SPICA and Its Instrumentation

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Abstract— SPICA (Space Infrared Telescope for Cosmology and Astrophysics) is an astronomical mission optimized for mid- and far-infrared astronomy with a cryogenically cooled 3.5 m telescope. Its high spatial resolution and unprecedented sensitivity in the mid- and far-infrared will enable us to address a number of key problems in present-day astronomy, ranging from the star-formation history of the universe to the formation of planets. To reduce the mass of the whole mission, SPICA will be launched at ambient temperature and cooled down on orbit by mechanical coolers on board with an efficient radiative cooling system, a combination of which allows us to have a 3.5-m class cooled (5 K) telescope in space with moderate total weight (3t). SPICA is proposed as a Japanese-led mission together with extensive international collaboration. The assessment study on the European contribution to the SPICA project has started under the framework of the ESA Cosmic Vision 2015-2025. US and Korean participations are also being discussed extensively. The target launch year of SPICA is 2017.

I. Introduction

The advent of infrared astronomical satellites with cryogenically cooled telescopes clearly demonstrated the effectiveness of mid- and far-infrared observations from space. Previous infrared astronomical missions include IRAS ([1]), IRTS ([2]), ISO ([3]), Spitzer Space Telescope ([4]), and AKARI ([5]-[6]). The telescopes onboard these missions were cooled with liquid He, since thermal emission from a telescope is a dominant source of noise in the mid- to far-infrared region. This cooling scheme with liquid He required big cryostats and thereby reduced the telescope aperture size of the previous missions to smaller than 1 m. Thus their spatial resolution was relatively poor, which degraded point-source sensitivity, since the source confusion noise, set by the number of detectable sources in a spatial resolution element, becomes a dominant noise source in the far-infrared.

This situation will be dramatically improved by the Herschel Space Observatory ([7]), which is scheduled to be launched in 2009. Herschel carries a 3.5 m telescope, which is much larger than those of previous missions, and is expected to have much better spatial resolution (and confusion-noise limited sensitivity) than previous missions with telescopes smaller than 1m. However, Herschel's telescope is about 80K, which is not cold enough for mid- and far-infrared astronomy. Hence the point-source sensitivity at the wavelength shorter than 100 μm is limited by the fluctuation of thermal radiation from the telescope.

On the other hand, James Webb Space Telescope (JWST) ([8]) with a 6.5 m telescope operating from 0.6 to 28 μm. JWST will represent a tremendous leap in our ability of observations in the near-infrared. However, the temperature of the JWST telescope is around 45 K, which is again too warm for sensitive observations in the far-infrared, and JWST does not cover wavelengths longer than 28 μm.

Thus, to achieve both good sensitivity and spatial resolution in the mid- and far-infrared, a cryogenically cooled, large telescope in space is required. For this purpose, we have been studying the mission concept SPICA (Space Infrared Telescope for Cosmology and Astrophysics (Fig. 1): SPICA is optimized for the mid- and far-infrared astronomy by employing a cryogenically cooled 3.5 m telescope.

In this paper, we describe the overview of the SPICA mission.

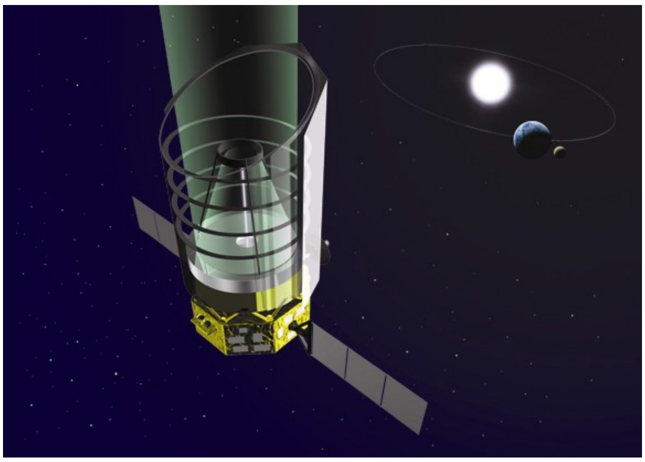

Fig. 1 Artistic view of SPICA in its orbit. SPICA is proposed to be launched into a halo orbit around the S-E L_2 point.

