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SPICA: space infrared telescope for cosmology and astrophysics

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Abstract

We present the current status of the SPICA (space infrared telescope for cosmology and astrophysics, previously known as the HII/L2 mission). Onboard SPICA, a 3.5 m telescope cooled to 4.5 K provides an unprecedented combination of sensitivity and resolution for mid- to far-infrared observations (core wavelength between 5 and 200 μm). SPICA will make great contributions in many areas of astrophysics. We propose a "warm launch", cooled telescope concept for SPICA: the telescope is to be launched at ambient temperature and is to be cooled to 4.5 K in orbit by a modest mechanical cooler system with the assistance of effective radiative cooling. We have been working on development programs focusing on two key technical issues: reliable mechanical coolers and the light-weight telescope system. The target launch year of SPICA is around 2010.

Keywords: SPICA; Space infrared telescope

1. Scientific objectives

SPICA (Fig. 1) is a unique mission with a large (3.5 m) telescope cooled to 4.5 K and optimized for mid- and far-infrared observations with high spatial resolution and unprecedented sensitivity.

A variety of scientific goals can uniquely be achieved by SPICA. In the following, the main scientific programs of SPICA are described: to reveal the birth and evolution of various objects in our universe.

1.1. Birth and evolution of galaxies

When and how were the first generation of stars and galaxies formed in our universe? How does the star-formation rate in galaxies change as a function of time? These are two of the most important questions to be answered in astrophysics.

Most previous studies of the history of star-formation in our universe were mainly based on optical observations (e.g. Madau et al., 1996). However, these observations analyzed ultraviolet radiation in the rest frame of high-redshift galaxies, and had large uncertainties due to dust extinction.

Mid- and far-infrared observations are essential to study the evolution of galaxies by disclosing the history of star-formation because these observations avoid the problem of dust extinction.

Sensitivity is a key issue in the study of star formation rates in high-z galaxies. The sensitivity of mid- to far-infrared observations is frequently limited by confusion of sources. Therefore, we need high spatial resolution in the mid- and far-infrared, not only to reveal detailed structure but also to achieve good sensitivity; we need a large-aperture telescope to detect faint galaxies at high-redshift in the confusion-limited far-infrared sky.

1.2. Birth and evolution of stars

Stars are basic constituents of galaxies. Stars are believed to be formed in the dense cores of molecular clouds. Many theoretical studies describe the dynamical evolution of stars once gravitational collapse starts and matter accretes in the center. Radio observations show that powerful jets emerge during the main accretion phase.

However, details of the early stages of stellar evolution outlined above are not yet well understood.

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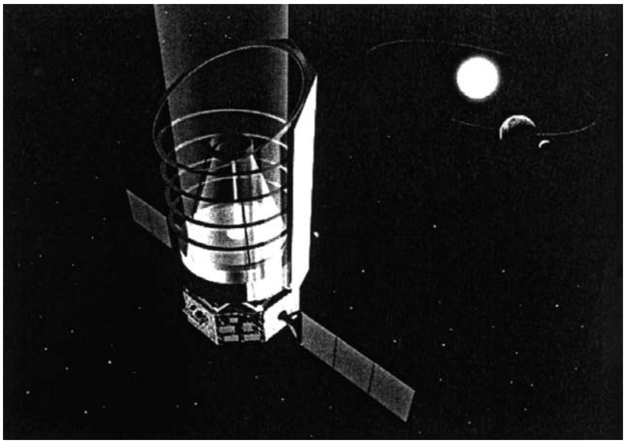

Fig. 1. Artist's impression of SPICA in orbit.

Unresolved questions remain, including what makes the cores gravitationally unstable so that they collapse to form stars, and what process regulates the stellar initial mass function.

The relationship of stellar mass to the spectral energy distribution in the near- to far-infrared will provide us with very useful information to help illuminate the early phases of stellar evolution. Mid- to far-infrared observations are also very important because star-forming regions are generally heavily obscured by dust.

Again, high spatial resolution is a key observational requirement, since star-forming regions are extremely crowded.

1.3. Formation of planetary systems

Since the first discovery of an exoplanet around 51 Peg (Mayor and Queloz, 1995), more than 100 giant exoplanet candidates have been found through indirect methods; almost exclusively by the radial-velocity method. These findings have revolutionized the study of planetary systems: the number of examples of planetary systems has increased from one (our solar system) to 100.

