Evolution of Solid Materials in Planet-Forming Disks — From *AKARI* to *SPICA*

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ABSTRACT

How are planetary systems formed? How is life created? As an approach to these subjects, we propose a study of chemical evolution of solid materials in planet-forming disks based on observations with the *SPICA* Coronagraph Instrument (SCI). We focus on silicate grains and hydrocarbon molecules including polycyclic aromatic hydrocarbons (PAHs) as origin of rocky-planets and life, respectively.

Our solar system is believed to be made of materials originated in the interstellar space. However, in our solar system, there are many kinds of materials, which are not common in the interstellar space (e.g. crystalline silicates and complex organic molecules). They must be formed at planet-forming stages. Because each material has its own condition for generation, we can obtain clues for events which occur at planet-forming stages, through studies of evolution of these materials.

AKARI performed all-sky surveys in six infrared photometric bands with the wavelengths from 9 to 160 μm. A global picture of life cycle of solid materials in our Galaxy has been revealed from these data. Solid materials are supplied from mass-losing old stars to the interstellar space, and then incorporated into star forming activities. During this cycle, solid materials are processed in local physical environments, changing the infrared spectroscopic features. Based on these scientific results, as a next step, we plan to make detailed analyses of the evolution of the solid materials in star- and planet-forming sites using the *SPICA*/SCI.

1. INTRODUCTION

In the *SPICA* era, coronagraph instruments on large telescopes will be working (e.g. MIRI/*JWST*, MICHI/TMT). They are powerful tools for new detections of exoplanets. Among them, the *SPICA* Coronagraph Instrument (SCI; Enya et al. 2010) will be the unique instrument. Taking advantages of the space-based coronagraph on the cooled telescope, the SCI can simultaneously realize high contrast, high sensitivity, and mid-IR (4–28 μm) spectroscopic capability.

Thus, one of the unique scientific objectives of the SCI is the study of solid materials in planet-forming disks. High contrast coronagraphic capability is necessary for observations of circum-stellar disks close to bright central stars. High sensitive mid-IR low-resolution ($\lambda/\Delta\lambda \sim 200$) spectroscopy matches observations of solid matters in space. Silicates show broad features at around 10 and 20 μm. From these features, we can diagnose compositions, temperature, and crystallization degree of them (e.g. Henning 2010). Hydrocarbons (e.g. polycyclic aromatic hydrocarbons; PAHs) also show features and plateaus in this wavelength region (Tielens 2008). We can diagnose size, ionization degree, and aromatic/aliphatic ratio of hydrocarbons from these features. We can also obtain temperatures and size distributions of dust grains from mid-IR continuum (Kuruegel 2003).

We can obtain clues for the planet-forming scenario from the observational results of solid materials in disks. Because each solid material has its own condition of generation (e.g. coagulation temperature of silicates), physical state of solid materials in a part of disks indicates the history of the region as well as current physical state of the region. In this paper, we focus on the chemical evolution of silicates and hydrocarbons, and size evolution of dust grains in planet-forming disks.

2. SCIENTIFIC OBJECTIVES

2.1. Evolution of Silicates

The first topic is on silicates. Figure 1 shows an overview of this subject. Silicates are important materials as main components of rocky planets like the Earth. We believe that stars and planets are made of materials originated in the interstellar medium (ISM). Silicates are mostly amorphous in the interstellar space, which show mid-IR broad absorption

