HII/L2 mission: future Japanese infrared astronomical mission

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ABSTRACT

We present a conceptual design of a future Japanese infrared astronomical satellite: the HII/L2 mission. We propose a "warm launch" cooled telescope; the telescope is to be launched at ambient temperature and is to be cooled in orbit to 4.5K by a modest cryogenic cooler with the help of radiative cooling. Since liquid helium and hence a heavy vacuum vessel are no longer required, the warm launch design reduces the weight of the satellite dramatically. We propose to launch this satellite into a halo orbit around S-E L2, one of the Sun-Earth Lagrangian liberation points. The S-E L2 is an ideal orbit for infrared astronomy, since (1) radiative cooling can become very effective, and (2) long-integration observations become possible. A 3.5 m class telescope can be put into a halo orbit around S-E L2 by the Japanese H-IIA launching vehicle. This mission focuses on high-resolution mid- to far-infrared observations with unprecedented sensitivity, since the large aperture reduces confusion noise and the cooled optics suppresses instrumental background radiation. The HII/L2 mission is an ideal observatory-type platform to make follow-up observations to the ASTRO-F/IRIS survey mission. The target launch year is 2010.

Keywords: infrared astronomical satellite, HII/L2 mission, warm launch, S-E L2

1. INTRODUCTION

1.1. Scientific Requirements for Large Infrared Telescopes

The *Infrared Astronomical Satellite* (IRAS[1], 1983) opened a new era of infrared astronomy. IRAS made the first all-sky survey in the mid- and far-infrared, and detected some 250,000 sources. Next, the *Cosmic Background Explorer* (COBE[2]) was launched in 1989, and made the first absolute photometric measurements of the whole infrared sky.

The infrared astronomical community in Japan launched a small infrared survey mission, the *Infrared Telescope in Space* (IRTS[3]) in 1995, and now promotes the ASTRO-F/IRIS[4] (*Infrared Imaging Surveyor*) project. ASTRO-F/IRIS is also a survey type mission, and has much better sensitivity and spatial resolution than those of IRAS. ASTRO-F/IRIS is scheduled to be launched in 2003, and is expected to detect millions of sources, and to discover many interesting objects.

To study in detail the interesting objects found in these survey missions, an observatory-type mission is needed. The first observatory-type infrared mission was the *Infrared Space Observatory* (ISO[5]), which was launched in 1995.

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The success of ISO demonstrated the effectiveness of an infrared observatory-type satellite. The *Space Infrared Astronomical Facility* (SIRTF[6]), which is now scheduled for launch in 2001, will also make many important observations.

But the mirror size of these missions (60 cm for ISO, and 85 cm for SIRTF) is much smaller than those of optical and radio telescopes, and hence the spatial resolution of infrared observations from space has been very poor. Thus, infrared astronomers have longed for observatory-type missions with much larger telescopes to make high resolution observations.

High spatial resolution is also important to achieve good sensitivity in the far-infrared, since the sensitivity of a well-designed space-borne mission is limited by confusion of sources[7]. In this case, longer integration does not improve the detectivity, and better spatial resolution with a large aperture telescope is the only way to improve the sensitivity.

Two large missions for infrared and sub-mm regions are now proposed for the launch by 2010. They are the *Next Generation Space Telescope* (NGST[8]) and the *Far-Infrared and Sub-mm Space Telescope* (FIRST[9]). They are powerful observatories, but their telescopes are only moderately cooled, and thermal radiation from the telescopes degrades the sensitivity especially in mid- and far-infrared.

Therefore, there has been a great demand for an observatory-type mission with a large aperture cooled telescope for mid- and far-infrared astronomy.

1.2. Constraints of Conventional Infrared Astronomical Satellites

In spite of large demand for large infrared telescopes, it is not easy to realize this type of mission. To achieve high sensitivity in the mid- and far-infrared, we have to cool the whole telescope and focal plane instruments down to liquid helium temperatures. Hence, all of the infrared astronomical satellites flown so far carried liquid helium. Consequently, these conventional satellites had the following severe constraints.

