

The next-generation infrared space telescope SPICA

Takao Nakagawa*^a, Hideo Matsuhara^a, Yasuhiro Kawakatsu^a, and SPICA Team

^aInstitute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA),
3-1-1 Yoshinodai, Chuo-ku, Sagami-hara, Kanagawa 252-5210, Japan

ABSTRACT

We present the overview and the current status of SPICA (Space Infrared Telescope for Cosmology and Astrophysics), which is a mission optimized for mid- and far-infrared astronomy with a cryogenically cooled 3.2 m telescope. SPICA has high spatial resolution and unprecedented sensitivity in the mid- and far-infrared, which 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-m class cooled (6 K) telescope in space with moderate total weight (3.7t). SPICA is proposed as a Japanese-led mission together with extensive international collaboration. ESA's contribution to SPICA has been studied under the framework of the ESA Cosmic Vision. The consortium led by SRON is in charge of a key focal plane instrument SAFARI (SPICA Far-Infrared Instrument). Korea and Taiwan are also important partners for SPICA. US participation to SPICA is under discussion. The SPICA project is now in the "risk mitigation phase". The target launch year of SPICA is 2022.

Keywords: space mission, infrared astronomy, cryogenics, SPICA

1. INTRODUCTION

To reveal the origin and evolution of galaxies, stars, planets is one of ultimate goals of astronomy. To achieve the goal, observations in the mid- and far-infrared are essential, since it is in this range that astronomical objects emit most of their radiation as they form and evolve in regions where obscuration by dust prevents observations in the visible and near-infrared.

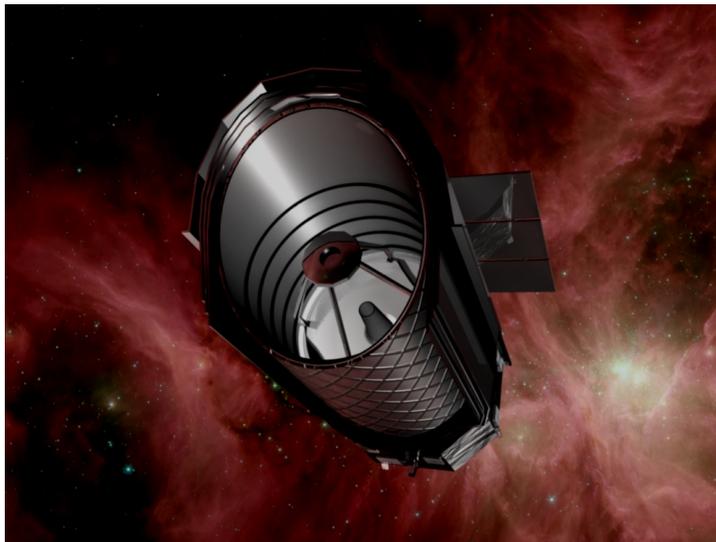


Figure 1. Artistic view of SPICA in orbit.

*Takao Nakagawa@JAXA; phone 81 50 336- 25920; fax 81 42 786-7202; JAXA

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Over the past quarter of a century successive space infrared observatories (IRAS, IRTS, ISO, Spitzer and AKARI) have revolutionized our understanding of the evolution of stars and galaxies. Mid- to far-infrared observations have led to stunning discoveries such as the Ultra Luminous Infrared Galaxies (ULIRGS), the basic processes of star formation from “class 0” pre-stellar cores through to the clearing of the gaseous proto-planetary discs and the presence of dust excesses around main sequence stars. The Herschel Space Observatory launched in 2009 extends this work in the far-infrared and sub-mm and JWST, due for launch in 2018, will provide a major boost in observing capability in the 2 – 28 μm range.

Although Herschel and JWST are powerful missions, they have some constraints for the observations in the mid- and far-infrared. Figure 2 shows the comparisons of celestial diffuse radiation (natural background radiation) and those of thermal radiation from space missions. The thermal radiation of telescopes onboard Herschel and JWST (if it is used for the far-infrared) is brighter than natural background radiation by a factor of one million in the far-infrared. Hence their sensitivity in the far-infrared could be degraded by a factor of one thousand from that of the natural-background limited observations. On the other hand, previous cryogenically cooled missions (e.g. IRAS, IRTS, ISO, Spitzer, and AKARI) had a telescope smaller than 1m. Hence, if a 3-m class space telescope is to be cooled below 6K, huge sensitivity improvement can be expected from that of Herschel.

