Studies of Exoplanets and Solar Systems with *SPICA*: An Overview

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ABSTRACT

SPICA will be a powerful facility to help us understand the formation and evolution of our solar system and exoplanetary systems in 2020's. The wavelength coverage (5–210 μm) is optimal for observations of key targets including exoplanets, protoplanetary and debris disks, and solar system small bodies. At this coverage *SPICA* will offer several dramatic advantages, including extremely high sensitivity and excellent image quality with a cooled (~6 K) monolithic 3-m class mirror telescope, a variety of capabilities for spectroscopy and spectro-imaging, and an unprecedented high spectral resolution for mid-infrared spectroscopy free from telluric absorption and emission. We briefly summarize our discussions for possible science impacts on the above targets and research topics.

1. INTRODUCTION

One of the ultimate goals for modern astronomy and astrophysics is understanding the formation and evolution of our solar system and exoplanetary systems. We have made dramatic progress in the past decades, with discoveries of a number of exoplanetary systems and solar system small bodies (in particular "Trans-Neptunian Objects" or TNOs), and extensive studies of these objects and protoplanetary/debris disks. We also expect significant progress over the next decade with the advent of the Atacama Large Millimeter/sub-millimeter Array (ALMA) and *James Webb Space Telescope* (*JWST*), and also through detailed analysis of data recently obtained using the *Herschel Space Observatory*.

The SPace Infrared telescope for Cosmology and Astrophysics (*SPICA*) is a proposed mission for mid-to-far infrared (5–210 μm) astronomy, consisting of a single 3-m class aperture space telescope with cooled (~6 K) instrumentation. The instruments presently proposed for installations are the Mid-infrared Camera and Spectrograph (MCS), which includes the Wide-Field Camera (WFC), the Medium-Resolution Spectrograph (MRS), and the High-Resolution Spectrograph (HRS) (see Kataza et al., this volume); the SpicA FAR-infrared Instrument (SAFARI; Roelfsema et al., this volume); the *SPICA* Coronagraph Instrument (SCI; Enya et al., this volume); and the Focal Plane Camera for Science (FPC-S; Lee et al., this volume). See Nakagawa et al., this volume, for a summary of the specification for the mission and the above instruments. Figure 1 shows the spectral energy distributions (SEDs) of our target objects compared with the wavelength coverage for *SPICA*, *JWST*, *Herschel* and ALMA. The figure shows that *SPICA* will cover essential wavelengths for studies of these targets, particularly at the wavelengths where the most energy is emitted. Furthermore, studies with *Spitzer Space Telescope*, *Heschel Space Observatory* and gound-based telescope have confirmed a number of spectral features in the wavelength coverage of *SPICA* which are useful for detailed studies of the target objects (see later sections).

The strengths of *SPICA* compared with the other missions are: (1) extremely good sensitivity at 20–210 μm; (2) a capability for spectro-imaging with a Fourier type imaging spectrograph (SAFARI) at 34–210 μm; (3) a high spectral resolution ($R \sim 30,000$) at 12–18 μm provided by MCS-HRS; (4) capabilities for mid-infrared coronagraphic spectroscopy provided by SCI; and (5) a wide-field of view for imaging capabilities at 2–210 μm. Such specifications will complement *JWST*, which is expected to have an extremely good sensitivity at 20 μm or shorter wavelengths, and *Herschel*, which covered wavelengths up to 672 μm. At 57–210 μm *SPICA* is expected to improve the sensitivities provided by *Herschel* by a factor of 10–100, thereby significantly improving the studies of disks and solar system small bodies being made using the *Herschel* data.

The science cases for *SPICA* for the above targets have been extensively discussed over the past several years. The documents open to public include Swinyard et al. (2009); Goicoechea et al. (2009); Takami et al. (2010), and the White papers and the Yellow Books for which the European Consortium lead the publications. The internal documents with science cases include the Mission Required Documents for Japan Aerospace eXploration Agency (JAXA), and the proposals for individual instruments recently submitted to the international review committee. Based on the above documents and some recent additional discussions, we present a brief summary for the possible science impacts with *SPICA* based on the specifications being confirmed.