1. The aperture size of the telescopes is small. Large amounts of liquid helium require big tanks. Moreover, liquid helium requires heavy vacuum vessels, needed only on the ground and not in space. This makes the satellites bigger and heavier, and reduced their telescope sizes. For example, in the case of the ASTRO-F/IRIS mission, the observing instrument weighs only 35 kg but the whole cryogenic system weighs more than 400 kg.
2. The mission life is limited by the hold time of the liquid helium.
3. Observations with long integration time are very difficult, since the satellites have to avoid the radiation not only from the sun but also from the earth, otherwise their radiative heat load evaporates the liquid helium very quickly.

Thus, on the basis of the conventional design concept, it is very difficult to make an observatory type infrared astronomical mission which has a large aperture telescope and can make long-integration observations with a long mission life. We need a totally new design concept to realize the "Infrared Astronomical Observatory" mission.

2. ORBIT

2.1. Orbits of Previous Infrared Missions

It is critical for infrared astronomical satellites to avoid radiation both from the sun and from the earth to minimize the heat load. This is a very difficult task for a satellite in a near-Earth orbit with low inclination (e.g., IRTS[3]).

For this reason, solar-synchronous orbits were chosen for IRAS[1] and COBE[2]. The solar-synchronous orbit is the most suitable for these infrared survey missions among various near-Earth orbits, because (1) the avoidance angles for the sun and the earth do not change very much, and the heat input by radiation can be kept relatively small, and (2) one can survey the whole sky in half a year without violating the avoidance-angle condition. We also chose the solar-synchronous orbit for the Japanese infrared survey mission ASTRO-F/IRIS[4].

Although the solar-synchronous orbit is suitable for survey missions, it is not for observatory-type missions, since observations with long integration times are very difficult in such an orbit to avoid radiation from the earth. For example, the longest integration which ASTRO-F/IRIS can make is only 10 minutes.

ISO was launched into a high-earth elliptical orbit. The long orbital period (about 24 hours[5]) enables ISO to make long integration. But ISO has to go through the earth's radiation belt in every orbit, and a high dose of ionizing radiation makes stable operation of detectors very difficult.

Therefore, we have to go away from the earth to make stable observations with longer integration.

2.2. Sun-Earth Lagrangian liberation point L2

First, we propose one of the five Sun-Earth Lagrangian liberation points (L2) as an orbit for an observatory-type infrared mission.

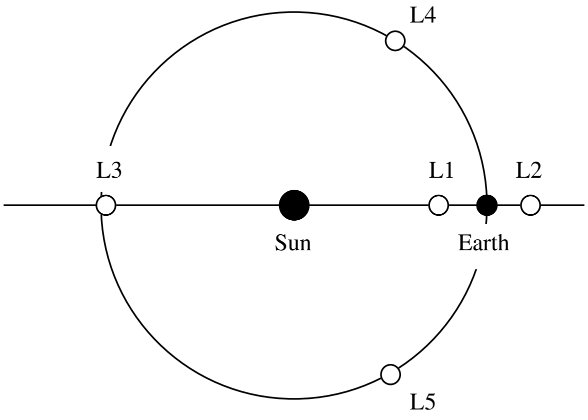

Figure 1. Sun-Earth Lagrangian liberation points.

Figure 1 shows the five Lagrangian liberation points of the Sun-Earth system. The nearest points to the earth among them are L1 and L2 points, which are about 1.5×10^6 km from the earth. They are on a straight line connecting the sun and the earth, and are thus metastable. But it requires a very small Δv (several m s^{-1} year^{-1}) to keep a satellite around them[10].

Among them, L2 (hereafter S-E L2; the point at the opposite side of the sun from the earth) is the best place for infrared astronomy for the following reasons:

1. Effective cooling by radiation
   The apparent size of the earth, which is one of the dominant heat source for satellites near the earth, becomes small ($\sim$ 30'), and all of the heat sources (Sun, Earth, Moon) are almost in the same direction. Hence, it is very easy to shield the telescope from the heat sources, and the radiative cooling becomes very efficient. Our simple estimate (Figure 2) shows that, if the telescope is properly shielded from the solar radiation, the temperature of the telescope can be cooled as low as 20 K only by the radiative cooling.

