Direct Observation of Icy Grain Distribution and the Snow Line in Circumstellar Disks Using *SPICA*

Mitsuhiko Honda,[1] Akio K. Inoue,[2] and Keigo Enya[3]

[1]*Department of Mathematics and Physics, Kanagawa University, Japan*
[2]*College of General Education, Osaka Sangyo University, Japan*
[3]*Institute of Space and Astronautical Science, JAXA, Japan*

ABSTRACT

Icy grains are supposed to play various important and critical roles on planet formation, though observational understanding of the ice distribution is quite limited so far. With the *SPICA* observations of ice and its distribution in the various disks, we can make a significant progress on our understanding of the icy grain distribution in the disk. In instruments proposed for *SPICA*, especially the SCI has big potential for tracing the distribution of the icy grain directly thanks to the function of the coroangraphic spectroscopy. The aims of the direct observations with the SCI are (1) to establish the existence of the water ice in the debris disk, (2) to measure spatial distribution of ice grain, and (3) to challenge to trace the "snow line", for the first time. Combined observations of SAFARI (aiming for 44 μm water ice feature) and SCI (aiming for 3, 6.2 μm water ice feature) will be especially effective for establishing the presence/non-presence of water ice grain in the debris disks.

1. IMPORTANCE OF ICE IN THE DISK FOR THE PLANET FORMATION

Ices, mostly consist of water ice, are supposed to play various important and critical roles on planet formation. Volatiles such as icy dust are not supposed to exist at the inner warm region of the disk where they immediately evaporate. While icy dust can indeed present at the outer cold region of the disk, thus there should be an ice condensation/sublimation front called "snow line" in the disk which are schematically shown in Figure 1. Following Hayashi et al. (1985), surface density of solid matter increases beyond the snow line due to the increase of the icy dust mass, which enables to form a massive 10 earth-mass solid core of the gas giant. This is the popular theory to explain why the rocky planets orbit at the inner region of the Solar system, while the gas-giants exist at the further out. To confirm this theory, it is strongly desired to observe the distribution of icy dust in the disk and location of "snow line".

Furthermore, to understand the origin of the water/ocean in the Earth, our understanding of the water ice distribution in the disk is the fundamental information, because there is a scenario that icy planetesimals or comets bring the water to Earth (Morbidelli et al. 2000; Raymond et al. 2004), of which depend on the assumption of water ice distribution of the disk. In addition, Yurimoto & Kuramoto (2004) suggested that water ice evaporation at the inner region of the disk brought the oxygen isotope anomaly seen in the meteorites. Thus our robust understanding of the water ice distribution in the disk is critical for various scenario and theories.

However, as will be stated later, our observational understanding of the ice distribution is quite limited so far, thus observations of the ice distribution in the disk are of great importance for various research fields and topics. With the *SPICA* observations of ice and its distribution in the various disks, we can make a significant progress on our understanding of ice grain distribution in the disk, which also enables us to verify the assumption of above scenario and theories, universality/diversity of ice distribution, and unique/common nature of our Solar system.

2. PREVIOUS OBSERVATIONS

Although a lot of theoretical studies on ice in the disk have been done so far, observations of the ice in the disk is limited. For example, the spatial distribution of the ice in the disk is not well constrained and no one directly resolved the "snow line" so far. We only know that ice grain can be present toward line of sight to the edge-on protoplanetary disks using the 3 μm water ice absorption feature (Terada et al. 2007; Aikawa et al. 2012), which indicate there is ice in some area (probably cold region) of the disk. The 44 μm and 62 μm emission features from the water ice grains are detected toward a few sources (Malfait et al. 1999), but the number of the detection is quite limited. Recently, using near-infrared multiband imaging of the scattered light from the protoplanetary disks from the ground-based telescope, the radial distribution of ice grains has been investigated (see Figure 2; Inoue et al. 2008; Honda et al. 2009). However, due to the lower spectral resolution, such multi-band imaging approach is difficult to distinguish water ice (~3.1 μm) and hydrated minerals (~2.7 μm), thus spatially and spectrally high resolution 2.5–5 μm observation of the disk is strongly desired. As for the debris disks, even the presence of ice grains is not clearly established observationally. A tentative detection of the 62 μm water ice emission feature is claimed (Chen et al. 2008), however, the significance is not high and there is little observational evidence for the water ice in the debris disks. With the *SPICA*, we can make a breakthrough

Honda, Inoue and Enya

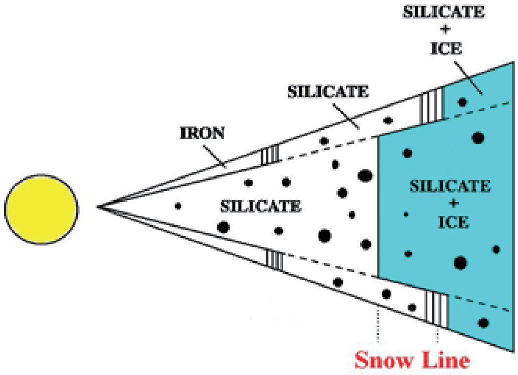

Figure 1. Schematic figure of the distribution of silicate and ice in the disk. Water ice sublimation front is called snow line (adopted from Chiang et al. (2001).)

to our understanding of the water ice in the disk. *SPICA*/SCI can make a spatially-resolved coronagraphic spectroscopic observations of the disk (Enya et al. 2011; Kotani et al. 2012), and *SPICA*/SAFARI will enable us to make observations of 44 μm water ice emission features from the disk. Such observations will bring us the first systematic studies on ice in the disk, which enables us to understand the evolution of the ice from the young protoplanetary disks (~ a few Myrs) to the old debris disks (more than 10 Myrs).

