WATER ICE AT THE SURFACE OF THE HD 100546 DISK

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ABSTRACT

We made near-infrared multicolor imaging observations of a disk around Herbig Be star HD 100546 using Gemini/NICI K (2.2 μm), H2O ice (3.06 μm), and L’ (3.8 μm) disk images were obtained and we found a 3.1 μm absorption feature in the scattered light spectrum, likely due to water ice grains at the disk surface. We compared the observed depth of the ice absorption feature with the disk model based on Oka et al., including the water ice photodesorption effect by stellar UV photons. The observed absorption depth can be explained by both the disk models with and without the photodesorption effect within the measurement accuracy, but the model with photodesorption effects is slightly more favored, implying that the UV photons play an important role in the survival/destruction of ice grains at the Herbig Ae/Be disk surface. Further improvement to the accuracy of the observations of the water ice absorption depth is needed to constrain the disk models.

Key words: circumstellar matter – protoplanetary disks – stars: pre-main sequence

1. INTRODUCTION

In planet formation theories, water ice is believed to play many important roles. For example, ice enhances the surface density of solid material in the cold outer part of a protoplanetary disk, which promotes the formation of massive cores of gaseous planets (e.g., Hayashi et al. 1985). Thus the ice sublimation/condensation front, called a snow line, is considered to be the boundary of the formation regions of the terrestrial and Jovian planets. The snow line is also suggested as a possible formation site of the planetesimals (Brauer et al. 2008). Furthermore, icy planetesimals or comets may bring water to the Earth (e.g., Morbidelli et al. 2000). Recently, numerous water vapor emission lines were detected in protoplanetary disks (e.g., Carr & Najita 2008; Salyk et al. 2008), and the position of the snow line has been inferred from the modeling (Zhang et al. 2013). On the other hand, observations of water ice distribution in the disk are limited at this moment. Crystalline H2O ice emission features at 44 and 62 μm have been found for several Herbig Ae/Be stars (Malfait et al. 1999; Meeus et al. 2001), but the limited angular resolution in far-infrared wavelengths hampers us from obtaining the ice distribution. While near-infrared (NIR) water ice absorption toward edge-on disks is reported (Pontoppidan et al. 2005; Terada et al. 2007), the ice absorption is formed somewhere through the line of sight, and thus it is still not straightforward to derive its radial distribution in the disk.

Inoue et al. (2008) proposed a new observational method to investigate the radial distribution of ice in face-on disks. They showed that ice absorption should also be imprinted in the light scattered by icy grains and that multi-wavelength imaging in NIR wavebands, including the H2O band at 3.1 μm, is a useful tool for constraining the ice distribution in the disk. Honda et al. (2009) applied this method to the circumstellar disk around a Herbig Fe star HD 142527 and showed that water ice grains are present in a disk surface at a radial distance of 140 au. On the other hand, Oka et al. (2012) calculated the stability and distribution of water ice grains in the disk surface considering the photodesorption (photosputtering) process by UV irradiation. They showed that the water ice grains can be rapidly destroyed at the disk surface around A/B type stars due to UV photodesorption processes. Although Honda et al. (2009) already detected water ice grains in the disk surface around F-type star HD 142527, it would be interesting to observe water ice grains in the disk surface around A/B type stars in order to check the prediction by Oka et al. (2012). In this paper, we show observations of water ice grains in the disk surface around Herbig Be star HD 100546 and discuss the presence/stability of water ice grains in the disk surface. Part of our data are already published in Currie et al. (2014), focusing on the planet candidate (Quanz et al. 2013).

2. OBSERVATIONS AND DATA REDUCTION

Direct imaging observations of Herbig Be star HD 100546 using the K band filter (central wavelength λc = 2.20 μm, and width Δλ = 0.33 μm), the H2O ice filter (λc = 3.06 μm, Δλ = 0.15 μm) and the L’ band filter (λc = 3.78 μm, Δλ = 0.70 μm) were performed using the Near Infrared Coronagraphic Imager (NICI; Chun et al. 2008) on the Gemini South Telescope on 2012 March 31. We fixed the instrument rotator during the observations of both the object and point-spread function (PSF) reference stars to fix the pupil and to obtain stable PSF patterns. A full width at half maximum (FWHM) of 0′′10 was achieved at all the wavelengths using the instrument AO system. The central region close to the central star was saturated; however, the outer part (r > 0′′22) is not saturated and can be used for disk observations.
The total exposure times were 1672 s, 3192 s, and 2128 s for K, H₂O ice, and L′, respectively. As a PSF reference star, we observed HR 4977 (A0V) just before/after HD 100546. HD 105116 (K band) and BS 4638 (H₂O ice and L′ band) were observed as photometric standard stars. The mean flux density for BS 4638 at 3.06 μm was estimated by scaling Kurucz’s stellar model atmosphere (T eff = 19,500 K, log g = 3.95, solar metallicity) to match the flux density in K (Allen & Cragg 1983; Carter & Meadows 1995; Soubiran et al. 2010). The calculated flux density was 5.87 Jy at 3.06 μm. Observation parameters are summarized in Table 1.