2. Long integration time
   Since the sun and the earth are in almost the same direction, large areas of the sky can be observed. With the help of a stable gravitational condition at the S-E L2, very long integration is possible.

Therefore, we conclude that S-E L2 is the best orbit for observatory-type infrared missions.

2.3. Technical Feasibility

One more advantage of the S-E L2 orbit is that we can launch relatively large mass into the orbit in spite of its large distance from the earth.

Table 1 shows the estimated mass which the Japanese latest launching vehicle, H-IIA, can carry into the S-E L2 orbit. The H-IIA series consists of three types of vehicles with different launching capabilities. Even the smallest of them, 2 t class, which can launch a 2 t satellite into a geosynchronous orbit, can put a 2.5 t satellite into the S-E

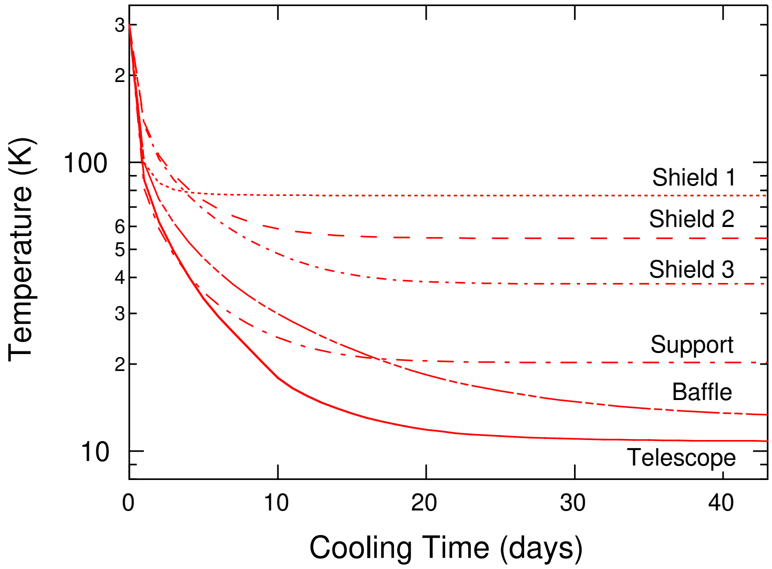

Figure 2. Temperature profile of a model payload with an effective shielding system. It is cooled only by radiation.

Table 1. Launching capability of the H-IIA series. W_0 is the mass of a satellite which can be launched into a transfer orbit to S-E L2, and ΔW is the mass of fuel required to put the satellite into a halo orbit around S-E L2 from the transfer orbit.

Class	2 t class	3 t class	4 t class
W_0	2,800 kg	5,700 kg	7,600 kg
ΔW	300 kg	500 kg	700 kg
$W_0 - \Delta W$	2,500 kg	5,200 kg	6,900 kg

L2 orbit. In other words, we can launch heavier satellites into the S-E L2 orbit than those into the geosynchronous orbit.

In spite of the large distance to the S-E L2 point, down link from a satellite to the earth is not a serious problem, since one ground station can contact the satellite for 8 hours a day. With a 40 cm aperture high-gain antenna on-board the satellite and the 64 m dish of the Japanese deep space ground station at Usuda, about 3 Gbytes of data per day can be sent from the satellite to the ground.

One point we should mention here is that the S-E L2 point itself is not a good orbit. Since the sun and the earth are in the same direction, command receivers, which have to receive signals from the earth, suffer large noise from the sun. Hence halo or Lissajous orbits around the S-E L2 are more appropriate for infrared missions.[10]

3. WARM LAUNCH

Next, we propose a "warm-launch, cooled telescope" design concept for the new infrared satellite. This concept means that the telescope and focal plane instruments are warm when the satellite is launched, but are cooled in orbit. SIRTF also has a warm-launch, cooled telescope, but still has a vacuum vessel and a liquid helium tank to cool its focal plane instruments[6]. Here we propose a satellite with no liquid helium. The satellite does not need heavy vacuum vessels and He tanks any more, and the mass of the satellite can be reduced dramatically. Hence we can increase the size of the telescope to a level which can be never achieved with the conventional infrared telescope design.

