SPICA: A MISSION OPTIMIZED FOR MID- AND FAR-INFRARED ASTRONOMY

T. Nakagawa and SPICA Working Group

Institute of Space and Astronautical Science (ISAS), 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan

Abstract

We present the concept of the SPICA (Space Infrared Telescope for Cosmology and Astrophysics) mission, which incorporates a 3.5 m telescope cooled to 4.5 K. SPICA will focus on high-resolution mid- to far-infrared observations with unprecedented sensitivity. It will make great contributions to our understanding of important astronomical questions, such as the history of star-formation in the universe, the birth and evolution of AGN, and the formation of planets in extrasolar systems.

In order to reduce the total weight, we propose a "warm launch" cooled telescope concept; the telescope is to be launched at ambient temperature and is to be cooled in orbit to 4.5 K by a modest mechanical cooler system with the assistance of effective radiative cooling. SPICA is proposed to be launched into a halo orbit around S-E L2 in 2010.

Key words: Galaxies: formation – Stars: formation – Planets: formation – Missions: SPICA

1. Introduction

Since the success of the all-sky survey by the Infrared Astronomical Satellite (IRAS), infrared observations from space have been one of the essential tools in many fields of astronomy. The first observatory-type infrared mission, the Infrared Space Observatory (ISO), also demonstrated the effectiveness of infrared observations from space.

Following these pioneering missions, two more missions are to be launched within the next four years. One is SIRTF (Gallagher & Simmons 2000), which is the last mission of NASA's great observatory series; it has an 85 cm cooled telescope, and is to be launched in 2002. The other is ASTRO-F (Murakami 1998, Nakagawa 2001), a survey mission of ISAS with a 70 cm telescope, and is scheduled to be launched in 2004.

Although these missions are very powerful, their mirror sizes are relatively small (60 – 85 cm), and the spatial resolution is not so high. Hence high-resolution observations with much larger telescopes have been long-awaited.

Two missions with large telescopes in the infrared and the sub-mm regions are now proposed to be launched within a decade. One is the "Next Generation Space Telescope" (NGST) (Mather & Stockman 2000) and the other is the "Far InfraRed and Submillimetre Telescope" (FIRST) (Pilbratt 2000). These will be powerful observatories, but their telescopes are only passively cooled and the thermal radiation from the telescopes degrades their sensitivity in the mid- and the far-infrared.

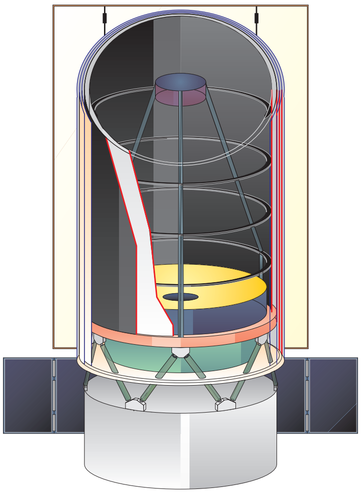

Figure 1. Conceptual design of the SPICA mission with a 3.5 m primary mirror cooled to 4.5 K.

We propose a new space observatory, the SPICA mission (formerly called HII/L2 mission), which incorporates a large-aperture (3.5 m) "actively cooled" (4.5 K) telescope, and is optimized for mid- and far-infrared astronomy.

2. Scientific Objectives

There are a variety of scientific goals that can uniquely be explored by SPICA. Here we list some representative goals.

2.1. Star-formation History of Our Universe

One of the most important questions in astronomy is the history of star-formation in our universe. Most of the previous studies were based on optical observations (e.g. Madau et al. 1996), which traced ultraviolet radiation in

Proc. Symposium *'The Promise of the Herschel Space Observatory'* 12–15 December 2000, Toledo, Spain
ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

the rest-frame of high-redshift galaxies and left large uncertainties due to dust extinction.

Far-infrared observations, on the other hand, are free from these uncertainties and can reveal the star-formation history reliably even at high-redshift. The high spatial resolution of SPICA is essential to detect faint galaxies at high-redshift in the confusion-limited far-infrared sky.