The images were first processed using the IRAF packages for dark subtraction, flat-fielding with sky flats, bad pixel correction, and sky subtraction. Since the stellar halo was very bright, PSF subtraction was required to investigate the faint structure near the central star. The reference PSF was chosen to match the PSF of HD 100546 for each frame, with careful visual inspection to determine whether the circular bright halo of the central point source was well-suppressed after PSF subtraction. The reference PSF was made by combining the adopted reference star images. The flux scaling of the reference PSF was performed so that no region had negative intensity after the subtraction, particularly the outer part of the central radius (r > 0.25). The reference PSF was shifted to match the central position and subtracted from each frame of HD 100546. Each subtracted frame was rotated to match the north direction. Then, the final PSF-subtracted image was made by combining the rotated object frames. In order to estimate the systematic uncertainty of the surface brightness due to the PSF subtraction process, we changed the scaling of the PSF before subtraction, and measured the acceptable range of the scaling factor. The systematic uncertainty of the surface brightness was measured to be 20%, depending on the position. This systematic uncertainty was typically larger than the statistical error derived from the standard deviation of the best PSF-subtracted object frames. The final PSF-subtracted images of HD 100546 disk are shown in Figure 1.

### Table 1

| Object     | Filter | Integ. Time (s) | Comment            |
|------------|--------|----------------|--------------------|
| HD 100546  | K      | 1672           |                    |
| HR 4977    | K      | 456            | PSF reference      |
| HD 105116  | K      | 152            | photometric reference |
| HD 100546  | H₂O ice| 3192           |                    |
| HR 4977    | H₂O ice| 2280           | PSF reference      |
| BS 4638    | H₂O ice| 152            | photometric reference |
| HD 100546  | L′      | 2128           |                    |
| HR 4977    | L′      | 532            | PSF reference      |
| BS 4638    | L′      | 152            | photometric reference |

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### 3. RESULTS

In Figure 1, an extended disk structure is detected in all three bands. Especially in the L′ band, a dark lane is seen in the southwest direction from the star, showing a typical inclined flaring disk morphology. The northeast side is facing us, while the southwest scattered light beyond the dark lane could be the scattered light from the other side of the disk surface. This morphology is consistent with previous studies (Mulders et al. 2011, 2013; Quanz et al. 2011; Avenhaus et al. 2014).

![Figure 1. PSF-subtracted images of HD 100546 disk at K(top), H₂O ice (middle), and L′ (bottom). The brightness unit is mJy arcsec⁻². North is up and the east is to the left.](image-url)
Using these three color images, we extracted the scattered light spectra of different regions of the protoplanetary disk. Since the position angle (PA) of this disk major axis is 145° (Mulders et al. 2011), we set the 0′′162 (9 pixel) square region along with the major and minor axes at distances of 0′′360, 0′′522, 0′′684, 0′′846, and 1′′008 from the central star. Figure 2. Positions of the spectra-extracted region shown in the L′ image of HD 100546 disk. 0′′162 square regions were set along the major (SE-NW) and minor (SW-NE) axes of the disk at positions of 0′′360, 0′′522, 0′′684, 0′′846, and 1′′008 from the central star.

The shallowness of this ice absorption feature could be due to the loss of ice grains at the disk surface. Oka et al. (2012) claimed that the water ice grains can be quickly destroyed at the disk surface around A/B type stars due to their strong UV photodesorption. To assess their prediction, a quantitative comparison with the model prediction is required.