II. Scientific Goals

SPICA is expected play essential roles to address important problems in the current astrophysics. In the following, we make a brief summary of SPICA's scientific goals.

A. Birth and Evolution of galaxies

Birth and evolution of galaxies is one of the biggest problems in astrophysics. SPICA can address this problem in many ways.

SPICA is expected to play a crucial role in this area by resolving Cosmic Infrared Background near its energy peak; SPICA can resolve more than 90 % of the Cosmic Infrared Background into individual sources at 70 μm ([9]-[10], See also the discussion in the next section.)

The mid- to far-infrared wavelength range is very rich with many important fine-structure lines, which are quite useful for the estimate of star-formation activities and AGN activities. Since these lines are less sensitive to extinction, they are expected to bring us essential information on the activities especially in obscured galactic nuclei. The unprecedented sensitivity of SPICA' spectroscopy will revolutionize the study in this area.

One more challenging goal for SPICA is to reveal the formation of the first-generation of stars, i.e. Population III (Pop III) stars. Since the Pop III stars are formed from primordial pre-stellar gas without metals, the gas cannot be cooled through metal lines but is expected to be cooed through molecular hydrogen lines. SPICA will challenge the detection of H_2 emission from large pre-galactic clouds that form metal-free stars.

B. Formation and Evolution of Stellar and Planetary Systems

SPICA is an ideal instrument to assess the formation and evolution processes of stars and planetary systems.

The study of star-formation has been regarded as a holy grail of infrared astronomy, and SPICA is also expected to play essential roles in this area. Photometric and spectroscopic studies of evolved stars are another important area for SPICA.

SPICA is also expected to address the formation processes of planetary systems. SPICA can make very sensitive observations both for gas phase and for solid state matter in the proto-planetary and debris disk systems. This capability of SPICA is essential for the understanding of planetary formation process.

One of the biggest challenges of SPICA is to make the direct detection and spectroscopy of exoplanets. The typical contrast between a central star and planets around it is estimated to be 10^{10} in the optical but to be reduced to 10^6 in the mid-infrared. Thus the mid-infrared is an optimum region to try direct detection of exoplanets. Moreover, SPICA has a smooth, well characterized Point Spread Function (PSF), since SPICA's telescope uses a monolithic mirror, and this characteristic is very important for effective coronagraphic observations ([11]).

Taking advantage of these points, SPICA will make direct observation of exoplanets including their spectroscopy, which is essential to characterize their nature.

C. Chemical Evolution of the Universe

The infrared wavelength is also unique in a sense that both gas phase and solid phase chemistry can be investigated. With its wide spectral coverage and excellent sensitivity, SPICA can observe many, important features (e.g. PAH and Silicate) over a wide range of red-shift to investigate chemical evolution of the universe.

III. REQUIREMENTS FOR SPICA

To achieve the scientific goals described in the previous section, SPICA has requirements on the following two aspects: telescope size and telescope temperature.

A. Telescope Size

The telescope size is an essential parameter for astronomical observations. SPICA has various scientific goals which require large telescopes. For example, Fig. 2 shows that a 3m-class telescope is required to resolve cosmic infrared background at its peak energy ([9]-[10]). Other scientific goals also require a 3-m class telescope.

