver for FIRST (SPIRE)*** as part of the payload for the FIRST Mission, subject to confirmation of funding.

A copy of the Astronomy Working Group (AWG) recommendation endorsed by the Space Science Advisory Committee (SSAC), which led to the approval by the SPC, is included for your information. Also included for your consideration is the FIRST Science Evaluation Committee report which contains specific recommendations regarding your proposal.

I would leave it to you to inform your Co-Investigators about the positive results of the selection.

I will ask the Project Scientist, Dr. G. Pilbratt, to contact you with regard to the initial activities of the FIRST programme.

I offer you my best wishes for the successful completion of this challenging project.

Yours sincerely,

R.M. BONNET
Director
Scientific Programme

Encl.

Copy: Dr. L. Vigroux, CEA Saclay
Dr. S. Volonte, ESA HQ
Dr. G. Pilbratt - ESTEC
Dr. F. Felici - ESTEC