THE FIRST MISSION: BASELINE, SCIENCE OBJECTIVES AND OPERATIONS

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ABSTRACT

The FIRST ESA cornerstone mission will perform photometry and spectroscopy in the $85 - 600$ μm range. The current baseline FIRST mission is outlined, and the spacecraft and the model payload introduced. FIRST will have 3 m radiatively cooled Cassegrain telescope and a payload complement of three instruments housed inside a superfluid helium cryostat. It will be launched by a dedicated Ariane 5 into an orbit around L2 where it will have a predicted cryostat lifetime of 4.5 years.

The key scientific topics to be addressed by FIRST will cover subjects as diverse as galaxy formation in the early universe, interstellar medium physics – including large- and small-scale star formation – in our own and external galaxies, and cometary and planetary (satellite) atmospheres. There has been a clear shift in emphasis towards extragalactic astronomy with respect to earlier assessments.

FIRST has been conceived as a multi-user observatory, and it will be open to the general astronomical community on the basis of calls for observing time proposals. The novel 'decentralised' science operations scheme being considered in order to increase efficiency and reduce overall cost is described.

Key words: space astronomy; IR; submillimetre.

1. INTRODUCTION

The 'Far Infra-Red and Submillimetre Telescope' (FIRST) is a multi-user 'observatory type' mission that targets the far infrared and submillimetre part of the electromagnetic spectrum, covering approximately the wavelength range $85 - 600$ μm.

FIRST is one the four 'cornerstone' missions in the European Space Agency (ESA) 'Horizon 2000' long term science plan [1]. It was selected for implementation as Cornerstone 4 (CS4) by the ESA Science Programme Committee (SPC) in its November 1993 meeting. Descriptions of the scientific objectives, reference model payload, spacecraft and system design, and science operations and overall management for the mission as selected were published in [2,3,4,5].

The mission selected for implementation as CS4, i.e. the concept in circa 1993, was based on the outcome of an industrial study performed in 1992 – 93. The spacecraft consisted of a payload module having a telescope assembly with a 3 m diameter Cassegrain telescope – entirely made of carbon fibre reinforced plastic (CFRP) – radiatively cooled inside a sunshade, a science payload 4.5 K environment created by mechanical cryocoolers, and a service module providing the necessary infrastructure. The science payload consisted of two instruments, and after injection into a geostationary transfer orbit (GTO) by a shared Ariane 5 launcher, FIRST would have operated from a highly eccentric (ISO-like) Earth orbit with a period of 24 hours.

The cost of the mission was driven by technical risk and by the overall complexity of spacecraft, payload, and operations. The primary technical challenges were identified as the telescope, the mechanical coolers, and in particular the whole cryogenic subsystem consisting of many such coolers working together, and the science instruments. Not only the design, but in particular the actual fabrication, testing, and verification of the novel cryogenic subsystem and the very stringent requirements on the science payload resulting from it, were noted.

When selecting FIRST, the SPC also decided that definition work on all aspects of the mission should continue with the objective of firmly establishing a mission that can be implemented with low technical risk and within the available financial allocation for a cornerstone mission. The SPC would then 'reconfirm' its decision at a later time.

The present baseline FIRST mission – the result of a critical reassessment of virtually all aspects – is described in the present and the following papers in this session of the meeting, setting the scene for the discussion about the science objectives.

Note: The present feasibility study of a 'merger' between the FIRST and Planck (M3, formerly COBRAS/SAMBA) missions is being carried out within the boundary condition that the science goals of both missions should be retained by any potential 'merged' FIRST/Planck mission. Thus, in what follows, no further reference (but cf. [6]) is made to this activity.