Although the radial-velocity method is a very powerful way to detect exoplanets, it cannot tell us the exact nature of these planets. Direct imaging of these exoplanets and spectroscopy of their atmospheres are essential to understand their nature.

The main observational problem is that planetary radiation is much weaker than stellar radiation. In the case of our solar system, the planetary radiation is 9–10 orders of magnitude weaker than stellar radiation in the visible range. This situation is much improved in the mid-infrared, where the difference between stellar flux and planetary flux becomes of order one million. Thus high spatial resolution observations in the mid-infrared are one possible way to make direct observations of exoplanets. We need coronagraphy to suppress the halo of bright central stars and to detect the flux from exoplanets around the stars (Tamura, 2000).

Of course, high spatial resolution and high sensitivity are the keys to enable these observations.

2. Mission concept

2.1. The need for a large, cooled telescope

Following two very successful missions, IRAS and ISO, two infrared missions are to be launched within a year or two. One is SIRTF (Gallagher and Simmons, 2000), which is the last mission of NASA's great observatory series. It has an 85 cm cooled telescope and was launched in August 2003. The other is ASTRO-F (Murakami, 1998), ISAS's survey mission with a 67 cm telescope and is to be launched in 2004. Although these missions are very powerful, their mirror sizes are relatively small (67–85 cm), so their spatial resolution is moderate.

As discussed in the previous section, high spatial resolution is essential for finding answers to many important questions in astrophysics. So, for high-resolution observations in the mid- and far-infrared, we need a mission with a telescope much larger than those of the previous missions.

Two missions with large telescopes in the infrared and the sub-mm regions have been proposed for launch within a decade. One is the "James Webb Space Telescope" (JWST, Mather and Stockman, 2000) and the other is "HERSCHEL Space Observatory" (HSO, Pilbratt, 2000). These will be very powerful observatories, but their telescopes are only passively cooled and thermal radiation from the telescopes themselves degrades their sensitivity, especially in the mid- and far-infrared.

To achieve high spatial resolution and good sensitivity in the mid- and far-infrared, we need a large-aperture telescope cooled to a very low temperature.

2.2. New design philosophy

To achieve high sensitivity, we have to cool the whole telescope and all focal plane instruments down to cryogenic temperatures. For this reason, all of the infrared astronomical satellites flown so far carried liquid helium. To carry liquid helium into space requires a large helium tank and a heavy vacuum vessel. This configuration (left panel of Fig. 2) makes the satellites bigger and heavier, and reduces their telescope sizes. Thus, this design scheme makes it very difficult to realize a large, cooled telescope in space.

To overcome these difficulties, we propose a "warm-launch, cooled telescope" design concept (right panel of Fig. 2), i.e., the telescope and focal plane instruments are "warm" at launch but are cooled in orbit. The cryogenic

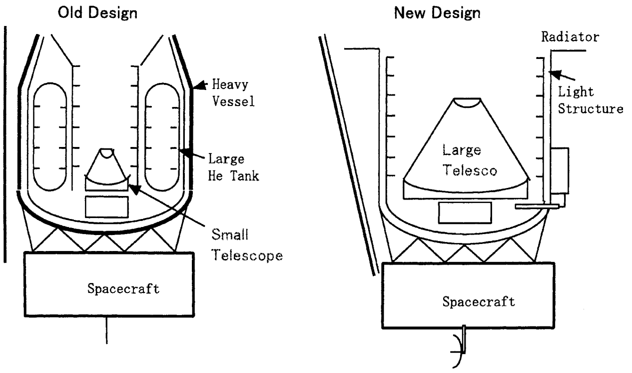

Fig. 2. Change of design philosophy. Left panel shows an old design with liquid helium. Right panel shows a new design without helium (“warm launch”).

Table 1
Summary of current specifications of SPICA

Parameter	Value
Mirror size	3.5 m
T_{Mirror} in space	4.5 K
T_{Mirror} at launch	300 K
Core wavelength range	5–200 μm (diffraction limit at 5 μm)
Orbit	S–E L_2 Halo
Cooling	Radiative cooling and mechanical coolers
Total mass	2600 kg
Launch vehicle	H-IIA Rocket
Launch year	2010

system, which enables this warm launch concept, is a key issue. We propose to cool the telescope in orbit by (1) effective radiative cooling, together with the help of (2) modest mechanical cryocoolers.