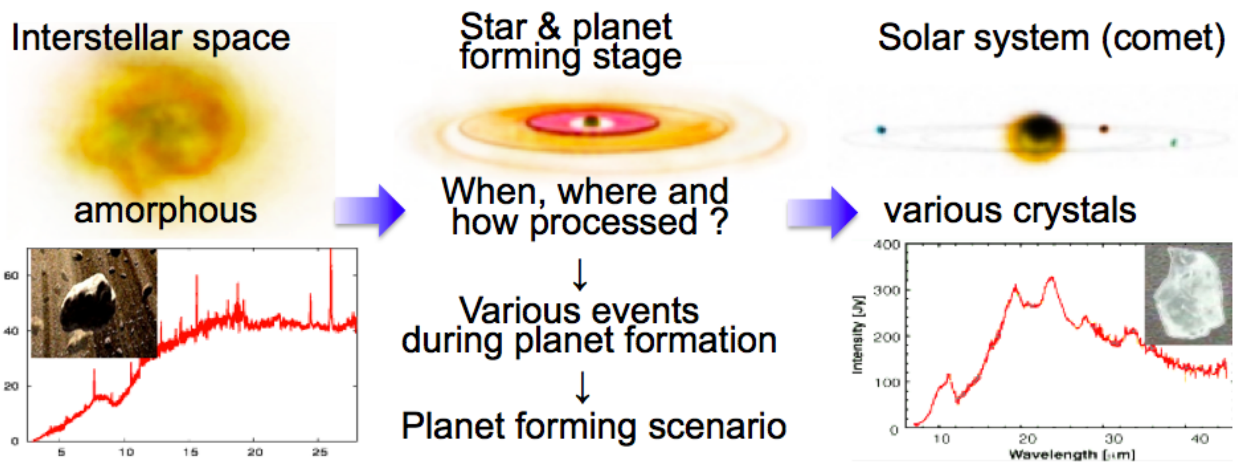

Figure 1. A Schematic image representing the evolution of silicates in planet-forming systems.

features (Kemper et al. 2004), while many kinds of crystalline silicates are found in our Solar system, which show sharp and complex mid-IR features. For example, crystalline forsterite and ferrosilite are detected from the ejecta of 9P/Tempel 1 comet (Lisse et al. 2006) by the *Spitzer*/IRS observation performed as a part of the Deep Impact project (A′Hearn et al. 2005). Our question is when and where these materials are processed. Crystallization of silicates requires annealing with temperature higher than 1,000 K (Hallenbeck et al. 2000). If silicates are crystallized at planet-forming stages, there must be some events, in which solid materials are heated to a temperature higher than 1,000 K.

RESULTS FROM *AKARI* OBSERVATIONS

One of the most important results from the *AKARI* all-sky survey is the detection of a new kind of debris disks, which have various kinds of a large amount of crystalline silicates (Fujiwara et al. 2009, 2010, 2012). These materials are not familiar in the ISM while they are common in our solar system. Furthermore, they are detected in orbits with lower equilibrium temperatures, which have not reached the generation temperature of these materials. As a next step, it is essential to spatially trace the processing of these materials in planet-forming disks.

CLUES FOR PLANET-FORMING SCENARIO

From future observations with the SCI, if concentration of crystalline silicates are found in the inner hot regions in younger objects, a transportation mechanism of materials from inner orbits to outer orbits will be suggested. If environmental dependence of crystallization is dominant, shock heating by external sources will be indicated. If crystalline silicates distribute in a spire-like hydrodynamic pattern in disks at early stages, shock heating by formation and destruction of massive fragments (Vorobyov 2011) will be indicated. These observational results will be clues for the events which occur in the planet-forming processes.

2.2. **Evolution of Hydrocarbon Molecules**

A question remains for hydrocarbons. In the interstellar space, hydrocarbons are dominated by aromatic molecules (Tielens 2008). However, those in our Solar system are different. For example, hydrocarbons in 81P/Wild 2 comet, which came from Kuiper-belt and should be filled with pre-solar grains, show features dominated by aliphatic molecules (Keller et al. 2006). Furthermore, complex organic molecules which may be the origin of life is not found in the interstellar space. Thus, they must be processed at star and planet-forming stages.

RESULTS FROM *AKARI* OBSERVATIONS AND ON-GOING ACTIVITIES WITH *AKARI* DATA

AKARI has revealed the all-sky distribution of the interstellar PAHs (Ishihara et al. 2010). On a global scale, PAHs show good spatial correlation with tracers of general ISM, such as CO, HI, and far-IR dust emissions. On a local scale, we recognize the variation of physical state and compositions of hydrocarbons (e.g. Kaneda et al. 2012). It is reasonable to presume that PAHs are incorporated into star- and planet- forming sites and processed in the local environment. *AKARI* stored near-IR (2–5 μm) spectra for about 10,000 fields, which were taken after exhaustion of liquid helium cryogen. They cover the 3.3 μm aromatic and 3.4 μm aliphatic features of hydrocarbons. By using these data, we can further make systematic studies of hydrocarbons in young stellar objects before the launch of *SPICA*. As a next step, it is important to trace the processing of hydrocarbons in planet-forming disks with spatially resolved spectroscopic observations.

