Exoplanet Science with the *SPICA* Coronagraph Instrument

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ABSTRACT

SPICA Coronagraph Instrument (SCI) is an instrument dedicated for direct detection and characterization of exoplanets and also for other science that needs a high-contrast imaging and spectroscopic capability in the near to mid-infrared wavelengths. We will present the major science cases for exoplanets from the instrument proposal of SCI. Thanks to the high-contrast imaging and spectroscopic capability, we will be able to tackle the various problems on the exoplanet science. SCI will give us the unique opportunity to observationally understand the formation process of Jovian planets, which is still poorly understood, by measuring temperatures of young Jovian planets. Spectroscopy of planet atmospheres will enable us to reveal the chemical compositions by measuring the abundances of various important molecules such as CO, CH_4, NH_3, H_2O, H_2 etc. We will also access to the structure of Jovian atmosphere, for example the existence of thermal inversion which is known for our Solar system planets. Furthermore, the direct detection of icy giants around early-type stars with SCI will open a new window to investigate these enigmatic planets.

1. INTRODUCTION

One of the most important uniqueness of *SPICA* is continuous wavelength coverage from the mid- to far-IR spectral region with a very cold (6 K) telescope. The spectral range of 4–28 μm, which is the core wavelength range continuously covered by *SPICA Coronagraph Instrument* (SCI, Kotani et al. 2012), includes many of the fundamental vibration modes of minerals, organic matter, and ices as well as many rotational modes of important molecular gases such as H_2. Space-based observations have a great advantage over ground-based observations in terms of the continuous spectral coverage not hampered by the atmospheric absorption, which is essential to unambiguously identify relatively broad spectral features inherent to solid particles. SCI is designed to have not only imaging (1 arcmin × 1 arcmin area) but also slit-spectroscopic (R = 200) capability, and coronagraph is applicable to both imaging and spectroscopic modes.

The primary scientific cases with the SCI are the characterization of the exoplanets with molecular gases and dust specific to the mid-IR region, and the discovery of icy giant planets which can be detected only at longer IR wavelengths. It is a

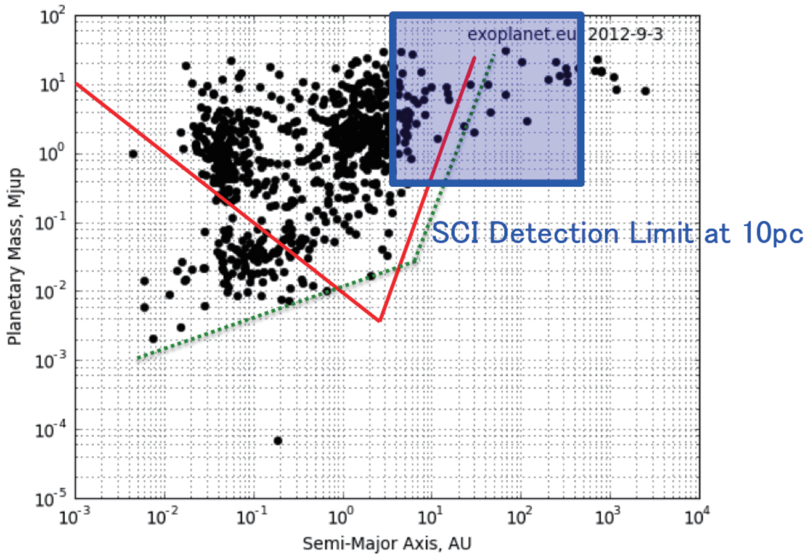

Figure 1. Planet search regions with *SPICA*-SCI (blue box), GAIA (red line), and radial velocity (green line) and the planets discovered so far (black dots). The detection limit of GAIA is derived based on Sozzetti (2010).

perfect complement to studies on exo-planetary science which are performed or to be performed by many other dedicated programs at shorter wavelengths. In particular, the mid-IR characterization would enable us to accurately determine temperatures of young planets at cooling phases, which are crucial to examine planetary formation theory: core-accretion model or disk instability model. The studies of solid materials around planet-forming stars will lead us to understanding raw materials of planets and even the origin of life on planets.

2. PLANET FORMATION PROCESS REVEALED BY THERMAL HISTORY

The key parameter to reveal planet formation process is the temperature of the planetary atmosphere soon after the planet is formed. The atmospheric temperature imposes constraint on the amount of the gas accretion onto the planet, which takes place at the final stage of the gas giant formation. Recent theoretical models (e.g. Spiegel & Burrows 2012) indicated that the initial conditions of the planet depend on the formation process, i.e. core accretion or disk instability, although their conclusions are still in debate. The planets formed through the two processes are different in the atmospheric temperature. The planets are expected to retain their initial conditions for 1 Gyr after the gas accretion onto the core is completed. Thus the planet temperature in the gas accretion stage is very important for understanding both the planet and the satellite formations. With the SCI, it will be possible to estimate the initial condition of the planet through measuring the planet temperature as a function of the age of a planet.

