Studies of Expolanets and Solar Systems with SPICA

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Abstract

The SPace Infrared telescope for Cosmology and Astrophysics (SPICA) is a proposed mid-to-far infrared (4-200 µm) astronomy mission, scheduled for launch in 2017. A single, 3.5m aperture telescope would provide superior image quality at 5-200 µm, and its very cold (∼5 K) instrumentation would provide superior sensitivity in the 25-200 µm wavelength regimes. This would provide a breakthrough opportunity for studies of exoplanets, protoplanetary and debris disk, and small solar system bodies. This paper summarizes the potential scientific impacts for the proposed instrumentation.

Key words: planetary systems, minor planets, asteroids, planets and satellites: formation, solar system: formation, infrared: solar system
1 Overview of SPICA

The SPace Infrared telescope for Cosmology and Astrophysics (SPICA) is a proposed mission for mid-to-far infrared (MIR/FIR) astronomy, consisting of a single 3.5-m aperture space telescope with cooled (∼5 K) instrumentation (see Nakagawa 2008). This mission would provide a significant step forward in detection sensitivity in the 4 to 200 μm wavelength regime, which would revolutionize our understanding of how galaxies, stars and planets form, and how interactions between complex astrophysical processes have ultimately led to the formation of our own Solar system and the emergence of life on Earth.

The role of SPICA would complement other forthcoming space infrared missions; Herschel and JWST. Herschel will provide improved capabilities at wavelengths longer than 57 μm, while its relatively warm temperature will produce a modest improvement over the Spitzer Space Telescope. JWST will provide the best performance at wavelengths shorter than 25 μm, and will have the highest angular resolution. SPICA would (1) achieve the best sensitivity at 25–200 μm, due to its cold mirror (∼5 K); (2) achieve a clean point-spread function at 5–200 μm due to its non-segmented mirror, thereby providing the best performance for high-contrast coronagraphy; and (3) fill the gap in wavelength coverage between Herschel and JWST.

SPICA would offer a unique opportunity for studying exoplanets, planet formation, circumstellar disks, and small bodies in the solar system. Table 1 summarizes the instruments proposed to date. Those selected for the mission will be chosen based on technical constraints (weight, volume, heat dissipation etc.) and scientific impact. In §2, we describe potential scientific achievements in the above areas of research. In §3 we briefly describe the project schedule, including the selection process for the instruments.

2 Potential Scientific Achievements

2.1 Exoplanets (I): direct detection using coronagraphy

In the last decade more than 300 gas-giant planets have been detected through measurements of the radial velocity of their parent stars and photometric measurements of transiting events. These have lead us to the discovery of exoplanets around 6–7 % of nearby main-sequence stars (see Udry et al. 2007, Charbonneau et al. 2007, and references therein). However, these detections are biased in favor of large exoplanets with small orbital radii and parent stars with late spectral types. Consequently, a number of extrasolar
planetary systems may have been missed by present observational techniques and capabilities.

Direct detection is a highly desirable method for the study of exoplanets. This technique has been hampered by the extremely high brightness contrast between planets and their parent stars. Extensive coronagraphic observations of nearby stars and possible planet-forming systems have been performed by the *Hubble Space Telescope (HST)*, Subaru, Keck, VLT and Gemini. Unlike the radial velocity method, this technique is sensitive to planets with large orbital radii (>30 AU) towards stars. Technical improvements in recent years have pushed detection limits to on order of a Jupiter mass, leading to the discovery of several candidate gas giants (Lafrenière et al. 2008; Kalas et al. 2008; Marois et al. 2008; Lagrange et al. 2008).

Space IR coronagraphy at wavelengths >3.5 µm could dramatically improve such studies as (1) observations using space telescopes are free from speckle and thermal noise caused by telluric atmosphere; (2) observations in the IR (>3.5 µm) minimize the brightness contrast with the parent star (e.g., Burrows et al. 2004). The high sensitivity of SPICA would also permit IR spectroscopic observations free from atmospheric effects, thereby allowing to study the physical properties and chemical abundances of planetary atmospheres. Such a combination of IR space coronagraphy and spectroscopic capability has only been proposed for SPICA.