CLUES FOR PLANET-FORMING SCENARIO

The observational results of hydrocarbons in disks contribute to understandings of the planet formation process. For example, we can investigate the hardness of local radiation fields in disks from observational properties of hydrocarbons (Berne et al. 2009). The number density of hydrocarbons is important for gas thermodynamics in disks, because they contribute to a majority of gas heating. Hydrocarbon molecules also play important roles in the size evolution of dust grains in disks. Dust grains with hydrocarbon mantle grow up faster than bare silicates because their elastic coefficients are smaller than silicates and comparable with that of H_2O ice.

2.3. Evolution of Size Distribution

The third topic is on the size evolution of dust grains. We believe that dust grains in debris disks are supplied from collisions of planetesimals. The fate of these dust grains depends on the relative strength of radiation pressure to gravitational force of the central star. This ratio of these forces is described as a function of the dust size and the spectral type of the central star as,

$$F_{\rm rad}/F_{\rm grav} \propto a^{-1}\rho^{-1}(L_*/M_*), \tag{1}$$

where $F_{\rm rad}$ is the force due to the radiation pressure from the central star, $F_{\rm grav}$ is the gravitational force, a is size of the dust grain, ρ is the density of the dust grain, L_* is the luminosity of the central star, and M_* is the mass of the central star. If this ratio is small, the replenished dust grains can stay near the parent orbit. If the radiation pressure is significant, the dust grains are blown out within a Kepler time.

RESULTS FROM *AKARI* OBSERVATIONS

We could investigate the effect of the parameter L_*/M_* of eq. (1), based on large samples from the *AKARI* all-sky survey. We made a systematic survey of debris disks from the data, and reported 24 excess objects (Fujiwara et al. 2013). Furthermore, we are making follow-up observations of accurate *J, H, Ks* photometries of the central stars of our excess candidates using the SIRIUS camera (Nagayama et al. 2003) on the IRSF telescope in South Africa. By improving the accuracy of the excess judgments, we obtained 13 additional 18 μm excess objects (Kiriyama et al. 2012). Our sample indicates that the inner radius of disks estimated from dust temperatures is a function of L_*/M_*.

CLUES FOR PLANET-FORMING SCENARIO

We will be able to investigate the effect of the parameter a of eq. (1) by spatially resolved observations of disks with the SCI. Because the dust temperature ($T_{\rm dust}$) is a function of the size of dust grains (a), and the distance from the central star (R) as,

$$T_{\rm dust} \propto a^{1/6}R^{-1/3}, \tag{2}$$

we can investigate the dust size (a) by comparing observed dust temperature with the calculated equilibrium dust temperature in the orbit (Kuruegel 2003). From the size of dust grains, we can investigate currently active planetesimal belts in the system because smaller grains are blown out faster than larger grains (e.g. Okamoto et al. 2004). We can also investigate the formation process of the disk by the spatial variations of size distributions of dust grains : radiation dominated, collision dominated, or Pointing-Robertson (P.-R.) effect dominated. We will also be able to detect the Solar-system type exo-Zodi. It may be difficult to detect 1 Zodi. level extra-solar systems with the SCI. But it is possible to detect solar-system type brighter exo-Zodi. that are dominated by the P.-R. drug effects instead of radiation pressure.

3. TARGETS

Our first strategy is observing spatial distributions of physical state and composition of solid materials in heavy disks, the size of which have been measured in previous studies. Figure 2 left shows the distance versus disk size of proto-planetary disks and debris disks[1]. There are 71 objects, which have disks larger than the inner working angle (IWA) of the SCI at 6 μm. Our second strategy is new detections and analysis of faint debris disks (exo-Zodi.). The SCI can make effective detections of circum-stellar disks if the IWA for a wavelength band matches the size of the orbit with the equilibrium dust temperature for the band. Figure 2 right compares the IWAs of the SCI for 6 and 20 μm with the loci of orbits for equilibrium temperatures of 300 K and 150 K, which show peak intensity at 6 and 20 μm, respectively. A histogram of the number of known dwarf stars as a function of distance (pc) is overlaid on Figure 2 right. At least, for 21 objects, the orbit corresponds to the equilibrium temperature for the SCI bands are spatially resolved by the SCI, though we will possibly be able to detect a larger number of disks due to the high sensitivity of the SCI.