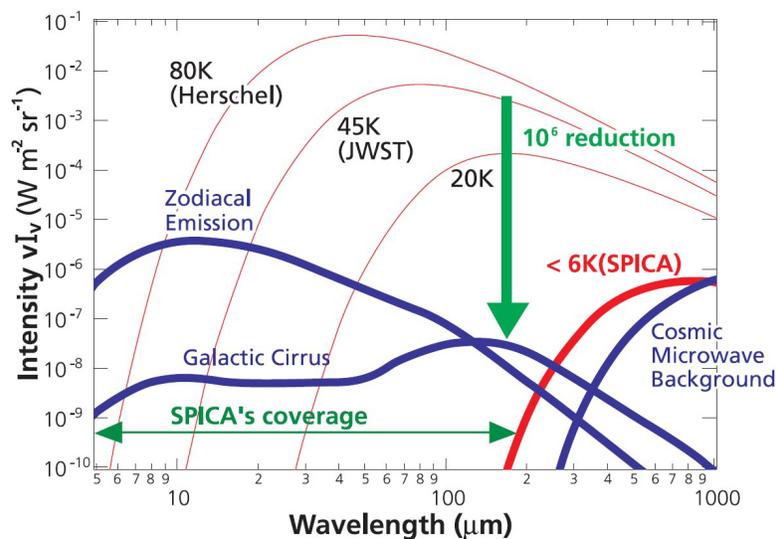


Figure 2. Comparison of natural background (zodiacal emission, Galactic cirrus, and cosmic microwave background radiation) with those of thermal radiation from telescopes as a function of temperature. SPICA, which is cooled below 6K, can achieve superior sensitivity by reducing the background radiation by a factor of a million from previous missions.

Hence SPICA (SPace Infrared telescope for Cosmology and Astrophysics, Fig.1) is proposed in this context and is optimized for mid- and far-infrared astronomy with a cryogenically cooled, large telescope^{1,2}. SPICA is an observatory that will provide imaging and spectroscopic capabilities in the 5 to 210 μm wavelength range with a 3.2 m telescope cooled to a temperature less than 6 K. In combination with a new generation of highly sensitive detectors, the low telescope temperature will allow us to achieve superior sensitivity over the full 5 to 210 μm band (Fig. 3). This unique capability means that SPICA will be between one and two orders of magnitude more sensitive than Herschel in the far-infrared band. SPICA will cover the full 5 to 210 μm wavelength range, including the missing 28 μm to 55 μm octave which is out of the Herschel and JWST domains with unprecedented sensitivity and spatial resolution. Hence, SPICA will be the only observatory of its era to bridge the wavelength gap between JWST and ALMA, and carry out unique science programs. In the mid-infrared, SPICA will be able to carry out wider field-of-view imaging and spectroscopic capabilities than those of JWST. In addition, the characteristics of the SPICA monolithic telescope will provide unique and optimal conditions for mid-infrared coronagraphy in imaging and, uniquely, spectroscopic mode.