Moreover, the mid- and far-infrared region is rich with many bright lines useful for the estimates of the redshift of each galaxy. In particular PAH features can be powerful tools, since these features can be measured even with low-resolution spectroscopic observations. SPICA covers most of the PAH features at any redshift, and will enable high-sensitivity determination of the redshifts of galaxies at high z with high efficiency.

2.2. Birth and Evolution of AGN

AGN are one of the important energy release mechanisms in our universe and are believed to be the result of mass accretion on to massive black holes. Their origins are still uncertain, although massive black holes seem to be ubiquitous in galactic bulges.

ISO demonstrated the effectiveness of spectroscopic observations in the mid-infrared to reveal the origin of the luminosity (AGN vs starbursts) of infrared luminous galaxies (e.g. Genzel et al. 1998), but these observations were limited to the local universe. The high-sensitivity of SPICA will enable this type of observation even for high-redshift galaxies and will reveal the formation process of AGN and its possible relations to starbursts.

2.3. Formation of Planetary Systems

Discoveries of "Vega-like stars" evoked much discussion on the formation process of planetary systems. The high-resolution capability of SPICA in the mid-infrared will reveal the density and temperature profiles of the dusty disks of "Vega-like stars", which are essential to understand the formation process of planetary systems.

One more important capability of SPICA is that it is expected to detect extrasolar planets directly. We now have ~50 giant planet candidates in extrasolar systems discovered through "indirect" methods. SPICA will enable the first "direct" detection of extrasolar planets beyond ~2 AU around nearby (~ 5pc) stars (see Tamura 2000 for details). The nature of these extrasolar planets will be revealed by mid-infrared spectroscopy of planetary atmosphere also by SPICA. These observations will reveal a general picture of the formation process of planets.

2.4. Discovery Potential

The capability of the 3.5 m telescope of SPICA is a big jump from those of previous missions with smaller telescopes (< 1 m). Moreover, SPICA is a very efficient observatory with its wide field of view (6′). Hence, SPICA has a great potential to discover interesting objects serendipitously. Since SPICA can make both photometric and spectroscopic observations, we can make follow-up observations of "serendipitously found objects" with SPICA itself.

Table 1. Current specifications of SPICA.

Parameter	Value
Mirror Size	3.5 m
$T_{\rm Mirror}$ in Space	4.5 K
$T_{\rm Mirror}$ at Launch	300 K
Core Wavelength Range	5-200 μm
	(Diffraction Limit at 5 μm)
Orbit	S-E L2 Halo
Cooling	Radiative Cooling and
	Mechanical Coolers
Total Mass	2,600 kg
Launch Vehicle	H-IIA Rocket
Launch Year	~2010

3. Outline of the SPICA Mission

3.1. Design Concept

To achieve high sensitivity in the mid- and the far-infrared, we have to cool the whole telescope and the focal plane instruments. All 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.

To overcome these difficulties, we propose a "warm-launch, cooled telescope" design concept, i.e. the telescope and focal plane instruments are "warm" at launch but are cooled in orbit. The cryogenic system, which enables this "warm launch" concept, is a key issue and will be discussed later.

3.2. Outline of the Mission

Figure 1 shows a conceptual design of the SPICA mission based on the above concept, and Table 1 summarizes its specifications. The "warm launch" concept reduces the total size significantly and enables the payload fairing of the Japanese H-IIA rocket to accommodate a telescope with a 3.5 m primary mirror.

We do not employ a deployable mirror design for the telescope of SPICA and use a conventional "monolithic mirror" design, in order to make the mission technically feasible and reliable.