4. SUMMARY

We propose a study on the chemical evolution of solid materials in planet-forming disks with the SCI. We can investigate events which occur at planet-forming stages by observing temporal and spatial variations of physical state and composition

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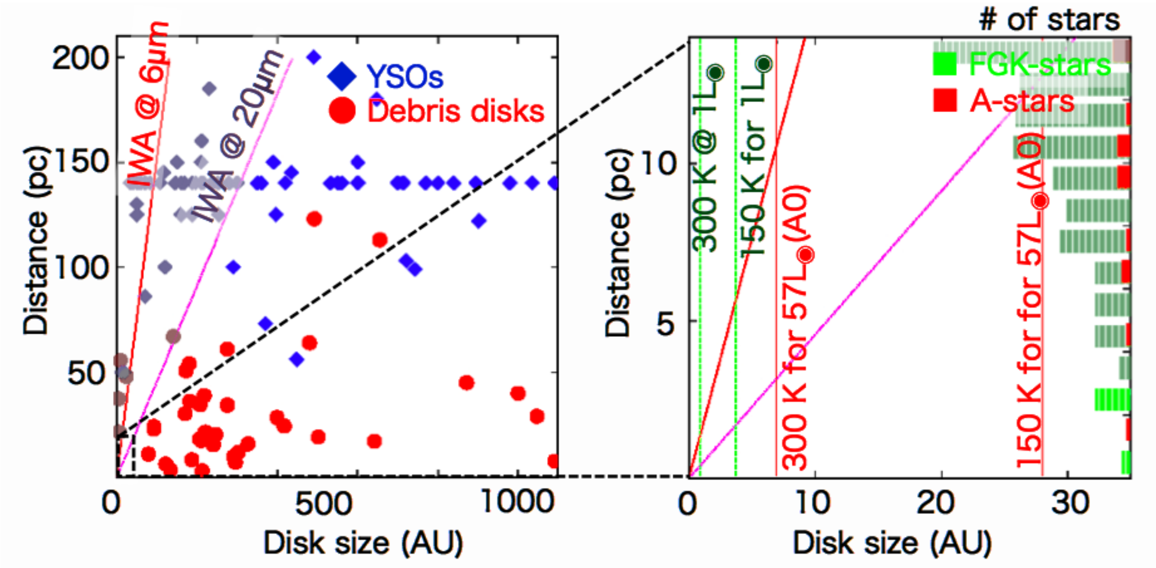

Figure 2. *Left:* Distance (pc) versus disk size (AU) of spatially resolved circum-stellar disks in previous observations[1]. Red points indicate debris disks while blue points indicate gaseous young stellar objects. Red and magenta lines indicate inner working angles (IWAs) of the SCI for $\lambda = 6\,\mu$m and 20 μm, respectively (Enya et al. in this volume). *Right:* Close-up of the left panel. Green vertical lines indicate loci where equilibrium temperatures reach 300 and 150 K in a disk of a G2V (1 $L_\odot$) type star. Red vertical lines indicate loci of 300 and 150 K in a disk of an A0V (57 $L_\odot$) type star. A histogram of the number of nearby (<15 pc) known stars is overlaid. The samples are taken from the Hipparcos catalog (Perryman et al. 1997).

of silicates and hydrocarbon molecules in disks. From size distributions of dust grains in disks, we can investigate the formation process of debris disks. This study is one of the important approaches for the origin of planetary systems and life. The required specifications for the instrument are the low-resolution ($\lambda/\Delta\lambda \sim 200$) mid-IR (6–28 μm) spectroscopic capability with the coronagraph.

This study takes advantages of the *SPICA*/SCI. It will be complementary with the studies performed by the coronagraph instruments on *JWST* and TMT. It is based on the scientific results from *AKARI*, previous successful Japanese infrared astronomical mission. It will be also based on the on-going activity for the data reduction of *AKARI*.

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