We have two methods to cool the telescope in orbit:

2. Cryogenic Mechanical Cooler

1. Radiative Cooling
   As mentioned in the previous section, radiative cooling works very effectively at the S-E L2. Radiative cooling alone can cool the telescope to 20 K, which is low enough for near-infrared observations.

2. Cryogenic Mechanical Cooler
   To cool the telescope and focal plane instruments below 20 K, we propose to use cryogenic mechanical coolers. Two-stage Stirling cycle coolers are to be onboard the ASTRO-F/IRIS mission[4]. The cooler is now under extensive checkouts, and is to be flight-proven in 2003. Since the lowest temperature of the two-stage Stirling cycle is above 10 K, we are now developing a Joule-Thomson type cooler to achieve lower temperature. Figure 3 shows the test configuration and its results; we successfully demonstrated a cooling power of 15 mW at 4.8 K.

The effective radiative cooling at the S-E L2 point makes the cryogenic coolers work more efficiently. Hence, even with the cryogenic coolers, it is very important to cool most of the observations instrument by radiation.

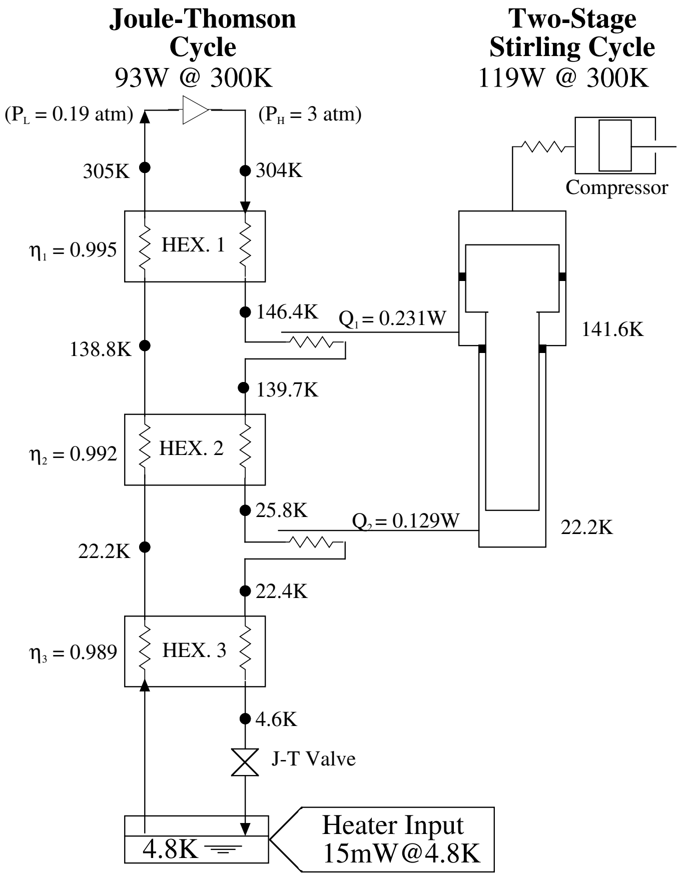

Figure 3. Test results of a Joule-Thomson cooler designed for space applications. We used a two-stage Stirling cycle to cool two intermediate stages of the Joule-Thomson cycle. We put 15 mW of heat load to the coldest stage.

4. HII/L2 MISSION

4.1. Conceptual Design

Following the above discussions, we propose a new infrared astronomical mission; it is a "warm-launch" type mission to be put into the S-E L2 halo orbit. The "warm-launch" concept enables a satellite to have a large-aperture telescope, and the stable environment around the S-E L2 orbit allows the mission to make deep observations with long integration time. The combination of cryogenic coolers and the effective radiative cooling can keep the "warm-launched" telescope very cool in orbit, and makes the mission suitable especially for mid- to far-infrared observations.

We plan to use the new Japanese H-IIA rocket to launch the satellite in to the S-E L2 halo orbit. We thus call this mission the "HII/L2 mission". Even the smallest type of the H-IIA series can launch a 2.5 t satellite into the S-E L2 orbit (Table 1).