SPICA would offer coronagraphy with an even higher contrast than JWST, since its non-segmented mirror would provide a clean point-spread function. The combination of SPICA and a dedicated coronagraph would reach a detection limit with a contrast of 10^{-6} (see Fig 1). Furthermore, the coronagraph for SPICA is designed to cover a wide wavelength range in order to study a variety of molecular bands, including CH\textsubscript{4} at 7.7 µm, H\textsubscript{2}O at 6.3 µm, and NH\textsubscript{3} at 6.1/10.3/10.6 µm. This spectroscopic capability, when combined with the coronagraph, would allow detailed observations of these features and the determination of atmospheric temperature and composition with high accuracy. See Tamura (2000) and Enya et al. (2008) for details.

### 2.2 Exoplanets (II): Observations of Transiting Planets

The number of extrasolar planets detected through the transiting planet method has been steadily increasing since the first discovery. To date, dozens have been confirmed by this technique. It is strongly expected that the number of such planets detected will continue to increase rapidly through SPICA’s launch. COROT, launched in 2006 December, is expected to detect many transiting giant planets and several transiting super-Earths (Borde et al. 2003).
Kepler, successfully launched in March 2009, is expected to detect numerous transiting giant planets and hundreds of transiting super-Earths (Basri et al. 2005). The statistics for transiting planets will also continue to improve through the use of ground-based observations.

While most transiting planets have been observed using the first eclipse, infrared photometry of the secondary eclipse (i.e., the passage of an extrasolar planet behind the parent star) allows to measure radiation from the extrasolar planet itself. A few extrasolar planets have been observed using this method, providing the temperature of their atmosphere (e.g., Deming et al. 2005; Charbonneau et al. 2005).

Spectroscopic observations of transiting planets are important for the determination of the physical conditions of planetary atmospheres. While the first eclipse allows to observe absorption features from the planetary atmosphere as the stellar light pass through it, infrared spectroscopy of the second eclipse provides spectra of the planetary radiation itself. Transiting spectroscopy of HD 209458b with HST revealed deep absorption in H I, O I and C II, suggesting the presence of an extended and escaping upper atmosphere beyond the Roche lobe (Vidal-Madjar et al. 2003, 2004). More recently, molecules such as H$_2$O, CH$_4$, CO, and CO$_2$ have been successfully detected using the Spitzer Space Telescope and HST in one such transiting planet, HD 189733b (Grillmair et al. 2007; Swain et al. 2008, 2009).

New missions such as Corot and Kepler, are expected to increase the number of known transiting planets. Therefore, follow-up spectroscopy with an IR telescope will be extremely valuable. The sensitivities of Spitzer, AKARI and ground-based 8-m telescopes are not sufficient for such observations, thus a space IR telescope with a large diameter is needed. SPICA, together with JWST, would have space-based mid-IR spectroscopic capabilities, allowing to extend such observations to the determination of the radius, density, and atmospheric compositions of newly discovered transiting planets.

2.3 Protoplanetary Disks

Exoplanetary systems and the solar system are believed to have formed in circumstellar disks, which are ubiquitous towards pre-main sequence stars. Testing planet formation theories will require the observation of disk in the process of active planet formation. Space IR spectroscopy is a powerful tool for observing gas and dust associated with these disks.

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 (e.g., Boss 2003), or providing gas
drag on rocky materials (e.g., Kominani & Ida 2002). So far, observational studies of gas disks have been conducted mainly through radio interferometry and ground-based optical-IR spectroscopy. The former technique allows to observe regions on a few hundred AU scale (see Dutrey et al. 2007 for review), while the latter allows to observe regions within a few AU of the central star (see Najita et al. 2007 for review). Recent advances in mid-to-far IR spectroscopy allow to explore the gas at intermediate radii from a star (1–30 AU), the key zone for the formation of planetary systems like our own. Such studies include: (1) Spitzer spectroscopy of atomic ([Ne II], [Fe II] etc.; e.g., Lahuis et al. 2007) and molecular lines (H$_2$O, OH, HCN, C$_2$H$_2$, CO$_2$ etc.; e.g., Carr & Najita 2008; Salyk et al. 2008); and (2) ground-based observations of [Ne II] and H$_2$ at 17 µm (Herczeg et al. 2007; Bitner et al. 2008).