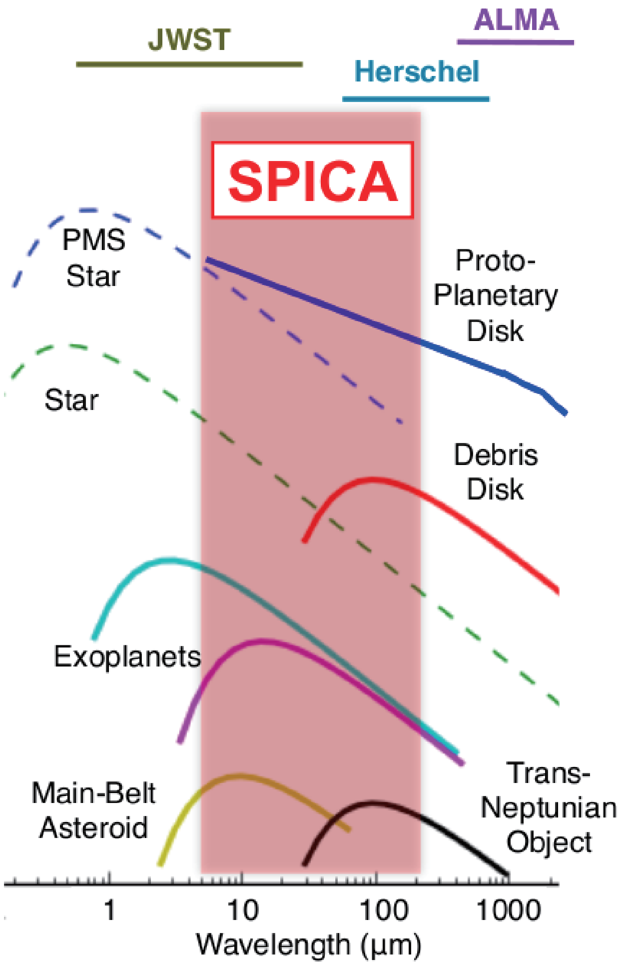

Figure 1. Schematic view of the SEDs of the various targets and the wavelength coverage of *SPICA*, *JWST*, *Herschel* and ALMA.

2. EXOPLANETS

In the last decade approximately 1000 exoplanets have been detected, mainly through measurements of radial velocity and photometry (i.e., the observations of transiting events) of parent stars[1,2]. The number of confirmed planets will significantly increase in the next few years due to the ~3000 candidates discovered during the Kepler mission[3]. While the majority of the exoplanets discovered to date seem to be gas giants like Jupiter and Saturn[1], some exoplanets with lower masses seem to be icy and rocky planets. The detection limits for mass and radii are now comparable to Earth and Mercury, respectively (Barclay et al. 2013). The habitability of some exoplanets has also been discussed (e.g., Wang et al. 2013).

In addition to the above techniques, direct imaging (coronagraphy) of exoplanets has also been progressing rapidly (e.g., Currie et al. 2012; Kuzuhara et al. 2013). Despite the severe contrast problem of the parent stars, such observations have allowed us to observe young exoplanets with large orbital radii. This dimension is complementary to the radial velocity and transiting methods, which are sensitive to small radii, and valuable for testing theories of the formation of exoplanets (see, e.g., Ida et al., this volume).

Our challenge for the next decade should be detailed characterisation of exoplanets, in particular with spectroscopy. This will allow us to investigate their temperatures, surface gravity, atmospheric compositions, climates etc. While spectroscopic observations have been made of some "hot Jupiters" (e.g., Bean et al. 2013), gas giants with small orbital radii, astronomers have just begun to obtain spectra of exoplanets similar to those in our solar system (e.g., Konopacky et al. 2013). We expect that coronagraphic observations from the ground will allow us to observe spectra of many exoplanets over the next decades. However, overwhelming thermal emission from the telluric atmosphere and telescopes hampers observations in the mid-infrared, thereby excluding most of the relatively cool and old planets (t ~1 Gyr or later) whose ages are closer to our solar system, and also icy giants analogous to Uranus and Neptune.