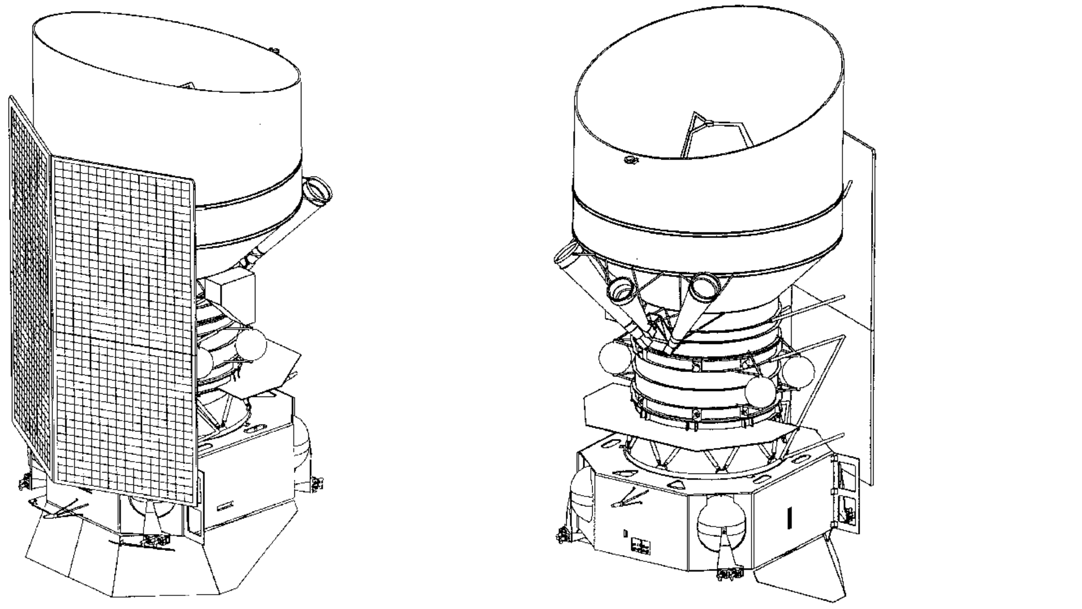

Figure 1. Two views of the FIRST satellite (based on the ISO cryostat) in flight configuration. Note: The illustrated satellite configuration was designed for a 48 hour highly eccentric orbit around the Earth, not the subsequently chosen orbit around L2. The satellite measures 6.6 m in height, 3.7 m in width, and has a launch mass of 3820 kg. The 3 m diameter main reflector with the tripod supporting the subreflector is inside the sunshade. The payload is housed inside the cryostat, which contains 2560 l of superfluid helium at 1.7 K giving a predicted cryostat lifetime of 4.5 years in the L2 orbit. The fixed solar panels and three startrackers in a skewed configuration are visible on the outside of the cryostat.

2. THE PRESENT BASELINE FIRST MISSION

Following the decision by the SPC in 1993, upfront technological development has taken place on the cryocoolers and telescope; the science objectives have been reassessed, the model payload updated, and the science operations optimised.

2.1. Spacecraft concept

Two different spacecraft concepts have been studied. On the one hand, the design of the cryocooler spacecraft has been refined, taking the current increased technical maturity and performance of the coolers into account. On the other hand, a 'wet' cryostat concept based on the (now well-proved) ISO superfluid helium cryostat technology has been studied. For both concepts, it has been studied whether the (re-)use of existing service module subsystems would be advantageous.

The two concepts were studied in parallel on a competetive basis, employing the same model payload, and sharing the same science objectives and ground segment philosophy. In addition, the scientific, technical, and financial implications of employing three different orbits were addressed. The three orbits considered were the inital baseline 24-hour orbit, an extended highly eccentric 48-hour orbit, and an orbit around the Lagrangian point L2 in the Sun-Earth system, located approximately 1.5 million km away from the Earth in the anti-Sun direction.

Following an extensive scientific and technical evaluation and trade off of the study results, including risk, choice of orbit, and cost, made by the project, and following the recommendation by the FIRST Science Advisory Group (SAG) in favour of the cryostat spacecraft concept and the L2 orbit, it has been decided to implement the FIRST mission with a cryostat spacecraft and to conduct in-orbit operations from an orbit around the Lagrangian point L2 in the Sun-Earth system. The present spacecraft (cf. Figure 1) is described in detail in the following presentation by Steinz [6].

2.2. Telescope development

The FIRST telescope will have a total wavefront error (WFE) of less than 10 μm (with a goal of 6 μm) – corresponding to 'diffraction-limited' operation at 150 μm (goal 85 μm) – in orbit, a very low emissivity. Inside a fixed sunshade, it will radiatively cool to an operational temperature of approximately 80 K (TBC) in the L2 orbit.

Until recently the baseline was an all-CFRP telescope, the manufacture of which is a very complex process, demanding precise control of a large number of parameters and skilled workmanship. In the course of reviewing the development programme it was concluded that the CFRP technology would not be the most cost-effective, and an evaluation of alternative concepts was performed. The currently adopted baseline is an actively temperature controlled aluminium 3 m (or 3.5 m TBC) diameter telescope.

