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HII/L2 Mission*: a New Space Telescope for Mid- and Far-Infrared Astronomy

By

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Abstract: We present the concept of the HII/L2 (or SPICA) mission, which incorporates a 3.5 m telescope cooled to 4.5 K. HII/L2 will focus on high-resolution mid- to far-infrared observations with unprecedented sensitivity. It will make great contributions to our understanding of basic astronomical questions, such as the history of star-formation in the universe, the birth and evolution of AGN, the formation of planets in extrasolar systems, and the history of our solar system.
To realize the mission, 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. HII/L2 is proposed to be launched into a halo orbit around S-E L2 in 2010.

1. INTRODUCTION

Since the success of the all-sky survey by the Infrared Astronomical Satellite (IRAS, 1983), 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, 2000), a survey mission of ISAS with a 70 cm telescope, 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 moderate (30 arcsec to several arcmin in the far-infrared). Hence, for high-resolution observations, a mission with a much larger telescope has been long-awaited.

* Although the mission was renamed "SPICA" (Space Infrared Telescope for Cosmology and Astrophysics) during the conference, the old name "HII/L2" is used in the current paper.

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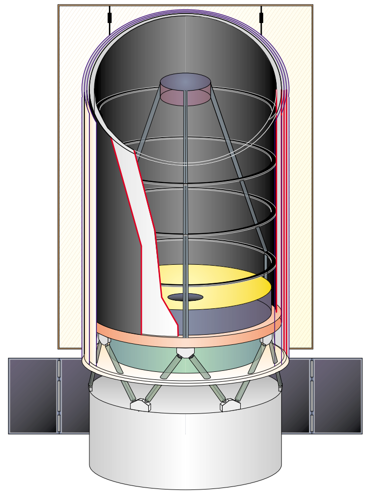

Fig. 1: Conceptual design of the HII/L2 mission with a 3.5 m primary mirror.

High spatial resolution is important especially in the far-infrared for the following two reasons: one is to study each object in detail, the other to achieve a good sensitivity, since the far-infrared sensitivity of most space-borne missions is limited by the confusion of sources.

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 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 especially in the mid- and the far-infrared.

We propose here a new space observatory, the 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

HII/L2, with its cold, large telescope, will be a unique observatory which will enable high-resolution, high-sensitivity observations in the mid- to far-infrared. Figure 1 shows a conceptual design of HII/L2.

There are a variety of scientific goals that can uniquely be explored by HII/L2. 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, since it determines the evolution of galaxies and the production rate of heavy elements. Most of the previous studies were based on optical observations (e.g. Madau et al. 1996), which traced ultraviolet radiation in 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

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reveal the star-formation history reliably even at high-redshift. The high spatial resolution of HII/L2 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. HII/L2 covers most of the PAH features at any redshift, and will enable high-sensitivity determination of the redshift of galaxies at high z with high efficiency.

2.2 Birth and Evolution of AGN

AGN are one of the dominant 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) even in very dusty galaxies (e.g. Genzel et al. 1998), but these observations were limited to the local universe. The high-sensitivity of HII/L2 will enable this type of observation even for high-redshift galaxies and will reveal how and when AGN were formed in the early universe.

2.3 Formation of Planetary Systems in Extrasolar Systems

Discoveries of "Vega-like stars" evoked much discussion on the formation process of proto-planetary systems. The high sensitivity of HII/L2 will increase the number of "Vega-like stars" dramatically and will enable a statistical study of the phenomenon. More importantly, the high-resolution capability of HII/L2 in the mid-infrared will reveal the density and temperature profiles of the dusty disks, which are essential to understand the formation process of planetary systems.

One more important capability of HII/L2 is that it is expected to detect extrasolar planets directly. We now have $\sim$50 giant planet candidates in extrasolar systems through "indirect" methods. HII/L2 will enable the first "direct" detection of extrasolar planets beyond $\sim$2 AU around nearby ($\sim$ 5pc) stars (see Tamura 2000 for details). The direct comparison of planets in extrasolar systems with those in our solar system, which will be possible by mid-infrared spectroscopy of planetary atmospheres also by HII/L2, will reveal how unique (or ubiquitous) our solar system is.

2.4 History of Our Solar System

The best way to understand the history of our solar system is to observe "primitive" objects which can throw light on the conditions in the early solar nebula. The Edgeworth-Kuiper Belt Objects (EKBOs) are the best candidates for this purpose. High-sensitivity observations by HII/L2 in the mid- and far-infrared will be indispensable to estimate two important parameters of EKBOs: albedo and temperature. These two parameters will provide information on the substrate of EKBOs and their chemical reaction history.

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Table 1: Summary of current specifications of HII/L2.