[1] http://www.exoplanet.eu/
[2] http://phl.upr.edu/projects/habitable-exoplanets-catalog/
[3] http://kepler.nasa.gov/

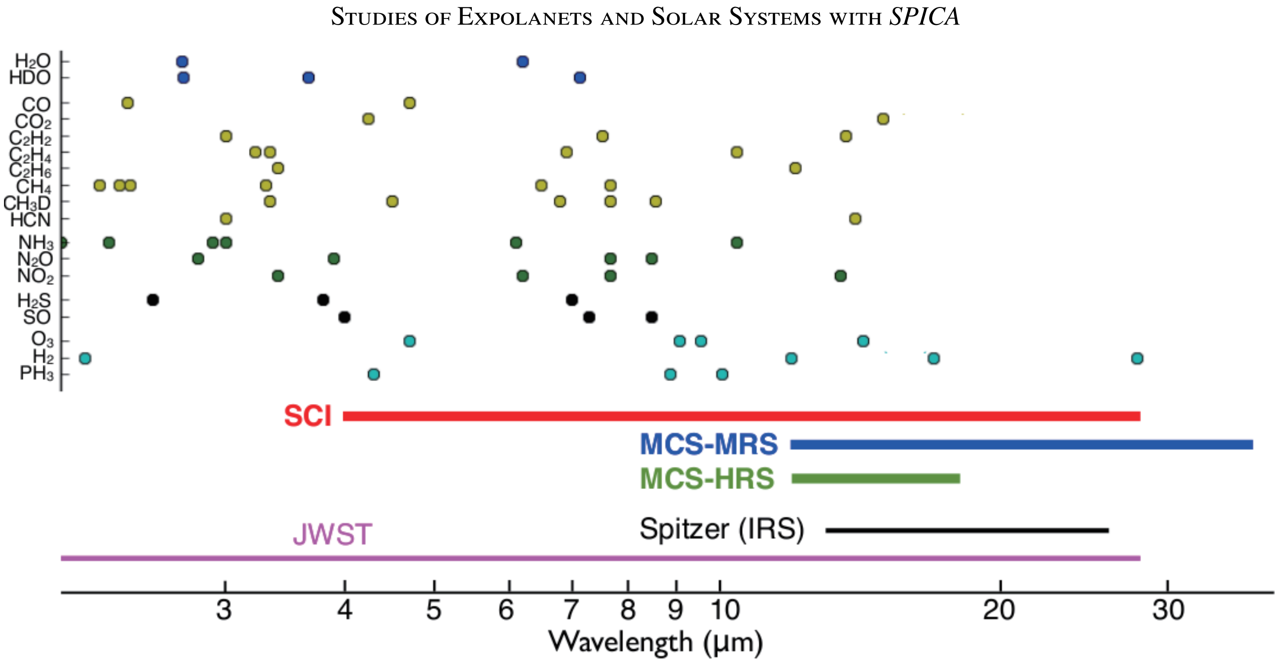

Figure 2. Wavelengths of absorption lines and bandheads for various molecules which could be associated with the exoplanetary atmospheres (adapted from Tinetti et al. 2012). The wavelengths coverage of *SPICA* instruments, *Spitzer* and *JWST* are also shown. Of the instruments above only *SPICA*-SCI will be capable of direct spectroscopy of exoplanets.

Together with *JWST*-MIRI, *SPICA*-SCI will be a powerful tool to explore this dimension, i.e., coronagraphy in the mid-infrared. Observations using space telescopes are free from speckle and thermal noise caused by telluric atmosphere effects, thereby dramatically improving the sensitivity. While *JWST* will offer a better inner working angle, *SPICA*-SCI will offer a spectroscopic capability at 4–28 μm ($R \sim 200$) as well as imaging. This will allow us to observe a number of absorption features associated with exoplanetary atmospheres (Figure 2) including major features such as H_2O, CO_2, CH_4, and NH_3 (e.g., Spiegel & Burrows 2012). These spectra will be extremely useful for improving theories for exoplanetary atmospheres, which currently have uncertainties for cloud formation and nonequilibrium chemical processes, leading us to derive fundamental parameters (mass, atmospheric compositions etc.) to constrain their formation theories. See also Kotani et al., this volume for details of possible studies.

In addition to coronagraphic imaging, photometric and spectroscopic capabilities will be useful for detailed studies of transiting exoplanets. See Narita et al., this volume and the Yellow Book for details.