2.3. Outline of SPICA

Fig. 1 shows a conceptual design of the SPICA mission based on the concept discussed above. Table 1 summarizes its specifications. The most important characteristic of this mission is that its telescope is cooled to 4.5 K, making it especially suitable for mid- to far-infrared observations.

Since this is a warm-launch type satellite, the telescope itself occupies a significant fraction of the total volume and mass. This situation is completely different from that of conventional infrared astronomical satellites. The warm launch significantly reduces the total size and enables the payload fairing of the H-IIA rocket to accommodate a telescope with a 3.5 m primary mirror.

To make the mission technically feasible and to improve reliability, we do not employ a deployable mirror design as in JWST, but use a conventional “monolithic mirror” design.

In order to achieve the most effective radiative cooling, we propose a halo orbit around one of the Sun–Earth libration points (L_2) (hereafter S–E L_2, the point at the opposite side of the sun from the earth) for SPICA. In this orbit, heat sources (Sun and Earth) are almost in the same direction and radiative shielding can be simplified. Hence radiative cooling is very effective at S–E L_2.

2.4. Cryogenic system

The biggest technical challenge of SPICA is its cryogenic system. As mentioned above, to cool the observing system, (1) radiative cooling and (2) mechanical cryocoolers are used. Fig. 3 shows a schematic drawing

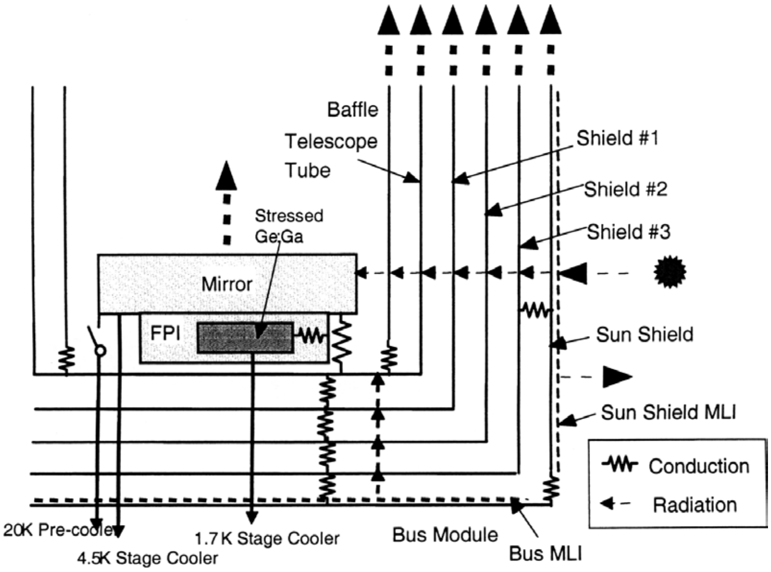

Fig. 3. Configuration of the Cryogenic System of SPICA.

of the cryogenic system. The SPICA telescope and its focal plane instruments (FPIs) are thermally shielded from solar radiation by the Sun Shield and Shields 1–3. These shields are also useful to radiatively dispose of most of the heat from the Sun into space.

The telescope and most of the FPIs are further cooled to 4.5 K by a ^{4}He Joule–Thomson (JT) cooler together with a 2-stage Stirling cooler. Some focal plane instruments require lower temperatures. For example, stressed Ge:Ga detectors for far-infrared radiation must be cooled to 1.7 K, so they will be thermally isolated from other FPIs and cooled by an additional JT cooler that can go down to 1.7 K.

The dominant cooling process at the various temperature stages is radiation, and the cooling power required for the 4.5 K JT cooler is only 30 mW at 4.5 K, i.e., we can cool the whole telescope and the focal plane instruments down to 4.5 K using a modest cryocooler system.

2.5. Focal plane instruments

The core wavelength range of SPICA will be 5–200 μm and two focal plane instruments are proposed to cover this wavelength range.

One is the Mid-infrared Camera and Spectrometer, which covers 5–25 μm with two channels. We propose three modes of observation. One is high-resolution, diffraction-limited imaging. The pixel size is 0.18″ (shorter wavelength channel) and 0.36″ (longer wavelength channel) with a common field of view of 6′. The second is the mid-resolution ($\lambda/\Delta\lambda \sim 10^3$) spectroscopy mode. The third is the coronagraphic mode for the direct detection of planets in extrasolar systems (Tamura, 2000). The single-segment, cold optics of the SPICA telescope will be an ideal platform for coronagraphic observations.