The spectral features of atmospheric molecules are crucial indicators of the planet temperature. Since there are several important molecular absorption lines in the wavelength coverage of the SCI, the atmospheric temperature can be determined through spectroscopy of the planet atmosphere. CO and N_2 are stable at temperatures higher than 1500 K. As the temperature decreases, they react with H_2 to form CH_4 and NH_3. As a result, they become the dominant carbon- and nitrogen-bearing species at low temperatures, respectively. At a total gas pressure of 1 atmosphere, CH_4 and NH_3 mainly form at temperatures below 1000 K and 700 K, respectively. In addition, the mixing fraction of H_2O increases by releasing the oxygen tied up in CO. Thus, while CO is an indicator of high-temperature objects, CH_4, NH_3 and H_2O are indicators of low-temperature objects. Therefore the planetary atmospheric temperature can be measured through observing the molecular absorption.

In order to observationally restrict the planetary formation process through the atmospheric temperature at the final stage of the gas accretion, both the age and the dynamical mass of the planetary system have to be known in advance. Therefore nearby young moving groups and open clusters, whose ages are determined by the H-R diagram, are observational targets for the SCI. Future precise astrometric observations with ground-based or space telescopes such as LBTI, VLTI, and GAIA, would discover planetary-mass objects even around young systems to determine those dynamical masses. Figure 1 compares the planet-search regions with the SCI and the future astrometric observations. The spectroscopic follow-up observations with the SCI will be able to determine the atmospheric temperatures of the planets whose ages and masses are already determined.

This study requires spectral resolution $R \sim 200$ and wavelength coverage from 4 to 12 μm to resolve the molecular absorption features due to CO (4.7 μm), CH_4 (6.5 μm, 7.7 μm), NH_3 (6.1 μm, 10.5 μm), and H_2O (6.2 μm). High contrast (10^{-6} level) is needed because the planet formed by the core-accretion process is already faint even at the final stage of the gas accretion. Therefore the SCI provides a unique opportunity for revealing the planet formation process from a point of view of the atmospheric temperatures.

3. H_2 AND HE IN THE ATMOSPHERE OF JOVIAN EXOPLANETS

H_2 is the major component in the atmosphere of Jovian planets and it is a main factor in determining the opacity. Investigation of the H_2 spectral feature is important in determining the cooling process and the heat balance in the Jovian atmosphere. For example, Jupiter and Saturn are two gas-giant planets in our solar system and similar in many characteristics, but the atmospheric He abundance of Saturn significantly differs from that of Jupiter; the He mass fraction of Saturn is much less than those of Jupiter (Conrath et al. 1987).The atmospheric abundance of He in the planets of evolved systems can be significantly reduced from the initial value due to the differentiation process of He in the atmosphere during the planet evolution (e.g. Gautier et al. 1981; Stevenson & Salpeter 1977). It is believed that the He differentiation process has not, or at least only recently, started in the atmosphere of Jupiter, while it has already proceeded in that of Saturn. Since we only know the cases of Saturn and Jupiter, we do not know which case is more typical in gas-giant planets. The effective approach to this issue is a systematic measurement of the atmospheric He abundances of gas-giant exoplanets with the SCI.

Mid-IR spectroscopy of Jupiter by *Voyager* revealed that the broad collision-induced S(0) and S(1) transitions of H_2 are seen in the wavelengths of 13–20 μm, and > 20 μm, respectively (Hanel et al. 1979). The SCI aims to obtain similar spectra for exoplanets in the coronagraphic spectroscopy mode. The opacity determined by measuring the H_2 features will contribute to understanding of the cooling process and the heat balance. It would be possible to obtain the abundance ratio of H_2 to He by fitting the spectra with the appropriate models considering the temperature dependence, as demonstrated by the *Voyager* 1/IRIS observation (Gautier et al. 1981). It requires the continuous spectral coverage from 10 to 28 μm with the spectral resolution of $R \sim 50$ to cover the entire S(1) feature and part of the S(0) feature.

4. ATMOSPHERIC STRUCTURE OF JOVIAN EXOPLANETS

4.1. Thermal Inversion

It is a controversial issue whether the thermal inversion, i.e., the turn-over of the pressure-temperature profile, is common or not in the atmosphere of planets. The thermal inversion would imply a thermal input from outside of the atmosphere. Mid-IR spectroscopy by *Voyager* contributed much to obtaining such information for outer planets in our solar system. In the case of extra-solar systems, infrared SEDs were recently obtained for transiting exoplanets (i.e. inner planets) and the pressure-temperature profiles were derived (Madhusudhan & Seager 2009), however the thermal structure of the atmosphere is yet to be understood well, especially for outer planets. The thermal environment of inner planets is expected to be quite different from that of outer planets, although the thermal inversion in the atmosphere of outer planets is currently studied only for our solar planets. SCI will provide the infrared spectra of outer exoplanets, which enable us to make a systematic study of the thermal inversion for outer exoplanets. Spectroscopy with $R \sim 200$ and continuous coverage between 4–20 μm is important for this study.