The payload fairing of the H-IIA rocket can accommodate a telescope with a 3.5 m primary mirror. On the basis of our experience with the 70 cm SiC mirror for the ASTRO-F/IRIS telescope[11], we estimate the mass of a telescope system with a 3.5 m monolithic SiC mirror to be about 1 t. This estimate is rather conservative, since some active support systems for the primary mirror can reduce the mirror mass while keeping the image quality good enough for $\lambda > 5$ μm. We are also studying the feasibility of a deployable mirror to increase the telescope aperture as large as 8 m. In the following, we take a conventional 3.5 m mirror design as a baseline (Table 2).

Figure 4 shows a conceptual design of the HII/L2 mission. Since this is a "warm-launch" type satellite, the telescope itself occupies a significant fraction of the total volume. This situation is completely different from that of the conventional infrared astronomical satellites, in which not the telescope but the cryogenical system occupies a dominant fraction of the total volume.

Figure 5 shows heat flows of the model payload based on the conceptual design of Figure 4. We assume effective shielding of solar radiation so that we can cool the instrument effectively by radiation. We also assume a Joule-Thomson type cooler together with a two-stage Stirling cycle as in Figure 3. Figure 5 indicates that *we can cool the whole telescope and the focal plane instruments down to 4.5 K by a modest cryogenic cooler system, such as shown in Figure 3, with the help of effective radiative cooling.* The heat dissipation by the focal plane instruments at the 4.5 K stage can be as high as 15 mW. If lower temperature is required for some focal plane instruments, we plan to use another cooler such as a Joule-Thomson type cooler with ^{3}He.

Table 2 summarizes the current specifications of the HII/L2 mission.

Table 2. Summary of current specifications of the HII/L2 mission.

Mirror Size (Baseline)	3.5 m
$T_{\rm Mirror}$ in Space	4.5 K
$T_{\rm Mirror}$ at Launch	300 K
Core Wavelength	5-200 μm
Orbit	S-E L2 Halo
Cooling	Radiative Cooling and Cryogenic Coolers. No liquid helium
Mass Budget	
Telescope	1,100 kg
Focal Plane Instrument	100 kg
Mission Structure	400 kg
Spacecraft	600 kg
Fuel	300 kg
Total	2,500 kg
Telemetry Rate	3 G bytes day^{-1}
Launching Vehicle	H-IIA rocket
Launch Year	2010

4.2. Sensitivity

A cooled 3.5 m telescope is a huge jump from previous infrared astronomical missions with small telescopes.

Figure 6 shows the photometric sensitivity of the HII/L2 mission 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[7]" at the longer wavelength.

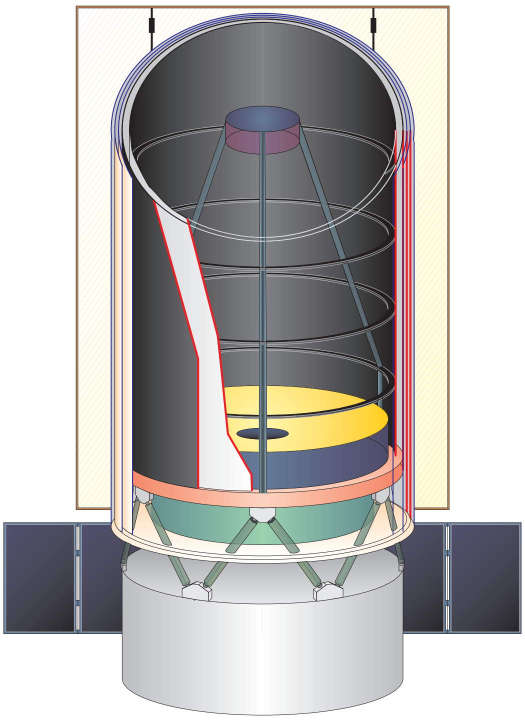

Figure 4. Conceptual design of the HII/L2 mission with a 3.5 m primary mirror.