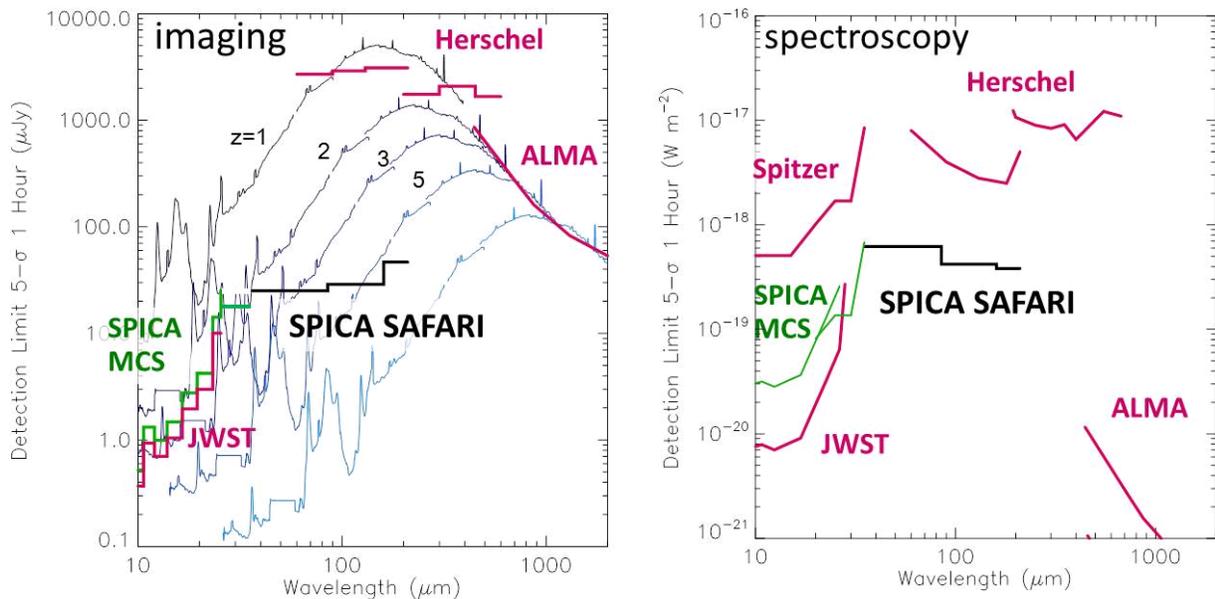


Figure 3. Left panel: Photometric performance expected for SPICA (without confusion), compared to Herschel, ALMA and JWST (black), for a point source (in μJy for 5σ in 1 hour) using the goal sensitivity detectors on SPICA ($\text{NEP} = 2 \times 10^{-19} \text{ WHz}^{-1/2}$). Note the ~ 2 orders of magnitude increase in FIR photometric sensitivity compared to Herschel-PACS. For illustrative purposes the SED of the starburst galaxy M82 as redshifted to the values indicated is shown in the background. Right panel: Spectroscopic performance expected for SPICA compared to predecessor and complementary facilities for an unresolved line for a point source in W m^{-2} for 5σ in 1 hour. For ALMA 100 km s^{-1} resolution is assumed.

2. MISSION OVERVIEW

2.1 Mission Configuration

Table 1 summarizes main specifications of SPICA and Figure 4 shows the overall configuration of SPICA. The SPICA spacecraft consists of the Cryo Payload Module (PLM) and the Bus Module (BM). The PLM is composed of the Cryogenic Assembly and the Scientific Instruments Assembly³. The Cryogenic Assembly includes mechanical coolers and radiative thermal shields that are required to cool down and maintain the temperature of the Scientific Instruments Assembly below 6K. The Scientific Instruments Assembly consists of the SPICA Telescope Assembly (STA)^{4,5} and the Focal Plane Instrument Assembly (FPIA).

The PLM is connected to BM via a low thermal conductivity truss structure, which also supports the STA.

The Bus Module, of a conventional design, hosts most of the spacecraft subsystems (power, propulsion, attitude control, data handling, thermal control and telecommunications), as required to operate the observatory.

The total mass of the spacecraft is about 3.7 ton, in line with the capabilities of the baseline launcher vehicle, JAXA's H-IIA-204.

The Sun – Earth L2 point is the optimum environment to obtain excellent sky visibility and a stable thermal environment to be able to cool the telescope. The required mission lifetime is 3 years. The absence of cryogenes onboard means that it is possible to extend the nominal lifetime beyond the nominal duration, with a goal mission lifetime of 5 years.

Table 1. Main specifications of SPICA

Item	Specifications
Scientific Objectives	To reveal (1) birth and evolution of galaxies, (2) formation processes of planetary systems
Telescope	Physical Diameter : 3.2m (Entrance Pupil Diameter 3.0m)
	Temperature: lower than 6K
	Wavefront error: better than 0.35 μ m
	Field of View: 30' diameter
Wavelength range	Core: 5-210 μ m
Mission Life	3 years (requirements), 5yeras (goal)
Orbit	Halo Orbit around S-E L2
Launch	2022 by H-IIA-204 launcher