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 L2 Halo
Cooling	Radiative Cooling and Mechanical Coolers
Total Mass	2,600 kg
Telemetry Rate	30 G bytes day^{-1}
Launch Vehicle	H-IIA Rocket
Launch Year	2010

2.5 Discovery Potential

The capability of the 3.5 m telescope of HII/L2 is a big jump from those of previous missions with smaller telescopes (< 1 m). Moreover, HII/L2 is a very efficient observatory with its wide field of view ($6'$). Hence, HII/L2 has a great potential to discover mysterious objects serendipitously. Since HII/L2 can make both photometric and spectroscopic observations, with a wide sky coverage visible at each epoch, we can make efficient follow-up observations of any "serendipitously found objects" with HII/L2 itself.

3. OUTLINE OF THE HII/L2 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 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 themselves significantly. Moreover, their mission lives were relatively short and 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 HII/L2 mission based on the above discussion and Table 1 summarizes its specifications. 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 most important characteristics of this mission is that its telescope is cooled down to

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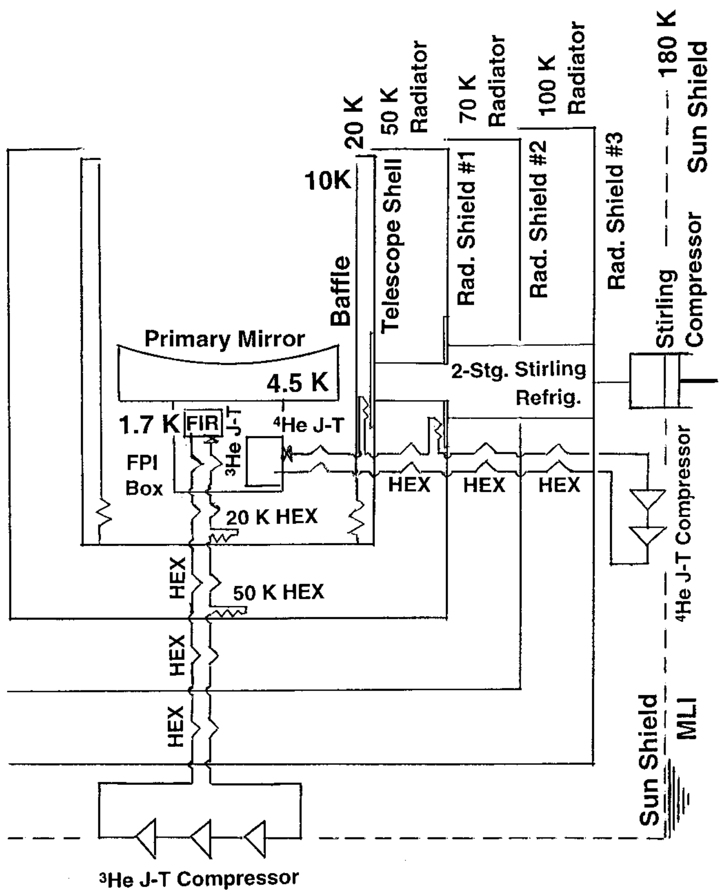

Fig. 2: Schematic drawing of the cryogenic system of the HII/L2 mission. The telescope is enshrouded with multi-layered radiators. One set of a JT cooler (with ^{4}He) and a two-stage Stirling cycle is used to cool the telescope and some of focal plane instruments to 4.5 K. Another set of a JT cooler (with ^{3}He) and a two-stage Stirling cycle is used to cool the far-infrared detectors to 1.7 K.

4.5 K and hence the mission is suitable especially for mid- to far-infrared observations.

The "warm launch" 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.

We do not employ a deployable mirror design as in NGST, but use a conventional "monolithic mirror" design, in order to make the mission technically feasible and reliable. A lightweight mirror system with a launching lock mechanism proposed for HII/L2 is discussed in detail by Mikami et al. (2000).

4. CRYOGENIC SYSTEM

4.1 Configuration

The biggest technical challenge for the success of the HII/L2 mission is the cryogenic system to cool the observing system. Here we outline the concept of the cryogenic system of HII/L2. De-