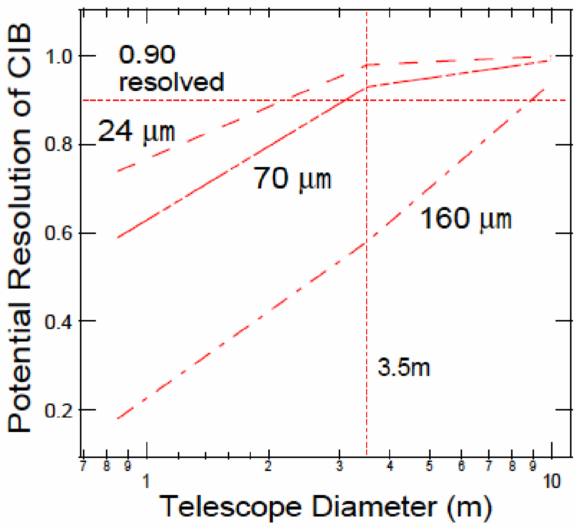

Fig. 2 Potential resolution of cosmic infrared background (CIB) as a function of telescope size and wavelength based on the model calculation by Dole et al[18]. 3.5m class telescopes are required to resolve 90% of CIB into individual sources near the peak of its energy distribution ([9]-[10]).

B. Telescope Temperature

The telescope temperature is another important factor. Fig.3 compares the radiation from the telescope (solid lines) as a function of temperature is compared with natural background sources (dotted lines: zodiacal emission, Galactic cirrus, and cosmic microwave background, [12]. The telescope temperature of around 5 K is required to achieve natural background-limited observations in the mid- and far-infrared.

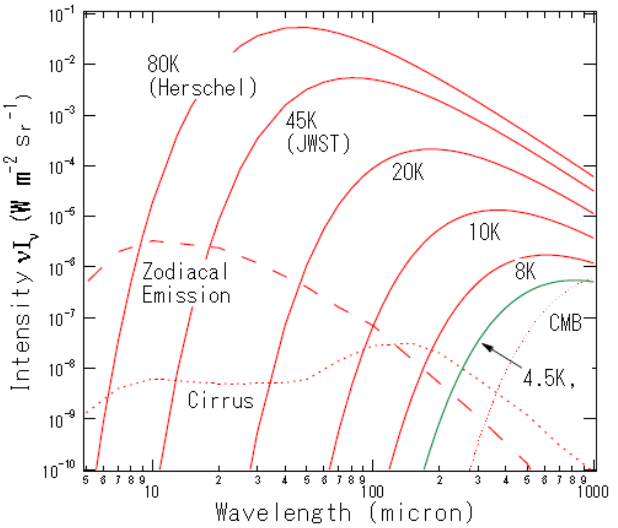

Fig. 3. Telescope background radiation (solid lines) as a function of temperature is compared with natural background sources (dotted lines: zodiacal emission, Galactic cirrus, and cosmic microwave background, [12]). Telescopes as cold as around 5 K are required to achieve natural background-limited observations in the mid- and far-infrared. 10% emissivity is assumed for the telescope emission.

IV. Mission Overview

A. Mission Specifications

Table I summarizes main specifications of the SPICA mission. The most important point is that SPICA incorporates a 3-m class telescope, which is cryogenically cooled. The combination of the low temperature and large aperture size of the telescope makes the SPICA mission the most sensitive instrument in the mid- and far-infrared as clearly illustrate in Figures 4 and 5.

Fig. 6 shows a baseline configuration of the whole SPICA satellite.

TABLE I
MISSION SPECIFICATIONS

MISSION SPECIFICATIONS	
Observation Instrument Telescope Aperture Size Telescope temperature Diffraction Limit Core Wavelength	 3.5 m 5 K (during observation) 300 K (at launch) > 5 μm 5-200 μm
Cryogenics System	 Mechanical Cryocoolers Effective Radiative Cooling
Total Mass	3 t
Launch Vehicle Orbit Year	 H-IIA S-E L_2 Halo 2017