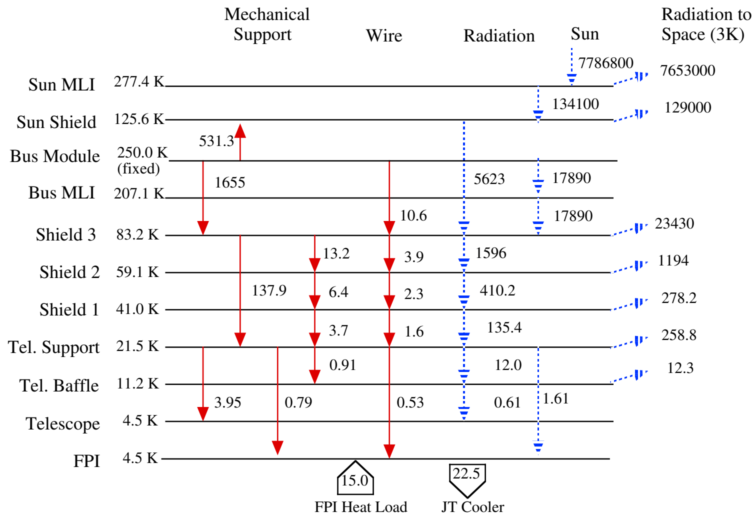

Figure 3. Heat flow (unit: mW) diagram of the SPICA mission cooled by radiation and mechanical coolers. Filled arrows show the heat flow by conduction and dotted arrows show the heat flow by radiation. We assume a structure of the conceptual design (Figure 1)

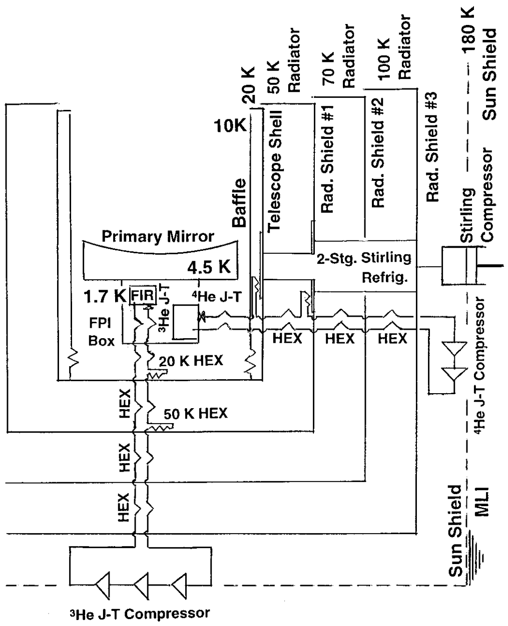

Figure 2. Schematic diagram of the cryogenic system of SPICA. The telescope is enshrouded with multi-layered radiators. One set of a JT cooler (with ^{4}He) and a two-stage Stirling cycle is used to cool both the telescope and focal plane instruments to 4.5 K. Another set of a JT cooler (with ^{3}He) and a two-stage Stirling cycle is used to cool far-infrared detectors to 1.7 K.

4. Cryogenic System

4.1. Configuration

The biggest technical challenge of the SPICA mission is its cryogenic system. In order to cool the observing system in orbit, we plan to use (1) radiative cooling and (2) mechanical cryocoolers. Figure 2 shows a schematic diagram of the cryogenic system and Figure 3 shows the heat flow of the current design.

In order to make radiative cooling most effective, we propose a halo orbit around one of the Sun-Earth libration points (L2) (hereafter S-E L2, 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 we can make radiative cooling very effective. Radiative cooling alone can cool the telescope below 30 K, which is low enough for near-infrared observations.

To cool the telescope further, we propose to use mechanical cryocoolers: the combination of a two-stage Stirling cycle cooler and a Joule-Thomson (JT) cooler with ^{4}He.

As the heat flow diagram (Figure 3) shows, the dominant cooling process of the whole system is through radiation at various temperature stages, and the cooling power required for the mechanical 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 by a modest cryocooler system.

4.2. Mechanical Cryocoolers

As discussed in the previous subsection, mechanical cryocoolers are key elements in the cryogenic system of SPICA. We have been developing two types of mechanical cryocoolers for space applications.