The mid-to-far IR spectrographs on SPICA would extend such observations to an unprecedented sensitivity and spectral coverage. The mid-IR high resolution spectrograph would be sensitive to the profiles of various emission lines, leading to the determination of the column density distribution and physical/chemical conditions as a function of radius (see Fig 2). To facilitate this, its spectral coverage is designed to observe a variety of emission lines. The mid-IR medium resolution spectrograph and far-IR spectro-imager would detect emission lines over a wider spectral range (10–200 µm), probing the total mass of the gas. Once we determine these physical parameters as a function of age, we would be then be able to determine the dissipation timescale of the gas disk. Furthermore, these lines are responsible for gas cooling, and the observations would reveal a clear picture of the energy balance in disks. All of the above physical parameters are of vital importance for testing various theories of planet formation.

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. In particular, water ice associated with dust grains is responsible for a significant amount of the total dust mass, and could be important for sustaining life in extrasolar planetary systems. While IR spectroscopic observations have previously been used for extensive studies of silicate and carbon in dust grains (see e.g., van Boekel et al., 2005; Kessler-Silacci et al. 2005; Honda et al. 2006), our understanding of water-ice in protoplanetary disks is far from complete. Water ice in protoplanetary disks is not readily observable; we must either observe emission features at 44/62 µm or 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).

Although observations with Herschel and ground-based coronagraphs will improve such studies, the high sensitivity of SPICA would provide much more dramatic advances. The far-IR spectro-imager could be used to observe ice
features at 44/62 µm for a number of protoplanetary disks. These features hold the key to identifying the nature of the ice (either amorphous or crystalline), and are therefore useful for determining the thermal (and thereby chemical) history of the disks. The MIR grism spectroscopy would allow us observe a variety of solid features (CO₂ etc.) in a manner similar to JWST.

2.4 Debris Disks

A number of debris disks have been discovered since the initial IRAS identification of an infrared excess from the A-type main-sequence star, Vega. While most pre-main sequence stars with low-to-intermediate masses host a dust disk, a recent census by Spitzer Space Telescope suggests that 10–15 % of nearby main sequence stars host such disks, independent of spectral type (see Meyer et al. 2007 for review). Further studies with Spitzer have marginally resolved the structure of the thermal FIR emission in the nearest and brightest debris disks (e.g., Stapelfeldt et al. 2004; Su et al. 2005). There is growing evidence that such dusty disks are formed from debris produced mainly through the collisions of planetesimals in the process of planetary system formation. Since the scales of most of the observed debris disks correspond to the Kuiper belt in our solar system, studies of these targets are important for understanding the origin and diversity of extrasolar planetary systems. More recently, the relevance of such studies has been highlighted by the discovery of a few exoplanet candidates towards stars which host bright debris disks (Kalas et al. 2008; Marois et al. 2008; Lagrange et al. 2008).

While observations of debris disks are often made at far-IR and mm wavelengths, observations at shorter wavelengths (optical to MIR) have significant advantages for the study of their structure. In particular, a combination of spectroscopy and polarimetry have revealed a non-uniform distribution of dust properties, providing clues for understanding their evolution (e.g., Okamoto et al. 2004; Tamura et al. 2006). Morphological studies have been used to investigate interactions with a possible exoplanet, providing an upper mass limit (e.g., Kalas et al. 2008). However, statistical studies have been severely hampered by the brightness of the central star: such optical to MIR observations have been carried out for only a handful of debris disks.