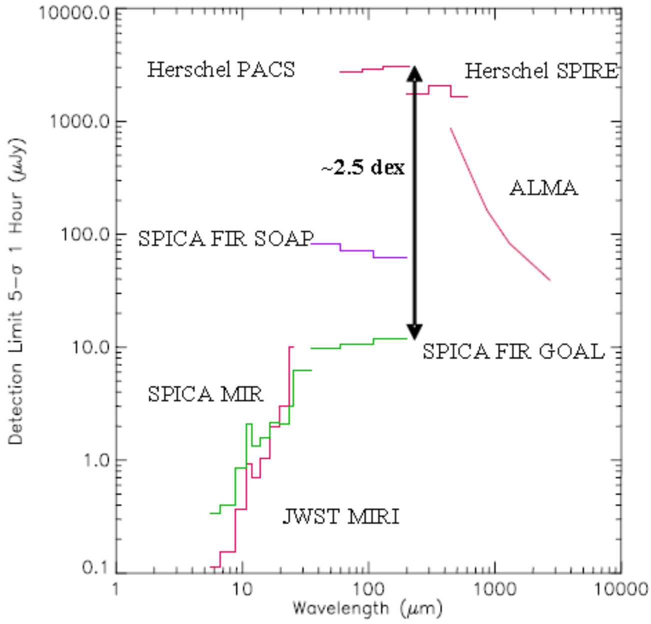

Fig. 4 Predicted photometric performance of SPICA (green and purple) compared to predecessor and complementary facilities (red) given as point source sensitivities in Jy for 5-σ in 1 hour over the bands shown indicatively as horizontal lines. Note the 2 ½ orders of magnitude increase in FIR photometric sensitivity compared to PACS that will be achieved using goal sensitivity detectors on SPICA. The figures here are raw sensitivity only, and the effects of confusion of sources are not included.

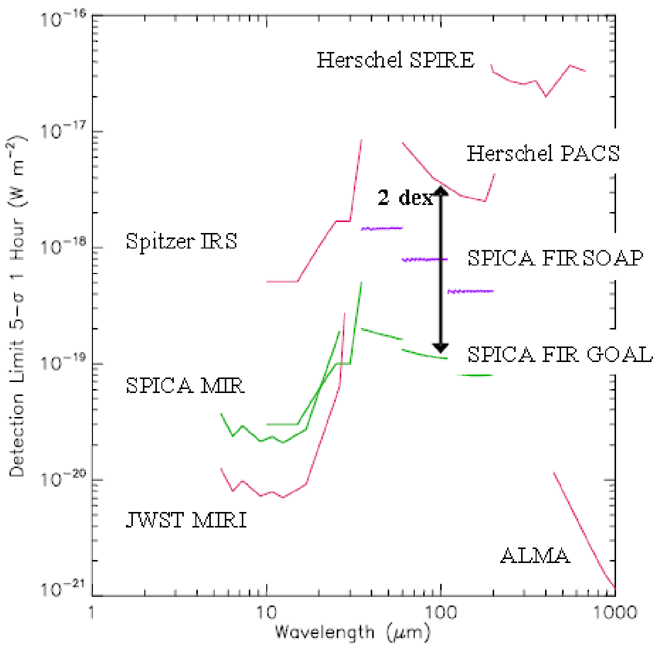

Fig. 5 Predicted spectroscopic performance of SPICA (green and purple) compared to predecessor and complementary facilities (red) given as single unresolved line sensitivity for a point source in W m^{-2} for 5-σ in 1 hour. For ALMA 100 km/s resolution is assumed as this is appropriate for extra-galactic sources. The SPICA MIR sensitivities are scaled by telescope area from the JWST and Spitzer IRS values respectively.

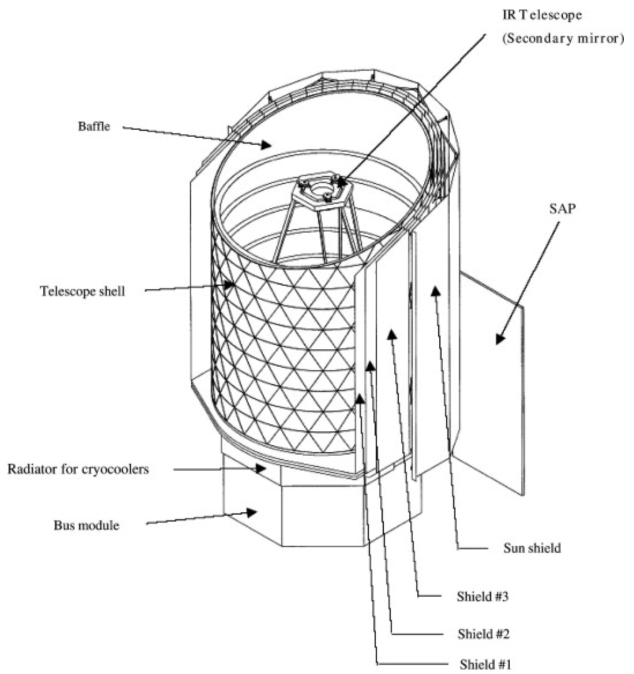

Fig. 6 Base-line configuration of SPICA.