2.3. Launch and operations

FIRST will be launched directly into an L2 orbit transfer trajectory by using a dedicated Ariane 5.

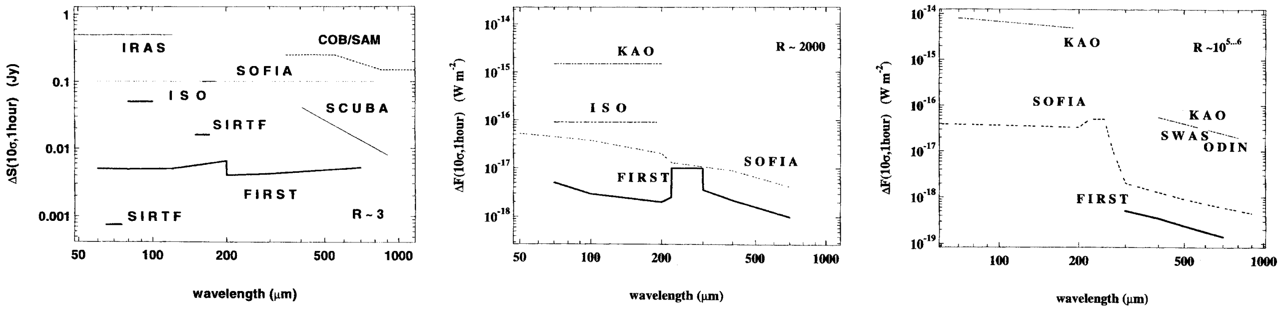

Figure 2. Calculated FIRST sensitivities for (from left to right) photometry ($R \sim 3$), medium ($R \sim 2000$), and very high ($R \sim 10^{5-6}$) resolution spectroscopy. Plotted are also actual or calculated sensitivities for a number of complementary facilities. Note that the curves are 10σ noise levels for 1 hour observations. From R. Genzel (private communication).

There exists a near midday launch window of about 45 min duration that is open throughout the year – except for a two week period around each of the two equinoxes and a couple of days per month (to avoid the Moon) – that allows a virtually eclipse-free orbit for the entire mission duration to be selected.

In the orbit around L2 the superfluid liquid helium cryostat, providing focal plane science instrument cooling, has a calculated lifetime of 4.5 years. Scientific operations are planned to be conducted 22 (TBC) hours per day, while 2 hours per day are allocated for data downlink by repointing the spacecraft to the Earth and using the 32 m antenna of the ESA groundstation in Perth, Australia. The science operations will be conducted using a 'decentralised' ground segment concept that is further described in section 6.

2.4. Management and schedule

As is customary in the ESA science programme, ESA is responsible for the overall FIRST project; it will procure the satellite with the exception of its scientific instruments; it is also responsible for testing and validation, for mission design, launch, and all realtime interaction with the satellite during orbital operations. The scientific instruments will be provided by Principal Investigators (PIs), representing instrument-building consortia, to be selected in response to an Announcement of Opportunity (AO) to be issued in September 1997. Further details of the present schedule, which leads up to a launch in late year 2005, are given by Steinz [6].

3. SCIENCE OBJECTIVES

The FIRST wavelength region of the spectrum, $85 - 600$ μm, bridges the gap between what can be observed from current and future ground-based and airborne (e.g. SOFIA) facilities, and that of other space missions (e.g. ISO, SWAS, Odin, WIRE, SIRTF, and IRIS). Black-bodies with temperatures between 5 K and 50 K peak in the FIRST wavelength range, and gases with temperatures between 10 K and a few hundred K emit their brightest molecular and atomic emission lines here. Broadband thermal radiation from small dust grains is the most common continuum emission process in this band. These conditions are widespread everywhere from within our own solar system to the most distant reaches of the Universe!

The science objectives of FIRST have been constantly discussed and reviewed since first formulated, most notably in a number of major symposia, including in Segovia, 1986 [7], in Liège, 1990 [8], and now here in Grenoble, 1997 [9]; and additionally, also in a special 'hearing' with invited experts organised by the FIRST SAG in September 1996. I will describe the outcome; it serves as starting point for our discussions here in this meeting.