One is a two-stage Stirling cycle. This has been developed to be onboard ASTRO-F and it is now under extensive tests. The cooling power is about 200 mW at 20 K. We plan to use this type of coolers as pre-coolers for the JT coolers.

The other type is a 4 K JT cryocooler (Narasaki & Tsunematsu 2000) for SMILES on the international space station. The cooling power of the JT cooler, together with the two-stage Stirling cooler, is about 30 mW at 4.85 K, which is sufficient for SPICA. The total input power for this system is about 180 W at room temperature.

Both systems are now being tested extensively and are to be flight-proven in 2004. We can use basically the same system for SPICA to cool the telescope to 4.5 K.

Some focal plane instruments require lower temperatures. For example, stressed Ge:Ga detectors for far-infrared have to be cooled to 1.7 K. Hence we plan to use another Stirling-JT system but with ^{3}He for the JT to achieve lower temperature as shown in Figure 3. We are now making a proto model of this system and will start extensive tests soon.

5. Focal Plane Instruments

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

One is the Mid-infrared Camera and Spectrometer, which covers 5–25 μm with two channels. We propose three modes of observations. One is diffraction-limited imaging. The pixels size is $0''.18$ (shorter channel) and $0''.36$ (longer 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 SPICA's cold telescope with a single-segment primary mirror will be an ideal platform for the coronagraphic observations.

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

6. Comparisons with other Missions

Figure 4 shows the photometric sensitivity of SPICA for point sources as a function of wavelength. Since SPICA has a cooled telescope, it can achieve superior sensitivity throughout the infrared wave band.

Figure 4 also shows the sensitivity of two other large missions (NGST and FIRST) in the infrared and sub-mm regions. Each of the three missions has its own unique capability. NGST is geared for the near-infrared and can achieve very deep observations with high spatial resolution. FIRST concentrates on longer wavelengths and can make high-resolution spectroscopic observations as well as photometric observations.

However, both NGST and FIRST will have only moderately cooled telescopes, and the thermal radiation from the telescopes could degrade the sensitivity at mid- and far-infrared wavelengths (see dotted lines in Figure 4). On the other hand, SPICA has good sensitivity throughout the infrared region and achieves excellent sensitivity especially in the mid- to far-infrared region, since its telescope is cold enough. In this sense, SPICA is complementary to NGST and FIRST. Since these three missions are unique and complementary to each other, we need these three missions to cover the whole infrared region with good sensitivity and high spatial resolution. International collaboration is essential to realize these big missions and also to make well-organized observations with these unique missions.

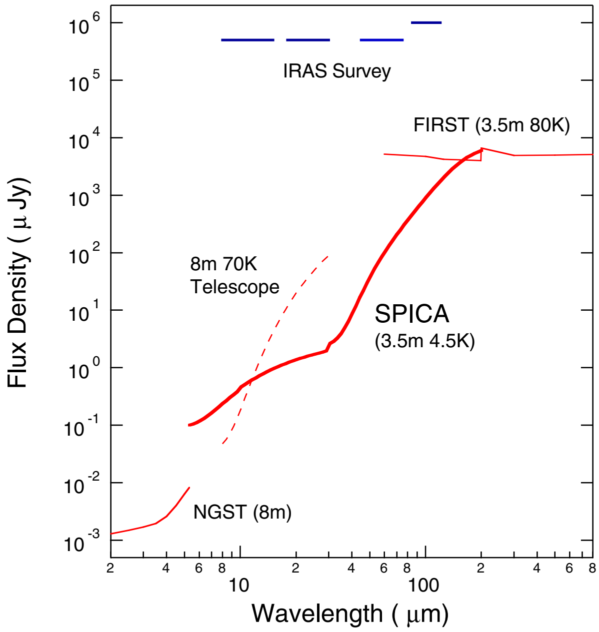

Figure 4. Comparison of point-source sensitivity (5σ flux density at 3,600 s integration) of various infrared missions. Diffraction-limited observations with $\lambda/\Delta\lambda = 5$ is assumed for SPICA.

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