B. *Cryogenics*

To achieve high sensitivity in the mid- and the far-infrared, we have to cool the whole telescope and the focal plane instruments. All of the infrared astronomical satellites flown so far carried liquid helium for cooling; this made the satellites big and heavy and reduced the sizes of the telescopes significantly. Moreover, their mission lives were limited by the hold time of liquid helium, and were relatively short.

To overcome these difficulties, we propose a ``warm-launch, cooled telescope" design concept, i.e., the telescope and focal plane instruments (FPIs) are ``warm" at launch since SPICA will not carry any cryogen. The telescope and the FPIs are to be cooled in orbit by a combination of effective radiative cooling and modest mechanical cryocoolers. Figure 7 shows its conceptual view. The cryogenic system is discussed in detail by [13] and [14].

The ``warm launch" concept without any cryogen reduces the total size significantly and enables the payload fairing of the H-IIA rocket to accommodate a telescope with a 3.5~m primary mirror. The ``warm-launch" concept also reduces the total mass of the mission dramatically; 3.5~m SPICA weighs around 3t.

One of the key technical components for the success of this ``warm launch" concept is mechanical cryocoolers. We have been working on strategic program for the development of cryocoolers for space applications. Some of the cryocoolers developed in this program has already been flown on an X-ray astronomical satellite SUZAKU ([15]) and on a infrared astronomical satellite AKARI ([16]). Other types of coolers dedicated for SPICA is shown in Fig.8.

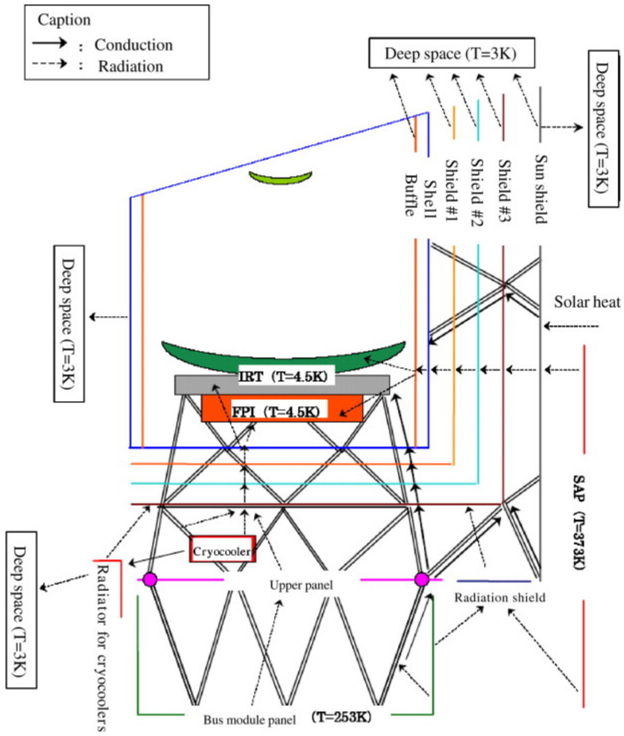

Fig. 7 Conceptual view of the SPICA cryogenic system, which consists of effective radiative cooling system and mechanical cryocoolers ([14]).