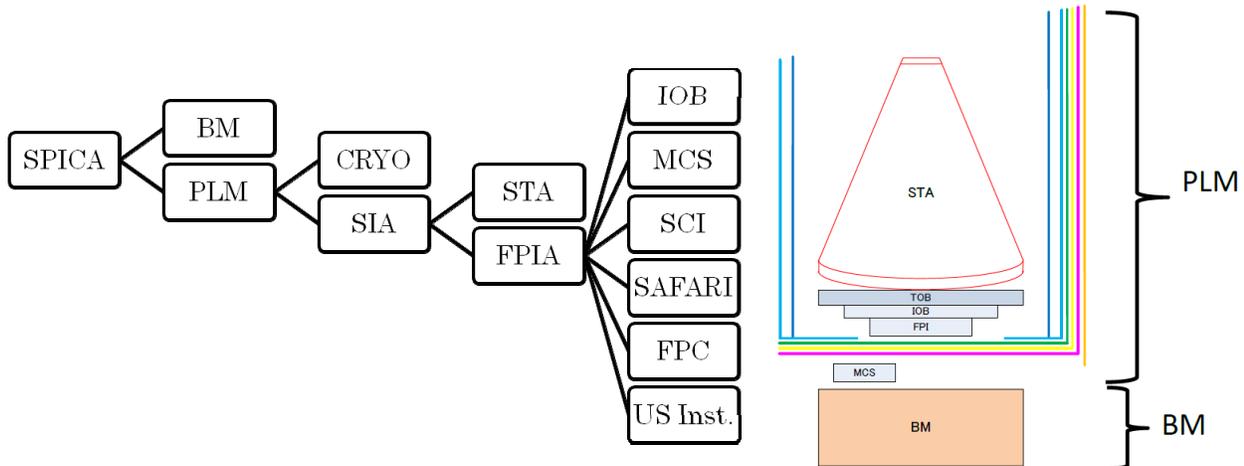


Figure 4. Configuration of SPICA.

2.2 Scientific Instruments

The SPICA mission is designed to achieve the scientific objectives described in the next section. To this goal, the spacecraft design is based on a 3-m class telescope (the physical diameter of the primary mirror is 3.2 m) operated at a temperature lower than 6 K. The telescope is designed to have diffraction limited performance at 5 μ m (with a WFE < 350 nm rms).

The main SPICA wavelength range is 5 – 210 μ m, covered with the following scientific instruments (Fig.5): MCS (mid infrared camera and spectrophotometer)⁶, SAFARI (SPICA far infrared imaging spectrometer)⁷, FPC (Focal Plane Camera)⁸, SCI (mid infrared coronagraph)⁹, a US instrument (FIR and sub-mm spectrometer, optional)^{10,11}. A part of FPC is to be used as a fine guidance sensor.

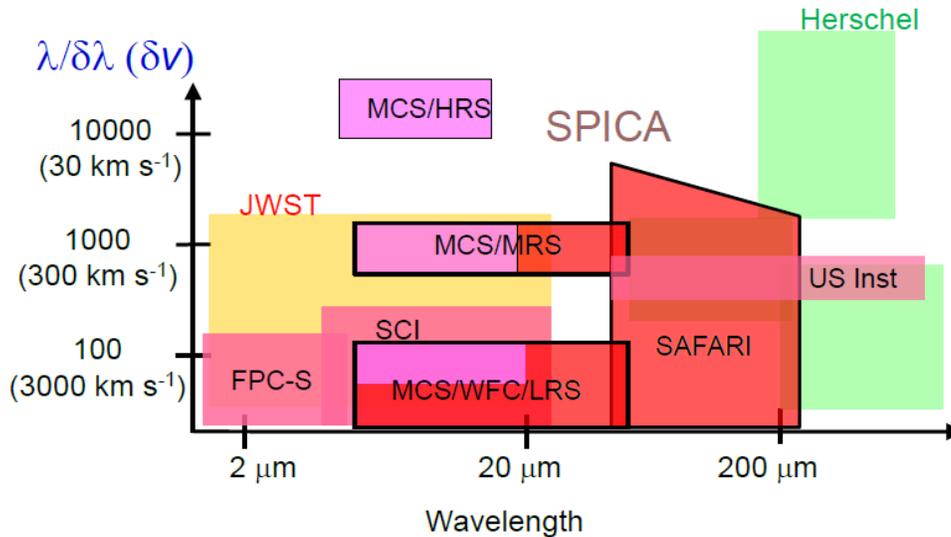


Figure 5. Capability of proposed SPICA Focal Plane Instruments.