3.1. Predicted sensitivities

Observing time from a space platform is particularly precious. It is therefore necessary to ensure that the available FIRST time is allocated to areas where its capabilities are unique and its scientific impact will be the most profound. As a starting point in the 'hearing', the predicted sensitivity of FIRST (cf. Figure 2) was compared to foreseen complementary ground-, air-, and space-based observing facilities. From the predicted sensitivities it can be concluded that:

- Progressing to shorter wavelengths there is a point somewhere in the $100 - 150$ μm range where a smaller cryogenic telescope will be more sensitive.
- Progressing to longer wavelengths there is a point somewhere in the $800 - 900$ μm range where larger ground-based instruments will be more sensitive.
- The sensitivity advantage offered by the relatively cold and very low emissivity FIRST telescope in the space environment decreases for (very) high resolution spectroscopy.

The conclusion is that FIRST has unique capabilities in performing photometry and (medium) resolution spectroscopy in approximately the $100 - 600$ μm

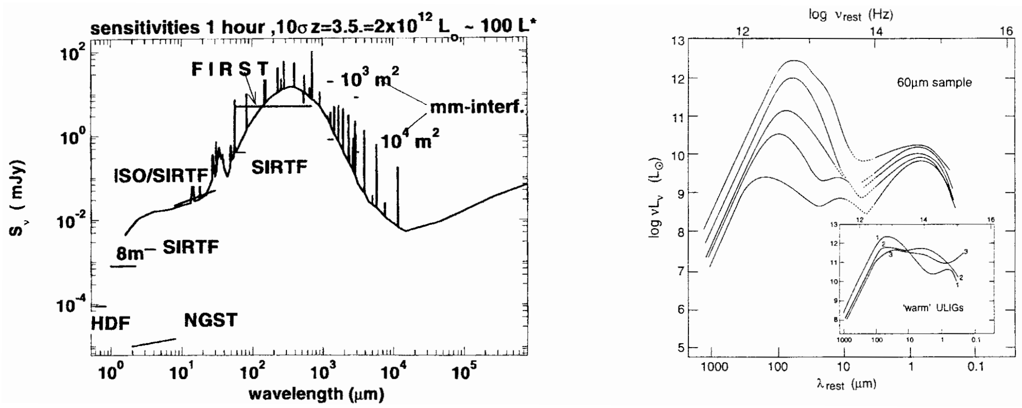

Figure 3. Left: Calculated 10σ 1 hour sensitivities (per detector) for detecting a 100L* starburst galaxy at z=3.5. From R. Genzel (private communication). Right: Spectral energy densities for a number of the IRAS 60 μm sample of galaxies. Ultraluminous IR galaxies emit 90 – 99 % of their bolometric luminosity in the IR. The optical/near-IR luminosity is a very poor indicator of bolometric luminosity. From Sanders & Mirabel, Ann. Rev. Astron. Astrophys. 1996, 34:749.

range. In addition, from space FIRST has access to lines – for very high resolution spectroscopy – that cannot be reached at all from e.g. aircraft altitude.

3.2. Conclusions by the 'hearing'

The outcome of the assessment made by the 'hearing' was the key scientific topics to be addressed by FIRST include (but are not necessarily limited to):

- Deep broadband photometric surveys in the 150 – 500 μm FIRST 'prime' wavelength band and related research. The main goals will be a detailed investigation of the formation and evolution of galaxy bulges and elliptical galaxies in the first third of the present age of the Universe.

  While optical/near-IR observations can detect the stellar light emerging from galaxies undergoing star-formation bursts out to very high redshifts (cf. Figure 3, left), they cannot unambiguously determine their total bolometric luminosity (i.e star-formation rate) since the fraction, depending on dust content, of reprocessed (into the IR) star-light is unknown (cf. Figure 3, right).

  Gravitationally lensed ultra-luminous IR galaxies such as e.g. FSC 10214+4724 [10,11] already prove the existence of dusty high redshift starburst galaxies, and the spatially integrated emission of a (yet to be detected) population of such galaxies may already have been detected [12]. Furthermore, the potential discovery of new classes of objects is an intriguing possibility.

- Follow-up spectroscopy of especially interesting programme objects discovered in the survey. The far infrared/submillimetre band contains the brightest cooling lines of interstellar gas, which give very important information on the physical processes and energy production mechanisms (e.g. AGN vs. star formation) in galaxies.