SPICA would offer several different approaches to the study of debris disks. First, broad-band imaging with the far-IR spectro-imager could lead to the discovery of an even larger number of debris disks associated with nearby stars. Based on the estimated sensitivity, we would be able to detect “extra-solar Kuiper belts” with a mass comparable to that in our own solar system around nearby stars. Secondly, FIR imaging and MIR coronagraphic imaging would allow the study of the geometrical and physical structure of bright
debris disks in detail. The morphological information provided by such an instrument would be used to study the origin of the diversity of debris disks, and determine the presence or absence of large gas-giant planets near such disks. The field of view of these instruments (2’×2’ for SAFARI, FIR; 1’×1’ for coronagraph, MIR) is sufficient to cover such disks in a single frame. Thirdly, MIR spectroscopy at 10–40 µm would enable us to observe the spatial distribution of a variety of silicate emission lines, probing the ongoing dust replenishment as a function of radius in a variety of debris disks. Finally, 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”, the possible boundary between terrestrial and gas-giant planets.

2.5 Solar System Small Bodies

Since the first discovery of Trans-neptunian objects (TNO) in the outer solar system (Jewitt & Luu 1993), more than a thousand such objects have been detected. Indeed, some have a size comparable to Pluto (e.g., Bertoldi et al. 2006; Brown et al. 2006), leading us to define a new category of solar system bodies at the IAU General Assembly in 2006. Ongoing observations at optical wavelengths are expected to find an even larger number, particularly at high ecliptic latitudes. These objects presumably belong to a physico-chemically unaltered population of the solar system.

The diameter and albedo of these objects will allow to investigate the initial conditions and dynamical evolution of the solar system. In order to determine the size, albedo and thermal inertia of unresolved small bodies, both the visible and thermal infrared brightness have to be measured. In particular, the measurement of the spectral energy distribution (SED), which peaks at ∼100 µm, dramatically decreases the uncertainties in the determination of the size and albedo. These observations require imaging or photometric facilities at far-IR (30–300 µm) wavelengths. Spitzer had only a few photometric bands in this range (24/70/160 µm), while Herschel will not be able to observe wavelengths shorter than 60 µm.

SPICA would be ideally suited to the observation of the SEDs of TNOs with unprecedentedly high sensitivity and accuracy (see Fig 3). Such observations of a large number of TNOs would probe the conditions of the 'Initial Solar Nebula’ in much greater detail than previously accomplished. Furthermore, low-resolution spectroscopy of the 44/62 µm water ice features would facilitate the study of the water ice content and thermal history of the outer solar system.
3 Summary and Project Status

SPICA would provide significant advances in the study of exoplanets, protoplanetary disks, debris disks and small bodies in the solar system. Its imaging capability would be able to detect debris disks with an unprecedented sensitivity. These capabilities would allow to measure the total flux of small bodies in the solar system, useful for the study of their size distribution and albedos. SPICA’s spectral capability would probe the gas and dust associated with circumstellar disks, and the atmospheres of the transiting planets. Its coronagraphic capability would lead to the discovery of a number of exoplanets, and the subsequent investigation of their atmospheres and the geometry and distribution of ice in the spatially resolved circumstellar disks. Possible achievements with the individual instruments are summarized in Fig 4.

The conceptual design of SPICA is currently underway, and we will begin the definition phase of the mission in 2009. This phase, which will include the final decisions for the instruments, will be completed in 2011.

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Table 1
Instruments Proposed for SPICA Mission