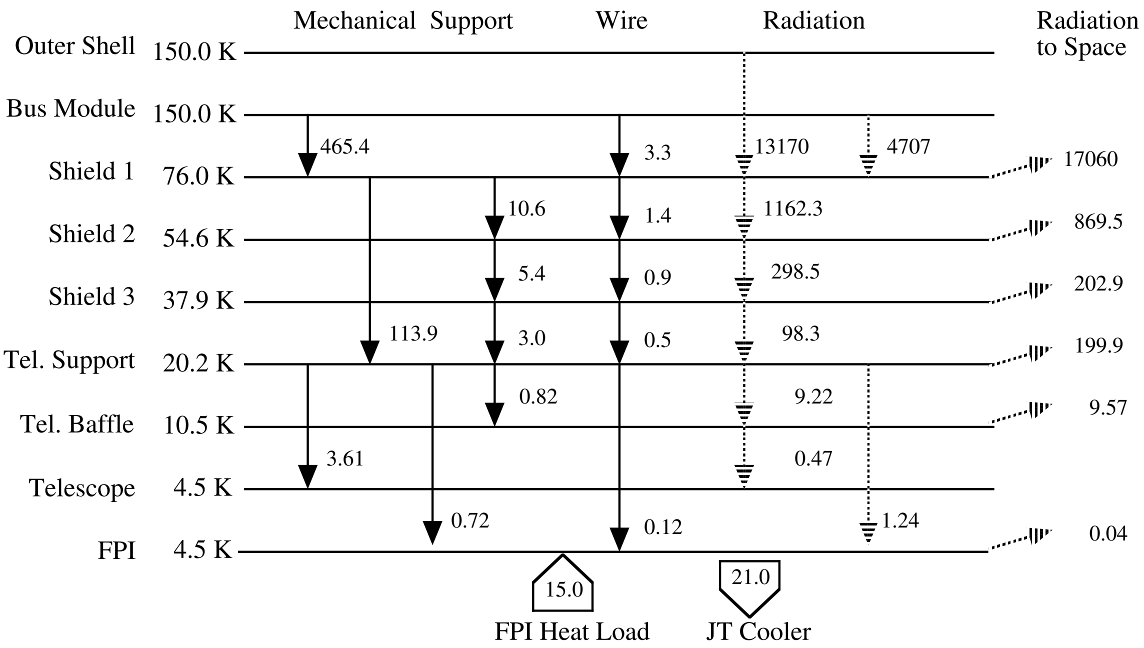

Figure 5. Heat flow (unit: mW) diagram of the HII/L2 mission cooled by radiation and cryogenic coolers. Black arrows show the heat flow by conduction and dotted arrows show the heat flow by radiation. We assume a structure of the above conceptual design (Figure 4) and to use a cryogenic cooler similar to that in Figure 3.

Since the HII/L2 has a cooled telescope, it can achieve superior sensitivity throughout the infrared wave band. With these sensitivities, we can make many, important observations. For example, HII/L2 is an optimum platform to challenge the direct detection of Jupiter-like planets in extrasolar planetary systems. The advantage of HII/L2 is that it has very good sensitivity at wavelength longer than 10 μm, where the ratio of planet to stellar flux increases significantly. The stable condition at S-E L2 allows us to use a coronagraphic camera in the diffraction-limited regime and to suppress the stellar flux efficiently. The high spatial resolution of HII/L2 (0.7" at 10 μm) offers the possibility to detect a planet 10 AU away from a star at the distance of 10 pc.

High resolution, diffraction-limited observations with a large aperture telescope are very important also in the far-infrared, where the sensitivity is limited by the confusion noise. At 50 μm, HII/L2 has excellent sensitivity (40 μJy) and good spatial resolution (3.6"). We can make detailed mapping observations of important objects, such as protostars and ultra luminous infrared galaxies, which are relatively weak at other wavelengths.

Spectroscopic observations are one of the key roles of the HII/L2 mission. The HII/L2 mission covers a unique wavelength range which includes many vibrational-rotational transitions of important molecules (in near- and mid-infrared) as well as many rotational transitions of light molecules (in far-infrared). Hence the HII/L2 mission will play an essential role to understand interstellar chemistry and physics. It will also serve as a unique tool to study circum-stellar material in detail.