- Detailed studies of the physics and chemistry of the interstellar medium in galaxies, both locally in our own Galaxy, as well as in external galaxies, including objects at high redshift. This includes implicitly the important question of how stars form out of molecular clouds in various environments.

- Observational astrochemistry (of gas and dust) as a quantitative tool for understanding the stellar/interstellar lifecycle and investigating the physical and chemical processes involved in star formation and early stellar evolution in our own Galaxy. Virtually all major components of this lifecycle (e.g. cloud collapse, freeze out, disk formation, dust coagulation, and planetesimal formation, cf. Figure 4) can be probed with FIRST.

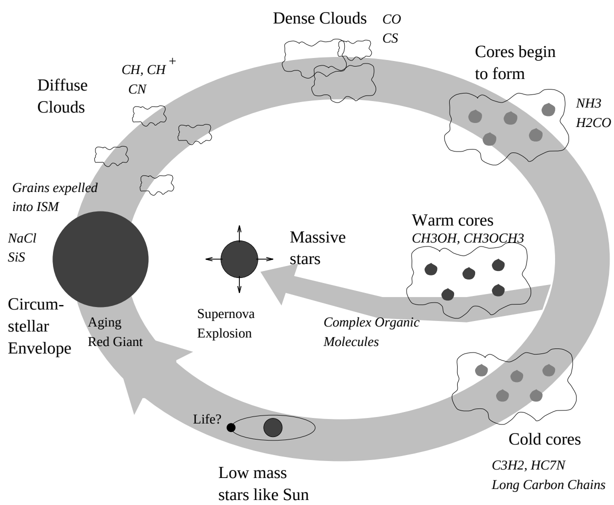

Figure 4. Schematic illustration of the processing of material in the interstellar medium. From van Dishoeck & Helmich, 1997, ESA SP–388, 3.

An important advantage of a space mission such as FIRST over ground-based or even airborne observatories is its complete spectral coverage over a wide wavelength range, unhindered by the atmosphere [13]. A thorough knowledge of these processes in our own Galaxy is a prerequisite for understanding galaxy- and star-formation at high redshifts.

- Detailed high resolution spectroscopy of a number of comets, high resolution molecular spectroscopy of the cool outer planets, and searches for Kuiper-belt objects.

From past experience, it is also clear that the 'discovery potential' is significant when a new capability is being exploited for the first time. Observations have never been performed in space in the 'prime band' of FIRST. As a space facility is essential in this wavelength range, FIRST will be breaking new ground!

4. MODEL PAYLOAD

The FIRST science payload will be selected through an AO process. In order to assess the scientific capabilites of FIRST a 'model payload' has been defined by the FIRST Payload Working Group (PWG). The model payload has also been used by the spacecraft study contractors for assessing payload accomodation, to identify the areas where the payload is critically driving the spacecraft design, and to define interfaces and requirements for payload and spacecraft.

The model payload as presently defined has evolved to consist of three instruments, it comprises:

- A heterodyne instrument, referred to as the 'HET'. It performs high to very high resolution spectroscopy in approximately the $500-1200$ GHz ($250-600$ μm) range. It is a multichannel SIS mixer receiver with solid state local oscillators and ('hybrid') digital autocorrelator and/or acousto-optical spectrometers. The SIS mixers need to be operated at a temperature of 4.5 K or lower, preferably at around 2 K.
- An incoherent photoconductor instrument, referred to as the 'PHOC'. It performs imaging line spectroscopy and photometry in the $85-200$ μm range using a 16×25 stressed 'bulk' Ge:Ga photoconductive detector array and an image slicer in combination with a long-slit grating spectrometer. The photoconductors need to be cooled to around 1.7 K.
- An incoherent bolometer instrument, referred to as the 'BOL'. It performs imaging photometry in the $200-600$ μm range, simultaneously covering the same field in three bands, and in addition, spectroscopy in the $200-350$ μm range, using bolometer detector arrays. The bolometers have an operating temperature of around 0.25 K.

The model payload described has been optimised with respect to the key science topics identified in the 'hearing'; the changes to the PHOC and the BOL have been considerable as a result of this process. A parallel objective has been to minimise technical complexity and risk, cost, and operational effort, while at the same time complying with the spacecraft constraints. The model payload instruments are described in detail in the talks by Whyborn [14], Poglitsch [15], and Griffin [16].