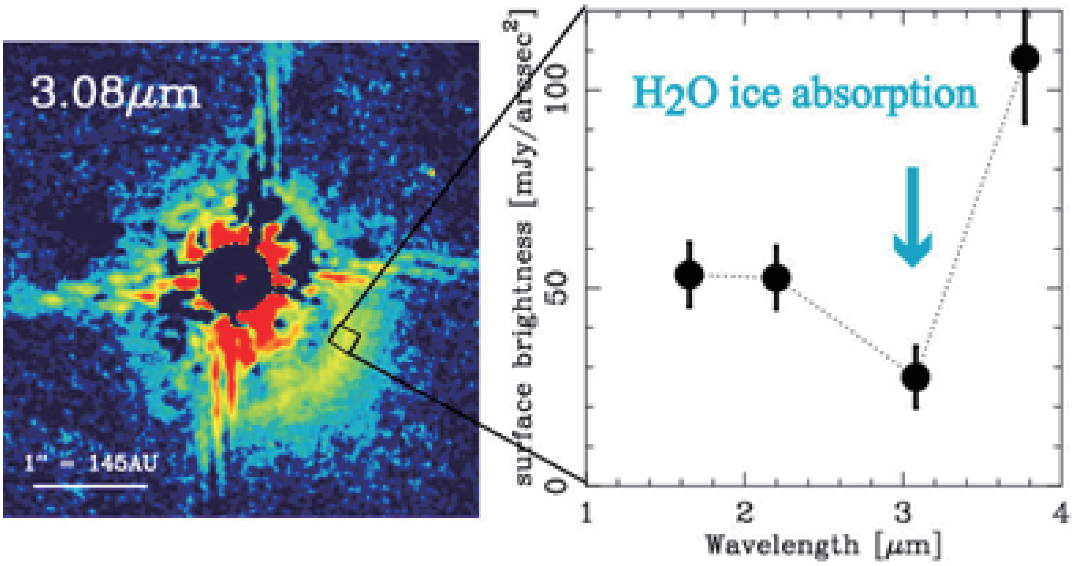

Figure 2. Ground-based trial for water ice grain detection from the scattered light from the disk (Honda et al. 2009).

3. WATER ICE DISTRIBUTION AS REVEALED BY *SPICA*/SCI

The aim of the *SPICA*/SCI observations in the context discussed here will be (1) the establishment of the existence of the water ice in the debris disk and (2) the detection of the water ice "snow line" directly for the first time. As already stated, it is not clear whether water ice grains exist in the debris disk. This is because the scattered light from the debris disk is relatively faint, thus it is hard to get a high S/N ratio imaging/spectroscopy data of 3 μm absorption in the thermal infrared wavelengths (2.5–5 μm) from the ground. Furthermore, the behavior of the "3 μm absorption" is expected to show a bit complex profile due to the optically thin dust scattering (Inoue et al. 2008), therefore it will require the spectroscopic observations to trace the water ice feature. Such capability is only provided by *SPICA*/SCI. To establish the existence or non-existence of the water ice grains in the debris disk is important from the view of the origin of the debris dust. When we confirm the water ice grains in the debris disk, it naturally indicates that this dust comes from the collision of ice-bearing planetesimals (cometesimals). On the other hand, when we find that the debris dust does not contain water ice, it is a surprising result that the debris dust originates non-ice-bearing planetesimals such as rocky asteroids even though its temperature is low enough. The radial distribution of the ice and detection of snow line are also of great interest. The radial position of the snow line is a function of the stellar luminosity and is predicted to be 10–30 AU assuming the stellar luminosity of 1–10 $L_\odot$ (Oka et al. 2012). Since SCI will provide the coronagraphic spectroscopy (IWA is 0.″4–0.″8 at 3.5 μm) between 2.5–5 μm with a resolving power $R\sim100$, we can resolve the snow line of the debris disk within ~30 pc from the earth. The possible targets will be the nearby Vega-like stars. We estimated the required contrast to be $\sim10^{-5}$ for detecting β Pic disk at 1.″5 from the central star (Mouillet et al. 1997). It is apparent that the observational confirmation of the snow line in the disk is fundamentally important to our understanding of planet formation and disk evolution. On the other hand, due to the limited spatial resolution, it would be difficult to resolve the snow line of the protoplanetary disks. However, thanks to the unique *SPICA*/SCI capability of coronagraphic spectroscopy, we will be able to obtain the scattered light spectroscopy from the outer region of the protoplanetary disks. With such spectra, we can clearly distinguish the water ice and hydrated minerals. Furthermore, we can trace not only water ice but also less abundant ices such as CO, CO_2, and so on. Therefore, we can investigate the evolution of ice in the disk systematically for the first time.

4. SYNERGY WITH SAFARI ICE OBSERVATIONS

SPICA/SAFARI far-infrared spectroscopy will also contribute to our understanding of the ice grains in the disk. Although one of the strongest feature of the water ice is the 44 μm feature, this wavelength is not accessed since ISO (SST and Hershel did not). Thus the systematic observations of 44 μm feature by *SPICA*/SAFARI will bring important information on ice in the disk. Clearly, we can expect a synergy with *SPICA*/SCI observations of water ices. In general, features of solid matter is relatively broad compared to the sharp lines of gases which leads to contamination/blending from other dust features, thus single feature identification is hazardous and multiple identification of the feature is required for reliable identification. Combined observations of SAFARI (aiming for 44 μm water ice feature) and SCI (aiming for 3 μm water ice feature) will be especially effective for establishing the presence/non-presence of water ice grains in the debris disks.

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