2.3 Cryogenic System

The thermal environment required to operate the telescope and the instruments is obtained by a combination of passive cooling (via dedicated Sun and thermal shields combined with radiators) and active cooling (including mechanical coolers of two thermal stages with base temperatures of 4.5 K and 1.7 K).

The SPICA adopts a new concept of cryogenic system that uses no cryogen¹². The elements maintained at 4.5K, including the STA, the IOB and some focal plane instruments (FPI), are cooled by the combination of mechanical cryocoolers and efficient radiative cooling in the stable thermal environment at the Sun-Earth L2.

The SPICA Mechanical Cooling System is based on a set of advanced Stirling and Joule-Thompson coolers. The 4K Mechanical Cooler for the 4.5 K stage is a 4K-class Joule-Thomson cooler (4K-JT) connected to a pre-cooler of a 20 K-class two-stage Stirling cooler (2ST). Far-infrared instruments such as SAFARI on the IOB require further cooling to 1.7 K, which will be achieved using a 1K Mechanical Cooler comprising a dedicated 1K-JT (with ³He as working gas) and an additional 2ST pre-cooler. Previous missions with similar mechanical cryocoolers, such as AKARI, SMILES, and ASTRO-H, will leave large heritage for SPICA.

3. SCIENTIFIC GOALS

3.1 Formation of Planetary systems

SPICA is expected to provide a robust and multidisciplinary approach to determine the conditions for planetary systems formation. This will include the detection for the first time of the most relevant species and mineral components in the gas and dust of hundreds of transitional protoplanetary discs at the time when planets form. SPICA will also be able to trace the warm gas in the inner (< 30 AU) disc regions and, by resolving the gas Keplerian rotation, will allow us to observe the evolution of disc structure due to planet formation. SPICA will study debris discs and make the first unbiased survey of the presence of zodiacal clouds in thousands of exoplanetary systems around all stellar types. It will allow us to detect both the dust continuum emission and the brightest grain/ice bands as well as the brightest lines from any gas residual present in the disc. SPICA will have the unique capability to observe water ice in all environments, and thus fully explore its impact on planetary formation and evolution and in the emergence of habitable planets. Figure 6 shows that, in the closest debris discs, SPICA will spatially resolve the distribution of water ice and determine the

position of the “snow line”, which separates the inner disc region of terrestrial planet formation from that of the outer planets.

SPICA will drastically enhance our knowledge of the Solar System by making the first detailed characterization of hundreds of Kuiper Belt Objects, and of different families of inner, hotter centaurs, comets and asteroids. SPICA will provide the means to quantify their composition and determine unambiguously their size distribution: critical observational evidence for the models of Solar System formation. No other planned or present facility will be able to carry out these observations.

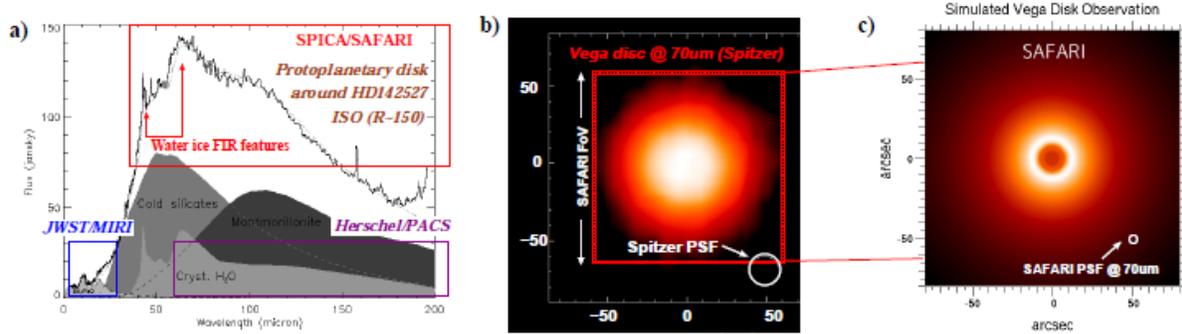


Figure 6: (a) ISO spectrum of the disk around HD142527¹³. Note that amorphous water ice only shows bands at 44 μm in the FIR¹⁴. Such features can not be accessed with Herschel or JWST. SPICA will take the equivalent spectra of objects at flux levels less than ~ 10 mJy per minute. (b) Image of Vega debris disk at 70 μm with Spitzer¹⁵. SPICA’s large FOV and smaller pixel size ($\sim 1.8''$ at 44 μm , red squares) will provide very detailed spectroscopic images of nearby disks. (c) Simulated image with SPICA at 70 μm assuming an inner hole in the disk with a radius of $\sim 11''$