4. DISCUSSION

4.1. 3.1 μm Absorption Optical Depth τ

Since we are interested in the water ice distribution in the disk and since it is necessary to quantify the absorption feature depth for comparison with the disk model, we will use the water ice absorption optical depth τ, following convention. Note that the absorption feature in the scattered light spectra is not a pure absorption but rather is an albedo effect (see Inoue et al. 2008); however, the optical depth τ is often used as an indicator of the depth of the feature, thus we use it for descriptive purposes. The optical depth is derived from the following formula as usual:

\[
\tau = \ln \left( \frac{I_{\text{cont}}}{I_{\text{obs}}} \right),
\]

where \(I_{\text{obs}}\) is the observed surface brightness at the H₂O band and \(I_{\text{cont}}\) is the estimated continuum surface brightness interpolated by a power law using the K and L′ brightnesses as shown below.

\[
\log(I_{\text{cont}}) = \log(I_{\text{obs}}) + \frac{\log(I_{L}) - \log(I_{K})}{\log(A_{L}) - \log(A_{K})} \times (\log(A_{L}) - \log(A_{K})) + \log(I_{K})
\]

where \(I_{K}^{\text{obs}}\) and \(I_{L}^{\text{obs}}\) are the observed surface brightness at the K and L′ filters, respectively, while \(A_{K}, A_{L},\) and \(A_{L′}\) are the central wavelengths of the K, H₂O and L′ filters, respectively. As the ice absorption depth becomes deeper, the optical depth τ value becomes larger. We derived the τ at each extracted-disk region, and these values ranged from 0 to 2. The τ map is shown in Figure 4. In this figure, the central region (<0′′22) is masked due to the saturation problem and the outer region (r > 1′′26) is also masked because of the low signal-to-noise ratio (S/N). In general, the southwestern (SW) region shows relatively high τ values (τ ≥ 1), which coincides with the dark lane seen in the L′ disk image. This can be qualitatively understood as some scattered light of this region possibly coming from the back side of the disk, which suffers more extinction than that from the front side of the disk. Other than the SW region, a possible trend that could be recognized is that the inner region shows lower optical depth (τ ≤ 1), which might imply a decrease of the ice grains toward the central star, as expected, although the patchy structure in the τ map hampers us from drawing a solid conclusion.

Since the τ map shows significant asymmetry along the disk minor axis (SW-NE) and scattered light intensity depends on the scattering geometry, discussing the scattered light spectra along the disk minor axis is more complicated than discussing that along the disk major axis (SE-NW). Thus we focus on a comparison with the model along the disk major axis. The radial distributions of τ, along with the disk major axis, are summarized in Table 2 and shown in Figure 5. As already described, the error is dominated by systematic error, but not a statistical error, and is estimated to be 20% of the surface brightness at each waveband.

4.2. Comparison with the Disk Model Including the Photodesorption Effect

To discuss whether the observed absorption feature is consistent with the model predictions, we derived the expected τ value based on the disk model calculations by Oka et al. (2012), who included the effect of the photodesorption of water ice grains by UV photons from the central star. Our calculation model consists of two parts: one is the disk structure calculation (Model Part 1) in which the density and temperature distributions in the disk, as well as the snow line, are obtained, and the other is the radiative transfer calculation (Model Part 2) that simulates observations.

In Model Part 1, we obtain the location of the snow line, which is primarily determined using two factors: the thermal sublimation and the photodesorption of water ice particles. In order to evaluate the thermal sublimation of ice particles, we obtain the temperature and the gas density distributions in the disk as follows. The temperature in the disk is determined by the energy balance between heating and cooling. Heating sources for the disk include the radiation from the central star illuminating the surface of the disk and the viscous heating due
to disk accretion. The cooling process is the radiative transfer, which finally emits energy from the disk to outer space by means of radiation. The surface density distribution is provided as a model parameter, and the gas density distribution along the vertical direction with respect to the disk is determined so that the hydrostatic equilibrium is achieved. The temperature in the disk and the shape of the disk surface affect each other, because the angle between the direction of the light from the central star and the disk surface determines the radiative energy received by the disk surface, and the inclination of the disk surface is a function of the temperature distribution. Thus, the temperature and the disk surface determines the radiative energy received by the disk surface, and the inclination of the disk surface is a function of the temperature distribution. Thus, the temperature distribution is determined.