The second instrument is the Far-infrared Camera and Spectrometer, which covers the 50–200 μm range with two channels. This instrument also has two modes: one is diffraction-limited imaging and the other is mid-resolution imaging spectroscopy with a Fourier-transform spectrometer.

Near-infrared (1–5 μm) and sub-mm observing capability are under study.

2.6. Spacecraft system

The SPICA spacecraft has several basic subsystems required for astronomical satellites. The subsystems are the attitude determination and control subsystem (including propulsion subsystem), the communication subsystem, the command and data handling subsystem, the power subsystem, the thermal subsystem, and the structure subsystem.

The most challenging subsystem is the attitude determination and control subsystem (ADCS). To fully utilize the capability of the coronagraph, which was discussed in previous sections, we need an pointing stability of 35 mas (rms). This is a very demanding requirement, and in addition to the spacecraft ADCS we are planning to install a tip-tilt mirror at the focal plane to achieve the required pointing stability.

2.7. Sensitivity

A cooled 3.5 m telescope is a huge jump from previous infrared astronomical missions with small telescopes ($D < 1$ m).

Fig. 4 shows the photometric sensitivity of the SPICA mission for point sources as a function of wavelength. Since SPICA has a cooled telescope, it can achieve superior sensitivity throughout the infrared wave band. With these sensitivities, we can make various kinds of important astronomical observations as discussed above.

The noise is dominated (1) by detector noise at the shortest wavelengths, (2) by photon fluctuation from zodiacal light in the mid-infrared, and (3) by "confusion noise" at longer wavelengths. High resolution diffraction-limited observations with a large aperture telescope are especially important in the far-infrared, where the sensitivity is limited by confusion.

Fig. 4 also shows the sensitivity of two other large missions (JWST and HSO) in the infrared and sub-mm regions. Each of the three missions has its own unique capability. JWST is optimized for the near-infrared

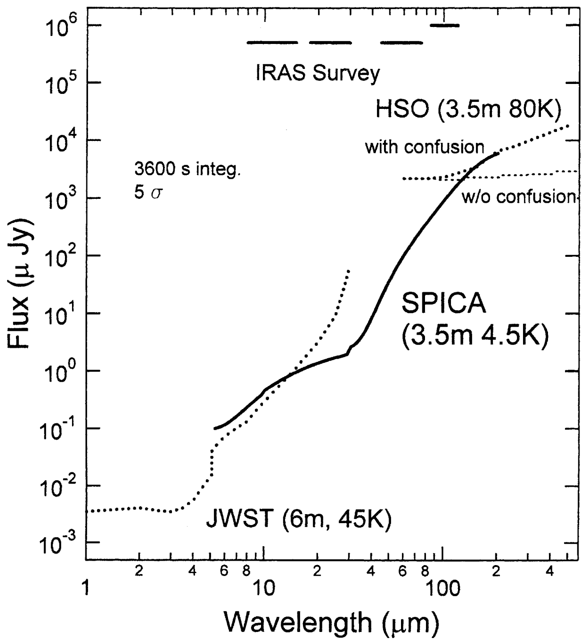

Fig. 4. Comparison of point source sensitivities of "Big Missions" scheduled within a decade.

(core wavelength range of 1–5 μm) observations and can make very deep observations in the near-infrared. HSO, on the other hand, concentrates on longer wavelengths.

However, both JWST and HSO will have only moderately cooled telescopes, and the thermal radiation from the telescopes themselves will degrade the sensitivity at mid- and far-infrared wavelengths (see dotted lines in Fig. 4). On the other hand, SPICA's telescope is cooled to 4.5 K, so it can achieve excellent sensitivity especially in the mid- to far-infrared region. In this sense, SPICA is complementary to JWST and HSO.

3. Technology development

We have been working on technology development programs for SPICA. Here we describe briefly the primary results of the programs.

3.1. Mechanical cryocoolers

3.1.1. Cryocoolers developed for other missions

Mechanical cryocoolers are key elements in the cryogenic system of SPICA. As Fig. 3 shows, we need several types of coolers for SPICA; Table 2 summarizes the specifications of cryocoolers required for SPICA.