The HII/L2 mission can also detect many fine structure lines from ions and atoms. Since these lines cover various stages ionization, they are useful tools to study physical conditions of various phases of interstellar gas. The lines also give us important information on energy sources of deeply embedded source, such as ultra luminous infrared galaxies, which cannot be studied in shorter wavelength due to large extinction.

The HII/L2 mission covers most PAH features. The features themselves are very important to understand interstellar chemistry and physics. Moreover, they can be used as very powerful tools to determine the redshift of many, faint galaxies. Since the equivalent width of the feature is very large, the features can be measured by low-resolution spectroscopic observations. Hence, using the PAH features, we can achieve good sensitivity and very high efficiency to determine the redshift of galaxies, and can reveal the history of galaxy formation and evolution.

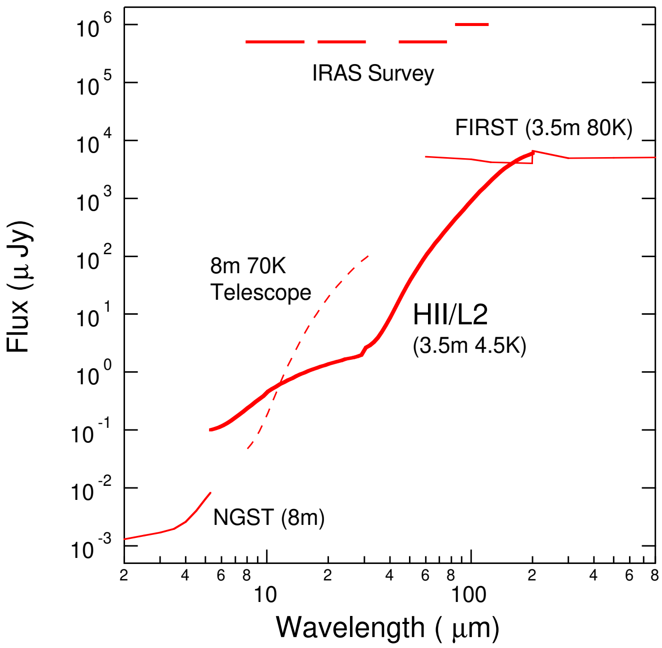

Figure 6. Comparison of point-source sensitivity (5 σ flux at 3,600 s integration) of various infrared missions. Diffraction-limited observations with $\lambda/\Delta\lambda = 5$ is assumed for the HII/L2 mission. An 8 m telescope at 1 AU is assumed for NGST[8].

4.3. Complementarity with Other Missions

Two other large missions (NGST[8] and FIRST[9]) for infrared and sub-mm regions have been proposed to be launched by 2010. Table 3 summaries characteristics of these missions together with those of the HII/L2 mission. Figure 6 compares the sensitivity of the three missions. Table 3 and Figure 6 shows that each mission has its own unique capability. NGST has its weight on near-infrared (1-5 μm) observations, and can achieve very deep observations with high spatial resolution[8]. On the other hand, FIRST has its weight on longer wavelengths, and can make high-resolution spectroscopic observations as well as photometric observations[9].

However, both NGST and FIRST have only moderately cooled telescopes, and thermal radiation from the telescopes degrades the sensitivity very much at mid- and far-infrared (see dotted lines in Figure 6). On the other hand, the HII/L2 mission has good sensitivity throughout the infrared region, and achieves supreme sensitivity especially in mid- to far-infrared region, since it has a cooled telescope. Hence, the HII/L2 mission is complementary with NGST and FIRST, and we need these three missions to cover the whole infrared region with good sensitivity and high spatial resolution. International collaborations are essential to make these important missions possible, and also to make well-organized observations with these three unique missions.

Table 3. Comparison of large astronomical missions planned for infrared and sub-mm range.

Mission	Aperture Size	Temperature of the Telescope	Core Wavelength	Launch Year
NGST[8]	6-8 m	< 70 K	1-5 μm	2007
HII/L2	3.5 m	4.5 K	5-200 μm	2010
FIRST[9]	3-3.5 m	80 K	80-600 μm	2005

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