5. OBSERVATION PROGRAMMES

The FIRST observation time will be shared between guaranteed and open time. The guaranteed time will be implemented in the form of a 'core programme' defined by the guaranteed time holders. The open time will be allocated to the general community on the basis of calls for observing proposals.

Given the science objectives of the FIRST mission it is anticipated that key projects in the form of large spatial and spectral surveys will constitute very important elements of the observing programme, requiring a substantial fraction of the available time of the overall mission. It is likely that early in the mission a significant time will be spent on several key programmes including spatial photometric surveys and with additional time devoted to spectral surveys of selected key sources.

The formation of large observer collaborations collectively addressing key topics will be actively encouraged. It is foreseen that there will be a separate initial call for observing proposals for key programmes and surveys only at an early stage. Only when these programmes have been established will the first call for 'normal' observing proposals be issued.

All proposals will be evaluated and graded by the FIRST Observing Time Allocation Committee (FOTAC) on the basis of scientific merit and technical feasibility. All scientific data will be archived and made available to the general astronomical community after a proprietary period of time has elapsed.

6. SCIENCE OPERATIONS

The scientific operations of FIRST will be conducted in a novel 'decentralised' manner. The proposed ground segment concept comprises five elements:

- a FIRST Science Centre (FSC), provided by ESA,
- three dedicated Instrument Control Centres (ICCs), one for each instrument, provided by their PIs,
- a Mission Operations Centre (MOC), provided by ESA.

The ground segment elements will be united by dedicated computer links into a coherent science ground segment. These computer links are part of the FIRST Integrated Network and Data Archive System (FINDAS) for which the FSC is responsible. The FSC acts as the single-point interface to the science community and outside world in general.

Each ICC will be responsible for the operation of its instrument, and also for the provision of calibration and data reduction tools for all data generated.

The execution of all in-orbit operations will be the responsibility of the MOC. The responsibility for the design, implementation, and operation of the MOC rests with ESOC.

The FIRST Ground Segment Advisory Group (FGSAG) will consist of representatives of all ground segments elements. It monitors the progress of the development of the ground segment elements, their operation, as well as providing analysis on system level in view of the overall mission and science ground segment objectives, and provides advice. The management of the whole science ground segment is shown in Figure 5.

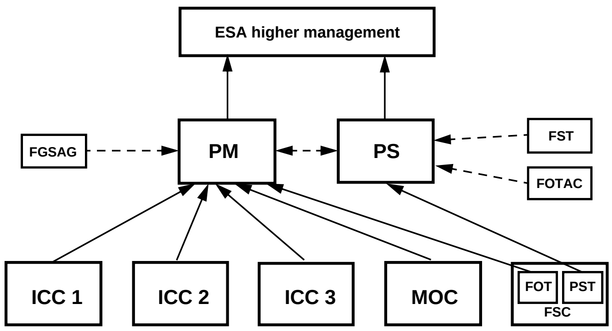

Figure 5. A box diagram of the FIRST ground segment during the development phase. For the ICCs, which are PI responsibility, there are formal links through agreements between the PIs and ESA. The FST is the FIRST Science Team, PM the Project Manager, PS the Project Scientist, PST the PS Team, and FOT the FSC Operations Team.

All scientific data will be archived and made available through FINDAS, together with software tools to produce 'standard' data products and to further process the data interactively. The 'end product' of the mission will be derived in the post-operational phase and will consist of:

- the 'raw' data products
- the 'final' software tools
- data reduced with the 'final' software tools to 'final standard' data products
- various documentation and manuals

The resulting 'historical' archive will be maintained 'indefinitely' by ESA, and will provide access to FIRST data for the benefit for the whole science community.

7. STATUS AND FUTURE

The FIRST World Wide Web homepage can easily be found by following links starting from the ESA Astrophysics Division homepage at URL `http://astro.estec.esa.nl/`.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the work and dedication of a large number of individuals in- and outside ESA, and by the FIRST contractors. The FIRST SAG is chaired by R. Genzel and includes P. Encrenaz, R. Hills, T. de Jong, E. Kollberg, J. Martin-Pintado, and G. Tofani; the FIRST PWG is chaired by P. Encrenaz and includes M. Griffin, J.-M. Lamarre, D. Lemke, A. Poglitsch, H. van de Stadt, and N. Whyborn. In addition, M. Rowan-Robinson and E. van Dishoeck have made important contributions.

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