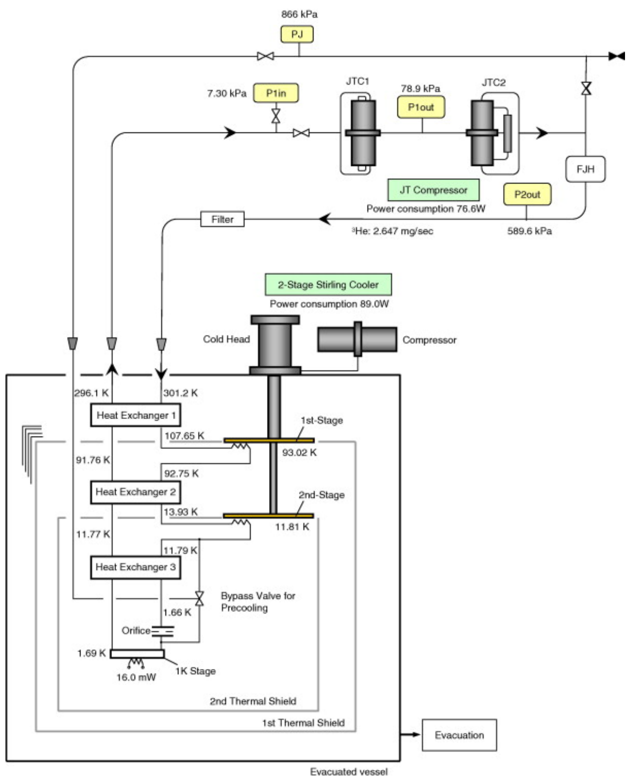

Fig. 8 Schematic view of the configuration of a 1-K class cooler for SPICA together with preliminary experimental results ([14]).

C. Telescope

Table 1 also summarizes the baseline specifications of the SPICA telescope assembly. The baseline model consists of a 3.5 m single aperture, primary mirror, which is required from scientific points view as discussed in the previous section. This size is a good choice also from technical points of view, since the H-IIA rocket fairing can accommodate this size of monolithic mirror and no deployable mechanism is required. This reduces the complexity in the operation at cryogenic temperatures in space.

Because of the high demands on the SPICA telescope system, the selection of the mirror material is of prime importance. At the current study stage, we have two candidate materials, sintered silicon carbide (SiC) and carbon-fiber reinforced SiC (C/SiC composite), for the SPICA telescope mirrors.

Sintered SiC mirrors are employed by Herschel ([7]), and thus benefit greatly from the heritage of their development programs. However, the SPICA requirement on the wavefront error (0.35 µm rms) is by more than one order of magnitude more stringent than that for Herschel (6 µm rms), and dedicated technical program is required to meet the requirements for SPICA.

The C/SiC composite ([17]) has relatively high fracture toughness since carbon fibers are incorporated into SiC. It is easily machined in the carbon-fiber carbon-matrix (C/C) composite stage. These characteristics enable a very light-weighted design of the 3.5 m blank.

Under the current scheme of the international collaboration (see the following sections), ESA is expected to be in charge of the development and manufacturing of the SPICA telescope under the collaboration with JAXA.

V. Focal Plane Instruments

A. Overview of SPICA Focal-Plane Instruments

In order to meet the science requirements discussed in the previous sections, we need at least two types of focal-plane instruments: one is for the mid-infrared and the other is for the far-infrared. Table 2, outlines the specifications of the SPICA focal-plane instruments. On the basis of the scientific requirements described in the previous section, we propose set of focal plane instruments which cover the observation parameter range shown in Fig.8 (see [18] for details).

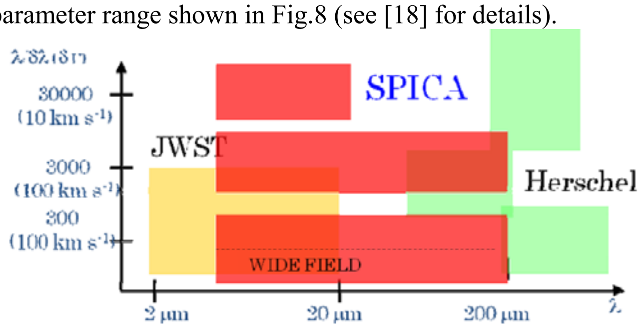

Fig. 8 Spectral coverage and spectral resolving power of focal plane instruments proposed for SPICA, together with those on Herschel and JWST. SPICA is optimized for mid- and far-infrared astronomy.