3. GAS IN PROTOPLANETARY DISKS

Exoplanetary systems and our solar system are believed to have been formed in circumstellar disks of gas and dust (protoplanetary disks). The *Hubble Space Telescope*, ground-based 10-m telescopes, and millimeter/submillimeter interferometry have provided images of dozens of protoplanetary disks, some of which show potential signatures for ongoing planet formation such as disk holes (e.g., Andrews et al. 2011; Hashimoto et al. 2012) and spiral structures (e.g., Muto et al. 2012; Grady et al. 2013). The spectral energy distributions (SEDs) at UV to radio wavelengths have also been observed toward a number of the star+disk systems, and the disk structures have been discussed through modeling calculations (e.g., Espaillat et al. 2010).

The gas comprises most of the initial disk mass and may consequently play an important role in the formation and evolution of planetary systems, allowing gravitational instabilities to occur (Durisen et al. 2007, for a review), or providing gas drag on rocky materials (Nagasawa et al. 2007, for a review). A number of observational studies of gas disks have been made to date using millimeter/submillimeter interferometry (Dutrey et al. 2007, for a review), infrared spectroscopy from space and the ground (Najita et al. 2007; Pontoppidan et al. 2010; Dent et al. 2013), and optical high-resolution spectroscopy from the ground (Najita et al. 2007). The millimeter/submillimeter lines are associated with the regions on a few hundred AU scale (see Dutrey et al. 2007 for review), while those in the optical and infrared are associated with regions within a few AU of the central star.

The spectroscopic capabilities of *SPICA* at mid-to-far infrared wavelengths will be the best to extend the studies made so far, in particular those made using *Spitzer* and *Herschel*. Its extremely high sensitivities will allow us to investigate the dissipation of the gas disks in detail, in particular for $t \sim 10$ Myr stars for which the dust disks are no longer observed. Indeed, SAFARI will offer a detection limit for far-IR lines of $\sim 3 \times 10^{-19}$ W m^{-2}, improving the detection limits of the existing *Herschel* studies by a factor of 10. MCS-MRS will cover some lines which may be even more useful for investigating the dissipation of gas disks (Figure 3, left). Covering a number of emission lines observed using *Spitzer* and *Herschel* (e.g., [O I], [C II], H_2O, CO, OH, CH^+, H_2) we will also be able to investigate the physical and chemical