Among the coolers shown in Table 2, two types have already been developed for space applications.

One is a 2-stage Stirling cycle cooler, which has been developed for the ASTRO-F project. The Stirling cycle cooler has a cooling power of 200 mW at 20 K. In the laboratory, we have been operating this type of Stirling cycle cooler for more than 3 years, and the cooler shows little degradation. ASTRO-F is to be launched in 2004, and then the cooler will become flight-proven.

The other is a ^{4}He Joule–Thomson (JT) cooler, which has been developed for a ISS-based project SMILES (Superconducting Submillimeter Limb-Emission Sounder, Inatani et al., 2000). It has a cooling power of 20 mW at 4.5 K. In the laboratory, a long-life test was performed over more than 9000 h of operation without significant degradation of performance.

3.1.2. 1 K-class cooler

Most challenging cooler in Table 2 is the JT cryocooler with a cooling power of 5 mW at 1.7 K. Hence, we focus our technical program on the development of this cooler, which will be called the "1 K-class cooler" hereafter. Taking a factor two as a margin of safety, we have set a goal of the development program at 10 mW of cooling power at 1.7 K.

The lowest temperature to be achieved with JT coolers is determined by the pressure at the exit of the JT valve and also by the gas used. Reaching 1.7 K with ^{4}He gas, this should be pumped below 10 Torr, which is very difficult to achieve.

Hence, instead of ^{4}He gas, we plan to use ^{3}He gas which has a relatively high gas pressure even at 1.7 K. Fig. 5 shows a picture of this ^{3}He JT cooler. Fig. 6 shows an example of test results of the ^{3}He JT cooler developed for SPICA. A cooling power of 10 mW at 1.658 K has been reached so far, which meets the requirements for SPICA.

3.2. Telescope systems

As shown in Table 1, the SPICA telescope has a monolithic 3.5 m primary mirror at 4.5 K, which reaches the diffraction limit at 5 μm. The mass budget allocated for the whole telescope system is 700 kg.

It is a very challenging task to keep the SPICA telescope within this mass budget. We have a couple of candidates for the SPICA mirror material to achieve the goal.

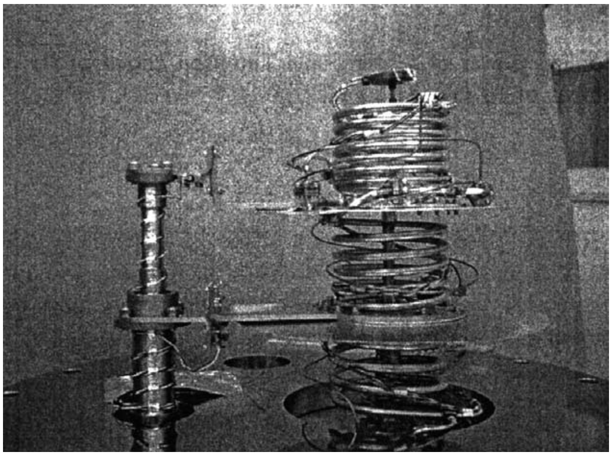

Fig. 5. Picture of a ^{3}He Joule–Thomson cooler under development for SPICA.

Table 2
Cryocoolers required for SPICA

	Cooler-1	Cooler-2	Cooler-3
Purpose	To cool telescope, Si:As detector	To cool unstressed Ge:Ga detectors	To cool stressed Ge:Ga detectors
Component	^{4}He JT + 2-stage Stirling cycle cooler	^{4}He JT + 2-stage Stirling cycle cooler	^{3}He JT + 2-stage Stirling cycle cooler
Cooling power	30 mW at 4.5 K	10 mW at 2.5 K	5 mW at 1.7 K
Development status	JT and Stirling developed	2.5 K JT under development	1.7 K JT under development

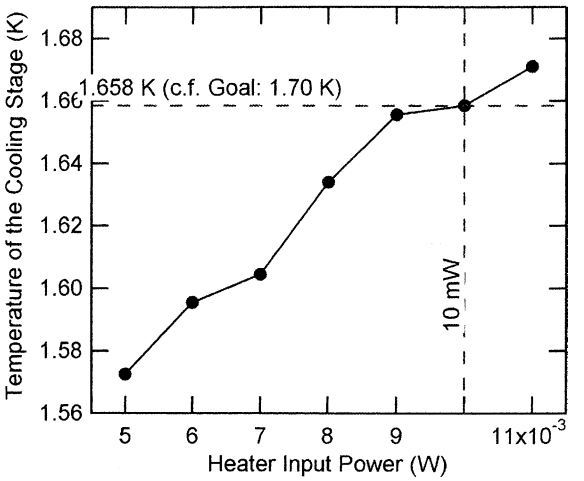

Fig. 6. Test results of the cooling power of a ^{3}He Joule–Thomson cooler under development for SPICA. The cooler meets SPICA's requirement of 10 mW at 1.7 K.