| Instrument                                | Wavelength (µm) | Performance                                                                 |
|-------------------------------------------|-----------------|-----------------------------------------------------------------------------|
| MIR Imager (MIRACLE)                      | 4–40            | 6’×6’ FOV, pixel scale = 0”.35 + capability of grism spectroscopy            |
|                                           |                 |                                                                             |
| FIR Spectro-Imager (SAFARI)\(^1\)         | 35–210          | 2’×2’ FOV, pixel scale = TBD with \(R\) up to \(\sim 2000\) (\(\Delta \lambda \geq 0.018 \mu m\)) |
|                                           |                 |                                                                             |
| Far-IR Spectrograph (BLISS)                | 38–430\(^*\)    | \(R=700\) (\(\Delta \lambda=0.05–0.6 \mu m\))                              |
|                                           |                 |                                                                             |
| MIR High-Resolution Spectrograph\(^2\)     | 4–18            | \(R \sim 3 \times 10^4\) (\(\Delta \lambda=0.001–0.005 \mu m\))            |
|                                           |                 |                                                                             |
| MIR Medium-Resolution Spectrograph         | 10–40           | \(R \sim 1 \times 10^3\) (\(\Delta \lambda=0.01–0.04 \mu m\))               |
|                                           |                 |                                                                             |
| Coronagraphic Camera & Spectrograph\(^3\)  | 3.5–27\(^*\)    | dedicated coronagraphy                                                     |
|                                           |                 |                                                                             |
|                                           |                 | 1’×1’ FOV, pixel scale = 0”.059 \(R=20–200\) (\(\Delta \lambda=0.02–1.4 \mu m\)) for spectroscopy |

\(^1\) Swinyard et al. 2009; \(^2\) Kobayashi et al. 2008; \(^3\) Enya et al. 2008
* The present design of the entire SPICA mission covers 4–200 \(\mu m\), although possible extension is optionally discussed for these instruments for greater scientific impacts.
Fig. 1. Pupil mask images (left) and diffraction patterns obtained by experiments (middle and right). In the right figure, the Airy pattern of the telescope with a circular aperture is also shown. The special pupil mask dramatically improves the contrast of the point-spread function, in particular close to the stellar position. See Enya et al. (2007) for details.
Fig. 2. (left) Band spectra of a variety of molecules at mid-IR wavelengths (optically-thin, 1000 K). (top-right) Numerical simulation for a protoplanet tidally interacting with a protoplanetary disk and opening-up a disk gap (Bryden et al. 1999). (bottom-right) Schematic view of how the disk clearing due to a proto-Jupiter would change the emission line profile.
Fig. 3. Spectral energy distributions of asteroids (Ceres, Itokawa) and a Trans-

s-neptunian object (Varuna), and detection limits of various facilities including
Akari (5-σ, 1 pointing), Subaru-COMICS, JWST, Herschel, ALMA and SPICA
(5-σ, 1 hour integration).
|                         | Exoplanets                                                                 | Protoplanetary Disks                                                                 |
|-------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| **MIRACLE**             |                                                                            | • Total gas mass & gas density                                                      |
| **SAFARI, BLISS**       |                                                                            | • Presence/absence of ice, silicate and PAH in the outer disk (r>10 AU)             |
| **MIR Mid-res. Spectrograph** | • Mass, temperature and chemical composition of atmosphere of transiting planets | • Geometry, physical & chemical conditions of possible planet-forming regions as a function of radius (1-30 AU) |
| **MIR High-res. Spectrograph** |                                                                            | To be discussed                                                                    |
| **Coronagraph**         | • Population of exoplanets                                                |                                                                                      |
|                         | • Planetary mass, chemical composition of atmosphere                       |                                                                                      |

|                         | Debris Disks                                                              | Solar System Small Bodies                                                           |
|-------------------------|                                                                         |                                                                                      |
| **MIRACLE**             | • Inner disk structure seen in thermal emission (> 50 K)                | • Distribution of size, albedo and thermal inertia                                  |
| **SAFARI, BLISS**       | • Population of faint disks (extrasolar Kuiper belts)                    | • Thermal history                                                                    |
|                         | • Distribution of ice in the nearest and brightest disks                 |                                                                                      |
| **MIR Mid-res. Spectrograph** |                                                                            |                                                                                      |
| **MIR High-res. Spectrograph** |                                                                            |                                                                                      |
| **Coronagraph**         | • Disk structure seen in scattered light                                | • Composition of volatile of icy bodies                                              |

Fig. 4. Summary of parameters we will be able to measure on individual topics with different instruments