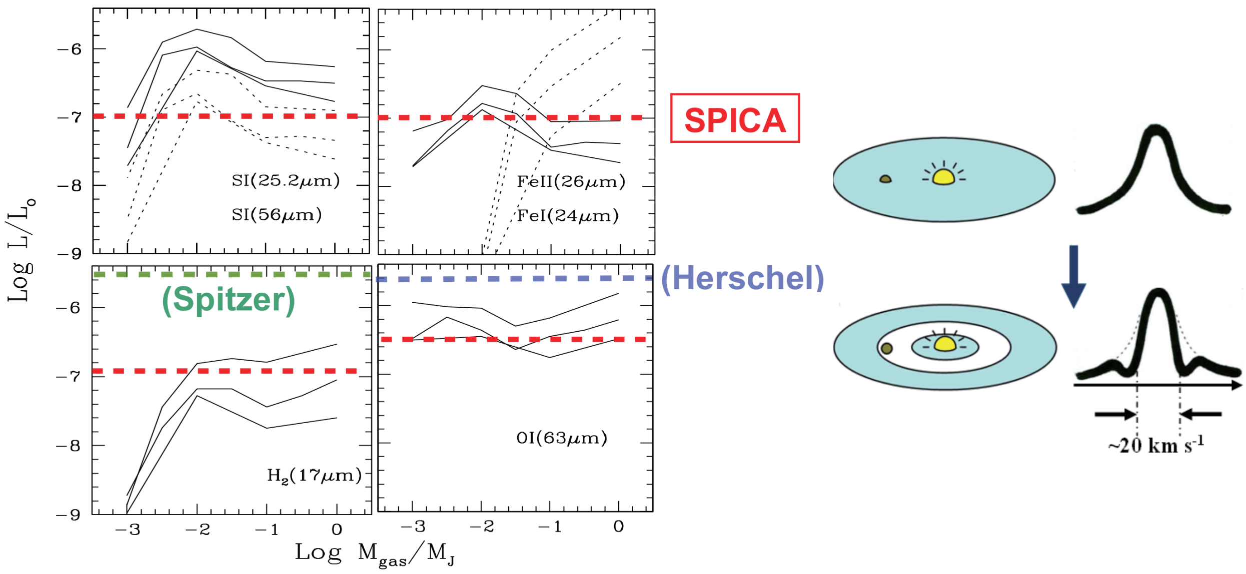

Figure 3. (*left*) Predicted line fluxes by Gorti & Hollenbach (2004) for a t = 10^7 yr disk, overplotting the detection limits of *SPICA* for a 1-hr integration, 5-σ. Typical detection limits for the studies with *Spitzer* and *Herschel* (Lahuis et al. 2007; Fedele et al. 2013; Dent et al. 2013) are also shown. The *Spitzer* study by Lahuis et al. (2007) also covers the S I, Fe I and Fe II lines and typical detection limits are above the range of the plot. (*right*) Schematic view for a change in line profile due to disk clearing by a Jupiter-like planet.

conditions of such gas in detail. Furthermore, observations of HD lines at far-infrared wavelengths will constrain the masses for a large sample of protoplanetary disks (e.g., Bergin et al. 2013).

Furthermore, MCS-HRS will allow us to observe the velocity profiles of various emission lines, leading to the determination of the column density distribution and physical/chemical conditions as a function of radius. The spectral resolution and coverage of MCS-HRS ($R \sim 3 \times 10^4$ and 12–18 μm, respectively) are designed to (1) resolve kinematics comparable to the orbital motion of Jupiter in our solar system; and (2) make follow-up studies of emission bands extensively observed using *Spitzer* (H_2O, CO_2, HCN, C_2H_2 — see, e.g., Pontoppidan et al. 2010; Carr & Najita 2011). The high spectral resolution of MCS-HRS will also be useful for deblending many emission lines (Carr & Najita 2011). The observations of line profiles will hopefully allow us to trace kinematic evolution due to planet formation within a few AU of the disks (Figure 3, right).

4. DEBRIS DISKS

Debris disks have been observed toward a number of main sequence stars. A recent census using *Herschel* suggests that about 20 % of nearby main sequence stars host such disks (e.g., Eiroa et al. 2013). Along with the Edgeworth-Kuiper and asteroid belts in our solar system, debris disks may be a useful fingerprint for the evolution of the associated exoplanetary systems (e.g., Wyatt 2008; Wyatt et al. 2012).

Observational studies have been traditionally made with infrared SEDs without direct spatial information. Most debris disks show a flux peak at a far-infrared wavelengths, thus these are considered as massive analogues to the Edgeworth-Kuiper belt in our solar system but with significantly larger dust masses. On the other hand, recent studies using *Herschel*, *AKARI* etc. have revealed new classes of debris disks significantly hotter or colder than the others, and their physical nature is being investigated (e.g., Fujiwara et al. 2013; Eiroa et al. 2013) (see also Onaka et al., this volume). However, some or all of the *Herschel* detections of “cold disks” have been suspected to source confusion with extragalactic sources (e.g., Krivov et al. 2013; Gaspar & Rieke 2013). See also Sibthorpe, this volume, for source confusion of *Herschel* observations.

Structures in some disks have been resolved using a variety of telescopes from optical to millimeter wavelengths. These observations show that some disks are not uniform either in the radial and azimuthal directions (e.g., Acke et al. 2012). In particular, *Herschel* and ALMA have allowed us to separate out a warm dust component at the star, which may be analogous to the asteroid belt at our solar system, from the bright remaining component at large radii (e.g., Acke et al. 2012; Su et al. 2013).

The extremely good sensitivity, wide wavelength coverage, and capability of spectro-imaging of *SPICA* will enable us to extend the studies at mid-to-far infrared wavelengths made using *Spitzer*, Heschel and *AKARI* in recent years. SAFARI and MCS will allow us to obtain the images of the disks at mid-to-far infrared wavelengths, significantly improving the detection limits and also improving the angular resolution at mid-infrared wavelengths. The morphological information provided by such an instrument will be used to study the diversity and the evolution of debris disks. As discussed for *Herschel* studies, spatial information is also useful to entangle the degeneracy between the disk structure, dust temperature, grain size and compositions (Booth et al. 2013), thereby understanding their physical nature in more detail. The field of view of these instruments (2’×2’ for SAFARI, FIR; 5’×5’ for MCS-WFS) is sufficient to cover such disks in a single frame.