TABLE II
PROPOSED SPICA FOCAL-PLANE INSTRUMENTS

Mid-infrared Camera and Spectrometer	**Imager** Imaging and R~200 grism spectroscopy Field-of-View (FOV): 180 – 280 arcsec
	Spectrometer Long-slit R=3000 spectroscopy at 4-38 µm R=30000 at 5-18 µm
	Coronagraph (Optional) 5-27µm cove rage with contrast > 10^6 Inner working angle 2-5λ/D Outer working angle 10-30λ/D
Far-infrared Camera and Spectrometer	**SAFARI (European Consortium)** 30-210 µm imaging Fourier-transform spectrometer 2 x 2 arcmin2 FOV R = 10 -1000 (variable) Detectors: TBD, Ge:Ga photoconductors or bolometers
	A Broad-band Grating Spectrograph (US concept, Optional) 132-320 (38-430) µm coverage R=300 (700)

B. Mid-infrared (MIR) Instrument

From scientific points of views, MIR instrument is required to have three basic capabilities; a wide-field imaging, spectroscopic capability, and coronagraphic observation capability as shown in Table II.

Our basic strategy is to implement an independent module for each mode of observation. Each module has simple structure and has its own detectors.

The camera has four channels to cover the wavelength range (5 to 40µm) with wide field-of-view. Pixel scale is optimized for the shortest wavelength at each channel to ensure enough sampling for diffraction-limited observations. To achieve wide total FOV, mosaic configurations of several detector arrays are proposed. The camera has several band pass filters ([19]) for wide-band imaging and a grism for low resolution spectroscopy with high efficiency.

The MIR spectrometer is a long slit grating spectrometer possibly with an Integral Field Unit ([20]-[21]). In the shorter wavelength region, high dispersion spectrometer with an immersion grating is used to achieve spectral resolution of R~30000 is proposed ([22]).

We are investigating to implement the coronagraphic capability for the MIR instrument with contrast better than 10^6 with both imaging and low-resolution spectroscopy. The main scientific targets for this instrument is detailed study of proto-planetary and debris disks and also to challenge the direct imaging and spectroscopic observations of exoplanets around near-by stars taking the advantage of relatively small contrast between planets and their main stars. Reference [11] discusses extensive activity on the SPICA coronagraph.

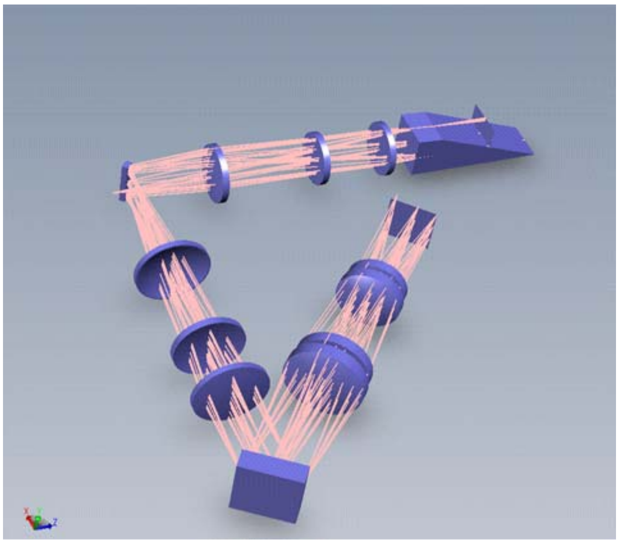

Fig. 9 Schematic view of an example of the optical configuration for the high-resolution spectrometer in the mid infrared. Immersion grating technology enables this compact design ([22]).

C. Far-Infrared (FIR) Instrument

The far-infrared instrument for SPICA has been studied extensively mostly by European Consortium (see below), and the instrument is now named SAFARI (SPICA Far-Infrared Instrument). The baseline optical configuration of SAFARI is a Mach-Zehnder imaging Fourier Transform Spectrometer. The principal advantages of this type of spectrometer for SAFARI are the high mapping speed of the Fourier-Transform Spectrometer (FTS) due to spectral multiplexing, the ability to incorporate straightforwardly a photometric imaging mode and the operational flexibility to tailor the spectral resolution to the science programs.