SPICA will provide direct imaging and low resolution mid infrared spectroscopy of outer young giant exoplanets (e.g., at ~ 9 AU from a star at 10 pc), which will allow us for the first time to study the physics and composition of their atmospheres in a wavelength range particularly rich in spectral signatures (e.g., H₂O, CH₄, O₃, silicate clouds, NH₃, CO₂) and to compare it with the planets of our Solar System. SCI has a spectroscopic capability also at the wavelength of an important bio-marker O₃¹⁶. In addition, mid infrared transit photometry and medium ($R \sim 1000$) or high ($R \sim 30,000$) resolution spectroscopy of “hot Jupiters” will be routine with SPICA. SPICA will also provide an unprecedentedly sensitive window into key aspects of the dust life-cycle both in the Milky Way and in nearby galaxies, from its formation in evolved stars, its evolution in the ISM, its processing in supernova-generated shock waves and massive stars, to its final incorporation into star forming cores and protoplanetary discs.

3.2 Formation and evolution of galaxies

SPICA observations will provide a unique insight into the basic questions about how galaxies form and evolve such as: What drives the evolution of the massive, dusty distant galaxy population, and what feedback/interplay exists between the physical processes of mass accretion and star formation? How and when do the normal, quiescent galaxies such as our own form, and how do they relate to (Ultra) Luminous Infrared Galaxies (ULIRGs)? How do galaxy evolution, star formation rate and AGN activity vary with environment and cosmological epoch?

Substantial progress in this area can only be made by making the transition from large-area photometric to large-area spectroscopic surveys in the mid- to far-infrared (left panel in Fig. 7), which will be possible with SPICA. This is because the mid- and far-infrared region plays host to a unique suite of diagnostic lines to trace the accretion and star formation (right panel in Fig.7), and to probe the physical and chemical conditions in different regimes from AGN to star-forming regions.

While the Herschel-PACS spectrometer will detect the brightest far infrared objects at $z \sim 1$, SPICA will be able to carry out blind spectroscopic surveys out to $z \sim 3$. This will lead to the first statistically unbiased determination of the co-evolution of star formation and mass accretion with cosmic time. Spectroscopic surveys will provide direct and unbiased information on the evolution of the large scale structure in the Universe from $z \sim 3$ and the unprecedented possibility to investigate the impact of environment on galaxy formation and evolution as a function of redshift.

The high sensitivity of SPICA will enable photometric surveys beyond $z \sim 4$ that will resolve more than 90% of the Cosmic Infrared Background (in comparison with 50% that Herschel will achieve). SPICA will also observe Milky Way type galaxies in the far infrared out to $z \sim 1$, where the cosmic star formation rate peaks. For the first time, we will be able to piece together the story of the evolution of our own galaxy and answer the question of whether we are in a “special place” in the cosmos.