Determining the SEDs at a wide wavelength coverage, *SPICA* will also be able to (1) search for more “warm disks” and (2) investigate the nature of “cold disks”. The spectroscopic capability of *SPICA* will allow us to search for emission lines associated with gas (see, e.g., Moór et al. 2011; Riviere-Marichalar et al. 2012; Roberge et al. 2013, for some detections). This will hopefully establish these lines as useful probes to study physical/chemical conditions of the disks. The spectroscopic studies for solid features will also be intriguing, as described in the next section, together with those for protoplanetary disks.

5. **MINERALOGY AND ICES IN DISKS**

Dust is the major building block for solid material in planets, and is the major constituent of the terrestrial planets and the cores of giant-gaseous planets. Of the materials included in dust grains, silicate has been extensively studied to investigate the thermal history of protoplanetary disks and pre-solar nebula. Mid-infrared spectroscopy of silicate features has revealed that, while the silicate in the interstellar medium is amorphous (Kemper et al. 2004), crystalline components exist in some disks and comets (Henning 2010, for a review) (see also Koch et al, this volume). This implies that thermal annealing at ∼1000 K occurred during the disk evolution, but the detailed mechanism is not clear. While the direct spatial information of their distribution may be useful for tackling this issue, such observations have been limited to the brightest disks (e.g., Okamoto et al. 2004).

A variety of ices associated with dust grains have been observed toward young stellar objects (van Dishoeck 2004, for a review), and it is likely these also exist in protoplanetary disks. Water ice is of the greatest among the ices, and is thereby responsible for a significant fraction of the total dust mass. The “snow line” due to water ice may be a key feature in disks when discussing the evolution of planetary systems (e.g., Nagasawa et al. 2007). Ices may also affect the atmospheric compositions of gas giants after comets are formed and fall onto the planets (Cavalié et al. 2013) and/or sustain life in extrasolar planetary systems. Despite its importance, water ice in protoplanetary disks (not the edge of the disk — e.g., Terada et al. 2012) is not readily observable; we must either observe (1) emission features at 44/62 μm or (2) absorption features in a spatially resolved disk. Both are extremely challenging, and there have been only a limited number of successful observations (Malfait et al. 1999; Honda et al. 2009).

The capabilities of spectroscopy and spectro-imaging at *SPICA* will be powerful tools for extending the above studies. Firstly, it will cover silicate features at a wide range of wavelengths at mid- to far-infrared (e.g., Malfait et al. 1998), leading to detailed understanding of silicate compositions in the individual disks. Since far-infrared features are expected for both protoplanetary and debris disks, these will be useful for conducting statistical studies for both types of disks and for discussing possible evolutionary schemes. Furthermore, SAFARI and SCI will allow the observations the spatial distributions of silicate features in bright debris disks. Detailed spectroscopy of silicate features will allow the determination of the abundance of minerals (i.e., the abundance of Fe, Mg etc.) in detail (e.g., Sturm et al. 2013), and will be useful for studying similarities and differences of their compositions in disks.

SAFARI will also be useful for observing ice features at 44/62 μm for a number of protoplanetary disks. After the Infrared Space Observatory (ISO), SAFARI will provide the unique opportunity to entirely cover the above feature. Spectro-imaging of the 44/62 μm ice features towards the brightest debris disks could be used to infer the presence or absence of the “snow-line” in the disks, the possible boundary between terrestrial and gas-giant planets. Finally, *SPICA*, as well as *JWST*, will offer observational capabilities for a variety of ice features in the mid-infrared associated with the edge-on disks.

6. **SOLAR SYSTEM SMALL BODIES**

Solar system small bodies (TNOs, comets, asteroids) are believed to contain clues for the initial or early stage of the formation of our solar system, and its dynamical evolution. Since the first discovery in 1992 (Jewitt & Luu 1993) more than a thousand TNOs have been discovered around and beyond the orbit of Neptune. Simulations show that kinematic interactions between the TNOs and planets may result in the formation of the asteroid belt and may supply water to the earth in the early stages of its evolution (Gomes et al. 2005; Levison et al. 2009). Discovery of an amino acid in cometary dust is providing a new clue for the formation of life in space (Elsila et al. 2009).