4.2. Photo-Chemistry in the Upper Atmosphere

In our solar system, strong C_2H_6 feature (12.2 μm) is detected in the mid-IR spectra of Uranus and Neptune (Conrath et al. 1989). It is believed that the photolysis of CH_4 under 1 μbar produces C_2H_6 found in Uranus and Neptune. The material produced by photo-chemistry is potentially of small particle origin, which can affect thermal phenomena via radiation cooling and the green-house effect. It is known that the ratio of C_2H_6 to CH_4 is 1.99 % in Uranus, but only 0.0006 % in Jupiter. The SCI has a capability to measure the intensity of the C_2H_6 feature. Spectroscopy with $R \sim 50$ and spectral coverage between 10–14 μm is important for the measurement of this feature.

4.3. Haze in the Atmosphere of Exoplanet

Haze, non-gas small particles floating in the atmosphere, which are also known as dust or cloud, is likely to play an important role in the atmosphere, affecting the thermal phenomena via radiation cooling and the green-house effect. In the case of brown dwarfs, dust is considered to be an important component in their photospheres (e.g., Tsuji et al. 1996). When the photosphere is cooled below the condensation temperature, dust forms in the photosphere, changing the thermal structure and chemical composition of the photosphere. However the haze in the atmosphere of exoplanets has not been studied well, especially that in outer exoplanets. One of possible studies on the haze with the SCI is to search for major dust features such as those due to hydrocarbon grains.

4.4. 4 μm Excess in the Spectra of Jovian Exoplanets

The clear evidence that exoplanets have the Jupiter-like atmosphere can be obtained by detecting an SED excess at wavelengths of 4–5 μm, which is caused by looking at inner warm regions through the opacity window of the Jovian thick atmosphere. The amplitude of the SED excess can also be an alternative indicator of the age of an exoplanet. Spectroscopy with R $\sim$ 50 covering 4–5 μm and longer wavelengths can detect this SED excess, as well as the baseline of the SED.

5. FONSTRAINING HEAVY ELEMENT ABUNDANCE

The temperature of the atmosphere of exoplanets is the key to understanding planetary formation process with the SCI. Another key is the abundances of heavy elements. The abundances of heavy elements in the envelope of a gas giant planet can be an indicator to determine whether the planet was formed via the core accretion model or the disk instability model. Gas giant planets formed via the core accretion model tend to have metal-rich envelopes through capture of planetesimals during runaway accretion of the envelopes (e.g., Shiraishi & Ida 2008). In contrast, the capture of planetesimals by fragmented clumps formed by disk instability is difficult especially in the case of distant gas giant planets like ones orbiting HR 8799 (Helled & Bodenheimer 2010). Therefore measurement of heavy elements for exoplanets can distinguish the planet formation models independently from that of the temperature of their atmosphere.

The SCI will perform systematic observations to obtain the infrared spectra of the outer exoplanets in order to give constraints on the abundances of heavy elements by comparing observed infrared spectra with model spectra, including the molecular features of CH_4, CO_2, CO, H_2O, and NH_3, etc. Such an approach is already applied to determine the abundances for transiting exoplanets (Madhusudhan et al. 2011). The coronagraphic spectroscopy with the SCI requires the wavelength coverage of 4–20 μm with R $\sim$ 200 so that we can compare observed spectra with model spectra directly. Only the SCI provides the capability of such coronagraphic spectroscopy in the mid-IR, which will be unique even in the *SPICA* era.

6. DIRECT DETECTION AND CHARACTERIZATION OF ICY GIANTS

Icy giants, consisting of Neptune-mass bodies, are mostly composed of mixtures of water, ammonia, and methane ices, whereas the helium and the hydrogen gas only exist in the outer envelopes of these planets, in contrast to Jovian planets. Mid-IR direct imaging observations of extra-solar icy giants with the SCI will enable us to better understand inner structures and the formation and evolution scenarios of these types of planets. The high sensitivity and the high contrast of the SCI at wavelengths longer than 10 μm will enable us to detect extra-solar icy giants orbiting around early-type stars, because the thermal emission from a planet relaxes the required contrast ratio to a host star. Early-type host stars are especially suited well for this study as they are typically younger than 1 Gyr and there exist enough samples (38 stars within 25 pc). Future near-IR high contrast experiments including *JWST* and ELTs cannot reach these icy giants due to their limited contrast, hence the SCI is a unique instrument for the study of extra-solar icy giants.

7. CONCLUSION

SCI is a high-contrast imaging spectrometer for *SPICA* and the primary scientific cases are the characterization of the exoplanets with molecular gases and dust specific to the mid-IR region, and the discovery of icy giant planets. High-contrast imaging / spectroscopy would enable us to accurately determine temperatures of young planets at cooling phases, which are crucial to examine planetary formation theory. The studies of solid materials around planet-forming stars will lead us to understanding raw materials of planets and even the origin of life on planets.

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