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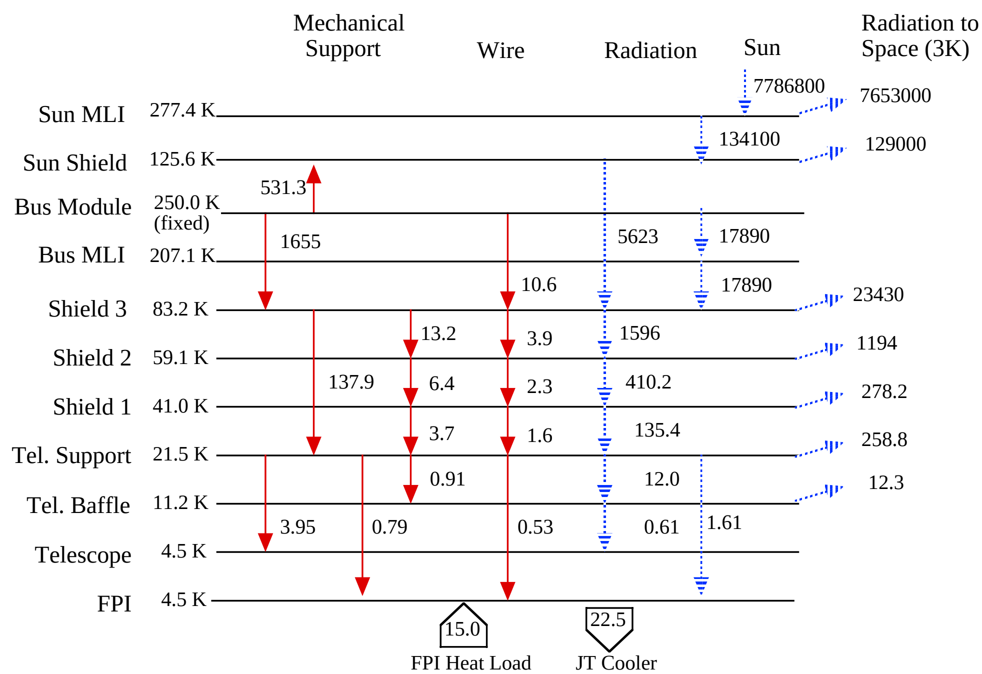

Fig. 3: Heat flow (unit: mW) diagram of the HII/L2 mission cooled by radiation and cryogenic coolers. Black arrows show the heat flow by conduction and shaded arrows show the heat flow by radiation. We assume a structure of the conceptual design (Figure 1)

tails of the cryogenic system are discussed by Murakami & Narasaki (2000) and by Hirabayashi et al. (2000).

In order to cool the observing system, we plan to use (1) radiative cooling and (2) mechanical cryocoolers. Figure 2 shows a schematic drawing of the cryogenic system and Figure 3 shows the heat flow diagram 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 HII/L2. 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 at S-E L2. 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 is through radiation at various temperature stages, and the cooling power required for mechanical coolers 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

Mechanical cryocoolers are key elements in the cryogenic system of HII/L2. 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

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it is now under extensive tests. The cooling power is about 200 mW at 20 K. We plan to use this type of cooler 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. Typical 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 HII/L2. Typical 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 HII/L2 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 HII/L2 will be 5–200 μm and we plan 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 high-resolution, 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 single-segment, cold optics of the HII/L2 telescope 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 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 also now under study. See Ueno et al. (2000) for details of focal plane instruments.

6. COMPARISONS WITH OTHER MISSIONS

Figure 4 shows the photometric sensitivity of HII/L2 for point sources as a function of wavelength. The noise is dominated (1) by detector noise at the shortest wavelength, (2) by photon fluctuation of zodiacal light radiation at mid-infrared, and (3) by "confusion noise" at the longer wavelengths. Since HII/L2 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 near-infrared (core wavelength range of 1-5 μm) observations and can achieve very deep observations in near-infrared 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 will degrade the sensitivity at mid- and far-infrared wavelengths (see dotted lines in Figure 4). On the other hand, HII/L2 has good sensitivity

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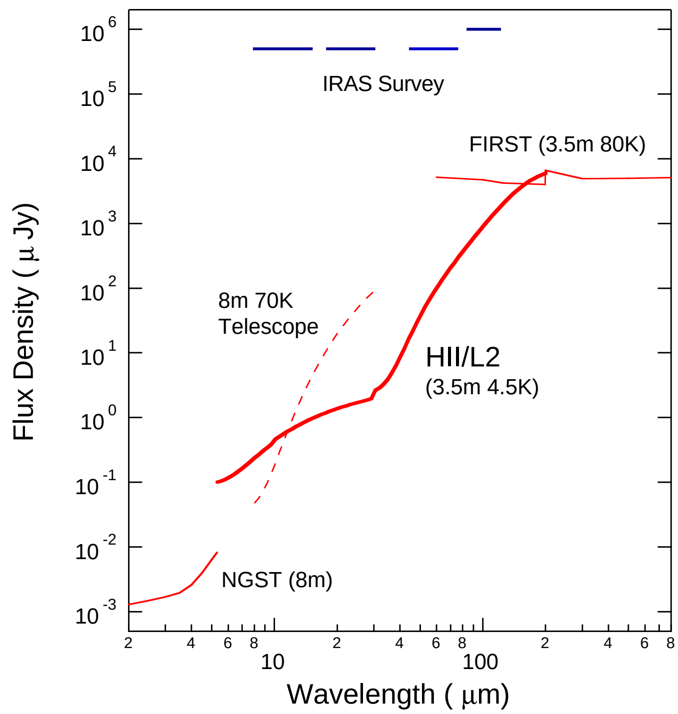

Fig. 4: Comparison of point-source sensitivity (5 σ flux density at 3,600 s integration) of various infrared missions. Diffraction-limited observations with $\lambda/\Delta\lambda = 5$ is assumed for HII/L2.

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, HII/L2 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 make these important missions possible and also to make well-organized observations with these three unique missions.

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