### Table 2

Measured Surface Brightness and Optical Depth $\tau$ along the Disk Major Axis

| Distance(au) | $I_{\text{obs}}^{\text{K}}$ | $I_{\text{obs}}^{\text{H}_2\text{O}}$ | $I_{\text{obs}}^{\text{L}}$ | $\tau$ |
|-------------|-----------------|-----------------|-----------------|-----|
| SE          |                 |                 |                 |     |
| 104         | 17.5 ± 3.5      | 10.0 ± 2.0      | 39.0 ± 7.8      | 1.06 ± 0.39 |
| 87          | 31.3 ± 6.3      | 18.4 ± 3.7      | 65 ± 13         | 0.99 ± 0.39  |
| 70          | 60 ± 12         | 35.3 ± 7.1      | 111 ± 22        | 0.92 ± 0.39  |
| 54          | 126 ± 25        | 71 ± 14         | 210 ± 42        | 0.90 ± 0.39  |
| 37          | 304 ± 61        | 223 ± 45        | 485 ± 97        | 0.61 ± 0.39  |
| NW          |                 |                 |                 |     |
| 104         | 18.9 ± 3.8      | 10.8 ± 2.2      | 37.5 ± 7.5      | 0.99 ± 0.39  |
| 87          | 31.4 ± 6.3      | 22.8 ± 4.6      | 63 ± 13         | 0.76 ± 0.39  |
| 70          | 52 ± 10         | 39.7 ± 7.9      | 109 ± 22        | 0.74 ± 0.39  |
| 54          | 106 ± 21        | 92 ± 18         | 219 ± 44        | 0.59 ± 0.39  |
| 37          | 250 ± 50        | 237 ± 47        | 506 ± 100       | 0.50 ± 0.39  |

Note.

$^a$ In mJy arcsec$^{-2}$.

![Figure 3](image3.png) Extracted spectra along the major (SE-NW) and minor (SW-NE) axes at positions of $0''360, 0''522, 0''684, 0''846$, and $1''008$ from the central star shown in Figure 2. The size of each extracted area is a square region with $0''162$ (9 pixels) on the side. In the spectra of almost all of the regions, a shallow dip at $3.06 \mu$m is seen, likely due to water ice absorption.

![Figure 4](image4.png) $\tau_{\text{H}_2\text{O}}$ map derived from our data. Since the inner region ($r < 0''22$) suffered from saturation and the outer region ($r > 1''26$) has a low signal-to-noise ratio, these regions are masked.
observations. The photodesorption effect is not included in the model of Oka et al. (2012), although the observed \( \tau \) values match with both the disk models with and without the photodesorption effect, the model with the photodesorption effect seems to be a slightly better match with the observations, at least for theNW region.

4.3. Future Prospects

It is worth noting that the water vapor is reported to be depleted in the disk atmosphere of Herbig Ae/Be stars by the observations of water vapor lines (Fedele et al. 2011). A plausible explanation is that this is due to the photodissociation of water by UV photons in the disk atmosphere. Although the photodissociation effect is not included in the model of Oka et al. (2012), they noted that the photodesorption process is very important for the water ice stability, while the photodissociation effect is crucial for water vapor destruction in the disk surface. In any case, the UV photons seem to play an important role in the survival of both water ice and gas in the disk surface around Herbig Ae/Be stars.

It is apparent that our data do not have a high enough S/N to distinguish between the models with and without a photodesorption process. This is because the systematic error dominates over the total error. Further observations with better photometric accuracy are strongly desired. Since the observations shown here have employed techniques similar to the so-called “lucky imaging” technique, an improvement of systematic error is principally limited. However, when we make use of the polarimetric differential imaging (PDI) and/or spectroscopy, the systematic error can be significantly reduced and this will change the situation dramatically. Thus L-band PDI and/or spectroscopy are promising for advancing these observations. Furthermore, other effects on the depth of water ice absorption, such as grain size, grain shape, grain structure, ice/rock ratio (abundance), dust settling, turbulent mixing, and so on, should be investigated in future theoretical studies in order.

\begin{table}[h]
\centering
\caption{Parameters Used in the Model}
\begin{tabular}{ll}
\hline
Parameter & Values \\
\hline
Stellar effective temperature \( T_\text{eff} \) & 10,500 K \\
Stellar mass \( M_\star \) & 2.4 \( M_\odot \) \\
Stellar luminosity \( L_\star \) & 36 \( L_\odot \) \\
Stellar radius \( R_\star \) & 1.8 \( R_\odot \) \\
Distance \( d \) & 103 pc \\
	Disk inner radius \( r_{\text{in}} \) & 0.5 au \\
	Disk outer radius \( r_{\text{out}} \) & 500 au \\
	Disk inclination & 45° \\
	Surface density at 1 au & 45 g cm\(^{-2}\) \\
	Surface density power-law index \( q \) & 1.0 \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Solid lines are radial profiles of the optical depth \( \tau \) of disk models based on Oka et al. (2012), with or without photodesorption (photosputtering; PS) along the disk major axis. The overplotted points are the measured \( \tau \) along the disk major axis (SE, NW directions). SE data points are slightly shifted (+1 au) to avoid overlapping with the NW error bars. Both disk models are consistent with the measurements; however, the model with the photodesorption effect (“with PS”) might show a slightly better match with the observations.}
\end{figure}
to comprehensively understand water ice distribution in protoplanetary disks.

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