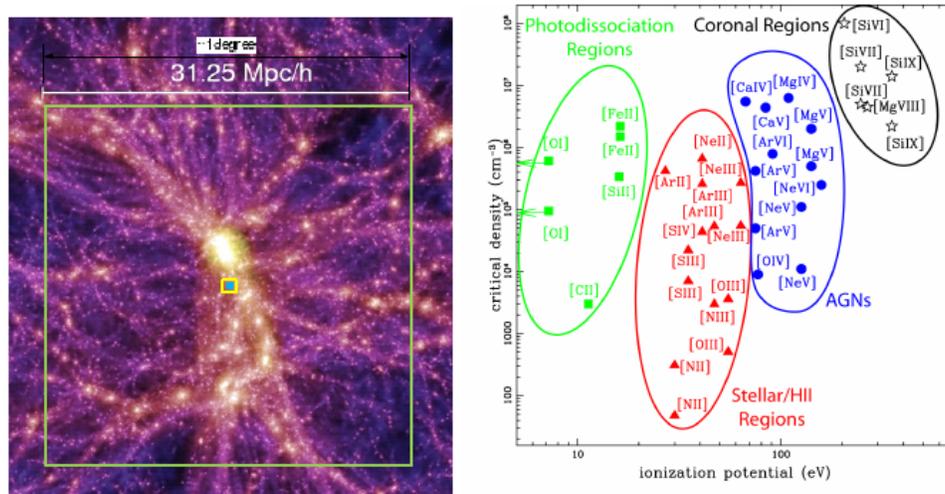


Figure 7: Left panel: Spectroscopic mapping speeds of the SPICA far infrared instrument (SAFARI) and Herschel-PACS superposed on a realisation of the Millenium simulation at $z \sim 1.4$ ¹⁷. In the centre are the footprints of the instantaneous spectroscopic FOV of PACS (blue, small box) and SPICA (yellow, small box). The large green box shows the area covered by SPICA in a 900 hour spectral full wavelength spectral survey (~ 1 degree). In this survey SAFARI will see down to $5 \times 10^{-19} \text{ Wm}^{-2}$ over the full $34 - 210 \mu\text{m}$ band. PACS would require approximately twice this time just to cover a single pointing to this depth over its full waveband. Right panel: A selection of the fine-structure atomic and ionic lines accessible with SPICA, plotted as a function of critical density and ionization potential. Using ratios between lines with different ionization or critical density, we can trace out a wide range of different physical/excitation conditions¹⁸.

4. CURRENT STATUS OF THE PROJECT AND SCHEDULE

4.1 Status in Japan and schedule

SPICA is a JAXA-led mission, and JAXA is in charge of the system integration, spacecraft, PLM with cryogenic system. JAXA will procure mid-infrared instruments together with universities and research institutes in Japan.

In Japan, following extensive discussions in the community for more than 10 years, the SPICA mission proposal was submitted to JAXA in 2007. After several reviews, the SPICA pre-project team was formed at JAXA in July 2008, and the three-year phase-A activity started. Following that, SPICA passed the System Requirements Review (SRR) successfully in 2010.

In 2012, SPICA has entered a new phase "Risk Mitigation Phase". The risk mitigation activities, which were formerly planned to be the part of the Phase B after the approval of the project, are now to be performed prior to formal approval of the project.

Following these activities, major industrial partners are to be selected, and main specifications of the SPICA mission will be fixed. SPICA will undergo a major technical review - the System Definition Review (SDR). Following this will be a management review by JAXA, the Project Phase-up (from pre-project to project) Review, which is expected to be held in FY 2013.

4.2 Status in Europe

ESA is an essential partner in the SPICA mission. The European SPICA Consortium submitted a proposal² to ESA under the ESA Cosmic Vision 2015-2025 framework. The proposal called on ESA to assume a partner agency role in SPICA by making the following contributions: (1) provision of the SPICA cryogenic Telescope Assembly (2) access to a European ground station (3) collaboration on science operations and (4) management of interfaces between JAXA and the European instrument, SAFARI. The SAFARI instrument itself is to be procured by ESA from the European Consortium.

The proposal was selected by ESA in October 2007 for further study as a candidate M-class mission, with the character of "mission of opportunity". The assessment study was carried out under this framework. SPICA is currently under extended study. A decision for ESA on whether to move into implementation phase will be taken on a timescale that is compatible with the decision by JAXA.

The SAFARI instrument is to be procured by the SAFARI consortium, whose PI is SRON, Netherlands. The SAFARI consortium is very well established and is carrying out very extensive development study.

4.3 Status in Korea

Korea is in charge of FPC (both FPC-G and FPC-S). The official SPICA/FPC team is now established with Korea Astronomy and Space Science Institute (KASI) as a PI institute.

4.4 Status in Taiwan

Taiwan has recently joined the SPICA project as a part of the MCS team. Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) is a PI institute in Taiwan.

4.5 US participation

A possibility that US procures one of focal plane instruments (far-infrared sub-millimeter spectrometer) has been discussed. The assessment study of the US contribution to SPICA was carried out by three teams under the contract with NASA in 2010. US participation was explicitly recommended in ASTRO2010, astronomy and astrophysics decadal survey in USA.

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