3.2.1. SiC mirror

Silicon carbide (SiC) was used for the ASTRO-F telescope mirrors and is also to be used for the HSO telescope. SiC has characteristics suitable for light-weight mirrors.

We have developed a light-weight (11 kg) 67 cm mirror for ASTRO-F using SiC. The ASTRO-F mirror has a unique, sandwich structure: the core is made of "porous" SiC to reduce mass, and the surface is coated with chemical vapor deposition (CVD) SiC which can be polished smooth enough for observations at wavelengths longer than 2 μm.

We have measured the surface accuracy of this mirror at cryogenic temperature, and found that the mirror meets our requirements. One lesson learned is that the surface deformation of the mirror at cryogenic temperature is caused mainly by the support structure and is not due to the mirror itself. Hence it is very important to design a support structure carefully to minimize any deformation of the surface of the mirror.

Unfortunately, there is no facility to make a CVD coating on a 3.5 m monolithic mirror, and we cannot apply this technology directly to SPICA.

We have started a development program to explore the possibility of using a sintered SiC mirror, originally developed for the HSO telescope. One of the key issues to be solved is its surface roughness. Another point to check is whether the accuracy required for SPICA can be achieved with passive supporting systems, originally developed for the HSO telescope with one order of magnitude less severe requirements.

3.2.2. C/SiC mirror

Carbon fiber-reinforced silicon carbide (C/SiC) composite is a composite material, and is made by capillary infiltration of porous C/C-structures with molten silicon, followed by partial reaction of the carbon matrix with silicon to form SiC. It has high strength, high stiffness, low density, and high damage-tolerance. Moreover, since this is a composite material, we can control its characteristics. Hence it is suitable for light-weight large optics, but has never been used yet for large astronomical optics.

Several samples of C/SiC composite were made to optimize its performance for space mirror systems, and the following results were reached:

1. To reduce the coefficient of thermal expansion (CTE) at cryogenic temperature. Our C/SiC sample shows CTE less than 0.15 ppm K^{-1} below 100 K, which is important for the tests of mirrors at cryogenic temperature.
2. To make a smooth surface. A polished C/SiC sample has a surface roughness of 20–30 nm (rms), which is acceptable for the SPICA telescope.

We are now working on a program to verify the uniformity of the material and also to produce large samples.

References

Gallagher, D.B., Simmons, L.L. Development of the Space Infrared Telescope Facility (SIRTF). Proc. SPIE 4013, 80–89, 2000.

Inatani, J., Ozeki, H., Satoh, R., et al. Submillimeter Limb-Emission Sounder JEM/SMILES aboard the Space Station. Proc. SPIE 4152, 243–254, 2000.

Madau, P., Ferguson, H.C., Dickinson, M.E., et al. High-redshift galaxies in the hubble deep field: colour selection and star formation history to $z \sim 4$. MNRAS 283, 1388–1404, 1996.

Mather, J.C., Stockman, H.S. Next generation space telescope. Proc. SPIE 4013, 2–16, 2000.

Mayor, M., Queloz, D.A. A Jupiter-mass Companion to a Solar-type star. Nature 378, 355–359, 1995.

Murakami, H. Japanese infrared survey mission IRIS (ASTRO-F). Proc. SPIE 3356, 471–477, 1998.

Pilbratt, G.L. The ESA FIRST cornerstone mission. Proc. SPIE 4013, 142–151, 2000.

Tamura, M. Exoplanet photometry and spectroscopy with HII/L2, in: Matsumoto, T., Shibai, H. (Eds.), Mid- and Far-Infrared Astronomy and Future Space Missions. ISAS Report SP, vol. 14. ISAS, Sagamihara, Japan, pp. 3–9, 2000.