The size distributions and chemical compositions of solar system bodies are fundamental parameters for studying the Edgeworth-Kuiper and asteroid belts in our solar system. In principle the visible and thermal infrared brightness have to be measured to determine the size, albedo (the parameter for investigating the surface composition for a large number of samples) and thermal inertia of unresolved solid bodies. The measurement of the SED, which peaks at ∼100 μm for TNOs, dramatically decreases the uncertainties in the determination of these parameters. Such observational studies have been conducted using *Herschel*, but the samples are limited to the brightest targets (e.g., Fornasier et al. 2013).

SPICA will be ideally suited to the observation of the SEDs for these targets, with unprecedentedly high sensitivity and accuracy. Indeed, *SPICA* will be able to measure the SEDs for most TNOs known to date (Figure 4.; see also Kiss et al., this volume) and also asteroids in the asteroid belt with diameters down to 50 m (Usui et al., this volume). Such observations of a large number of TNOs will probe the conditions of the ‘Initial Solar Nebula’ in much greater detail than previously accomplished.

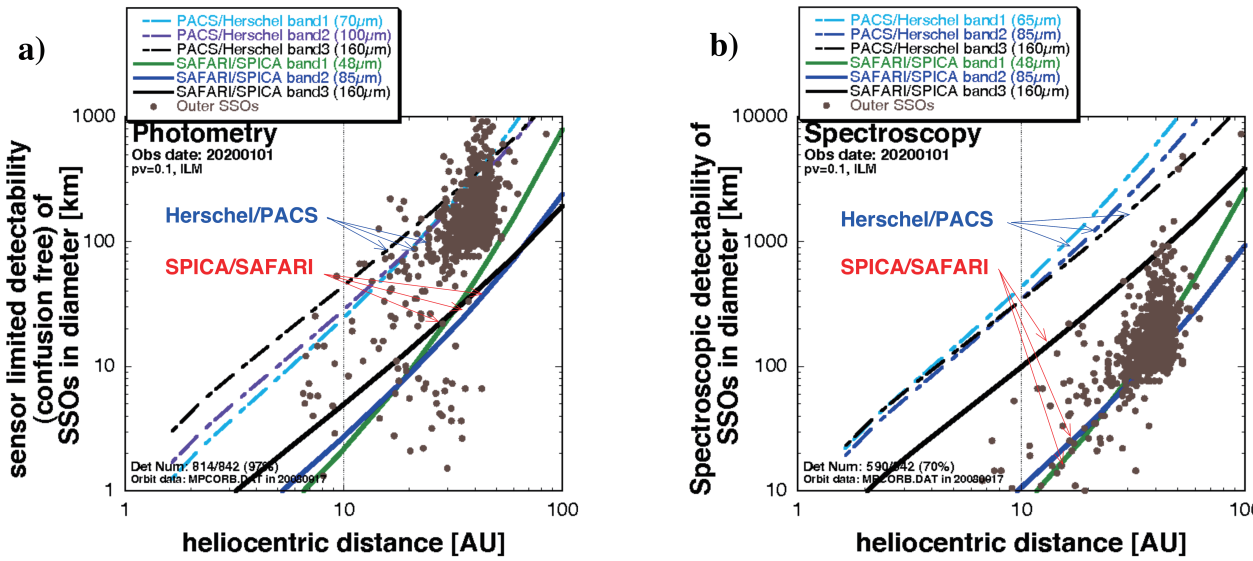

Figure 4. Detection limits of known outer solar system objects (SSOs) using *SPICA* and *Herschel* as a function of heliocentric distance and diameter (Yellow Book). The left and right plots show those for photometry and spectroscopy, respectively.

Furthermore, low-resolution spectroscopy of the 44/62 μm water ice features will facilitate the study of the water ice content and thermal history of the outer solar system. The wide spectral coverage of *SPICA* also contain a variety of features useful for studying comets, and also comet-like asteroids. Comparing the dust and gas features with those of debris disks, we will be able to obtain another clue about their similarities or differences.

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