A possible optical layout of the instrument is shown in Fig. 10. The field of view is 2 arcmin with a spectral resolution higher than 1000.

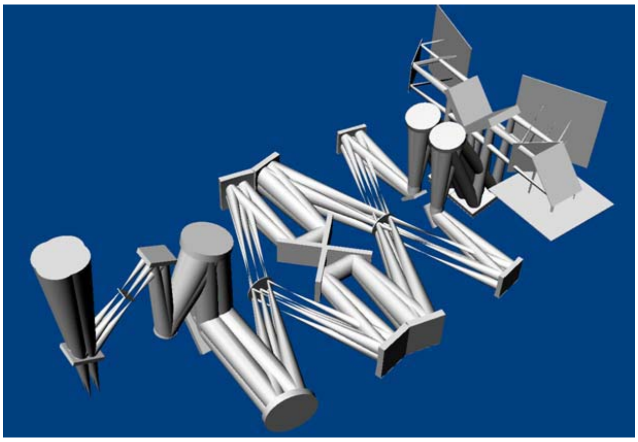

Fig. 10 Schematic view of an example of the optical configuration of the SAFARI instrument, which is designed to make both photometric and spectroscopic mapping observations in the far-infrared using an imaging Fourier-transform spectrometer ([23]).

Another FIR spectrometer which incorporates a grating-spectrometer has been proposed by the US community (BLISS/BASS, [23]).

VI. Current Status and Schedule

A. Status in Japan

In September 2007, the SPICA mission proposal was submitted to ISAS/JAXA by the SPICA working group, who had been working on this mission since 2000. Following that, SPICA went though the Mission Definition Review (MDR, which is a review mostly from scientific points of view) procedure by a dedicated committee, and the results of the review was approved by the Space Science Steering Committee of ISAS/JAXA in March 2008.

Then SPICA went through the Project Preparation Review, which is a management review, by JAXA. The review result was approved and the SPICA pre-project team was formed officially in July, 2008. This means that the SPICA team's activity is officially to be endorsed by JAXA at least during the pre-project phase.

JAXA's pre-project phase roughly corresponds to Phase-A and consists of two phases: "concept design phase" and "system definition phase". At the end of the pre-project phase, we are requested to go through the System Definition Review, which is expected to be held in early 2011 for SPICA. By SDR, we have to define not only technical details but also who is in charge of which parts of the mission. We are also requested to decrease the uncertainty of the cost estimates of the whole project.

Following SDR, we will be requested to go through the Project Go/No-go review, which is a management review by JAXA. This is an important review to decide if SPICA can go to phase-B and later stages. We are proposing to have this review in mid 2011 for SPICA, so that we can launch SPICA in 2017.

B. Status in Europe

The European SPICA Consortium (P.I.: B. Swinyard, RAL, UK) submitted a proposal to enable European participation to SPICA. It was submitted to ESA in June 2007 under the framework of the ESA Cosmic Vision 2015-2025. The proposal called for ESA to assume a partner agency role in SPICA by making the contributions: (1) SPICA Telescope Assembly, (2) European SPICA Ground Segment: (3) SPICA Far-Infrared Instrument System (SAFARI) Engineering and Management, and (4) SPICA Mission support. The proposal also assumed that the SPICA Far-Infrared Instrument System (SAFARI) was to be developed by the European Consortium. The proposal was selected by ESA in October, 2007, as one of the candidates for future missions. Following this, the assessment activity on SPICA lead by ESA started in November 2007.

A harmonised overall schedule incorporating the ESA Cosmic Vision M-class mission schedule, the Japanese SPICA schedule, and the SAFARI schedule has been drafted.

C. Other International Collaborations

Collaborations with US and Korea have been discussed extensively.

Reference [24] discusses BLISS/BASS instrument, which is a possible US contribution for sensitive spectroscopy in the far-infrared as discussed in the provisos section.

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