PHOTOMETRIC MEASUREMENTS OF H$_2$O ICE CRYSTALLINITY ON TRANS-NEPTUNIAN OBJECTS

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Received 2016 January 22; revised 2016 May 16; accepted 2016 June 9; published 2016 August 8

ABSTRACT

We present a measurement of H$_2$O ice crystallinity on the surface of trans-neptunian objects with near-infrared narrow-band imaging. The newly developed photometric technique allows us to efficiently determine the strength of a 1.65 $\mu$m absorption feature in crystalline H$_2$O ice. Our data for three large objects—Haumea, Quaoar, and Orcus— which are known to contain crystalline H$_2$O ice on the surfaces, show a reasonable result with high fractions of the crystalline phase. It can also be pointed out that if the grain size of H$_2$O ice is larger than ~20 $\mu$m, the crystallinities of these objects are obviously below 1.0, which suggests the presence of the amorphous phase. In particular, Orcus exhibits a high abundance of amorphous H$_2$O ice compared to Haumea and Quaoar, possibly indicating a correlation between the bulk density of the bodies and the degree of surface crystallization. We also found the presence of crystalline H$_2$O ice on Typhon and 2008 AP$_{129}$, both of which are smaller than the minimum size limit for inducing cryovolcanism as well as a transition from amorphous to crystalline phase through thermal evolution due to the decay of long-lived isotopes.

Key words: Kuiper belt: general – planets and satellites: surfaces

1. INTRODUCTION

Trans-neptunian objects (TNOs) are believed to be ice-rich bodies formed in regions distant from the Sun. Several kinds of icy species have been detected from TNOs by previous visible and near-infrared spectroscopic observations. H$_2$O ice, known as the most abundant volatile material in the solar system, is generally the primary component on icy surfaces of TNOs except for the largest objects, such as Pluto, Eris, Sedna, and Makemake, which are covered by CH$_4$ ice (e.g., Owen et al. 1993; Barucci et al. 2005; Brown et al. 2005; Licandro et al. 2006). H$_2$O ice is condensed from the vapor in nebula gas in the amorphous phase in a cold environment far below 100 K (Jenniskens et al. 1998, p. 139; Mastrapa et al. 2008). The transition from amorphous to crystalline ice requires ~1 hr at 130 K, but ~10$^3$ yr at 90 K (Jenniskens & Blake 1996). Primitive H$_2$O ice remains in an amorphous state from the beginning of the solar system if the temperature remains below ~80 K. Although the typical surface temperature of TNOs is ~40–60 K (Stansberry et al. 2008, p. 161), the spectra of large TNOs clearly exhibit the absorption feature of crystalline H$_2$O ice at 1.65 $\mu$m, e.g., Charon (Brown & Calvin 2000; Buie & Grundy 2000), Quaoar (Jewitt & Luu 2004; Dalle Ore et al. 2009), Haumea (Barkume et al. 2006; Merlin et al. 2007; Trujillo et al. 2007), and Orcus (de Bergh et al. 2005; Barucci et al. 2008). Haumea’s satellite Hi’iaka (Dumas et al. 2011) and collisional family members (Barkume et al. 2006) are also known to be covered by crystalline H$_2$O ice. Additionally, several moderate-size TNOs/Centaur have been suggested to have surfaces covered in crystalline H$_2$O ice (e.g., Barucci et al. 2011).

These objects are highly likely to have experienced a certain process resulting in the production and/or provision of crystalline H$_2$O ice on their surfaces. Several mechanisms have been suggested, including radiogenic heating (Merk & Prialnik 2006; Guilbert-Lepoutre et al. 2011), cryovolcanism (Cook et al. 2007; Desch et al. 2009), and micrometeorite impact annealing (Porter et al. 2010). However, it remains unknown which of them primarily causes the presence of crystalline H$_2$O ice on the surfaces. Elucidation of the generation process could provide insight into the formation, evolution, and possibly the interior structure of icy small bodies in the outer solar system. For this purpose, it is essential to answer the following questions: (i) Is the presence of crystalline H$_2$O ice on the surfaces ubiquitous among TNOs? If yes, is the crystallinity constant among them? (ii) Does the presence/abundance of crystalline ice depend on the size of the body and/or other parameters? In the former case, what is the size limit for the surface to contain crystalline ice?

In the present circumstances, however, our general knowledge regarding the abundance distribution of surface crystallinity in the TNO population is still poor because of a lack of observational constraints. Most of the known TNOs are too faint for us to obtain spectra with sufficient quality to accurately determine the ratio of crystalline and amorphous phases on their surfaces, even using the largest class of telescopes.

In this paper, we introduce a new technique for measuring H$_2$O ice crystallinity on icy small bodies with near-infrared photometric data acquired by the Subaru telescope. We use the narrow-band filter called “NB1657,” allowing us to evaluate the strength of 1.65 $\mu$m absorption of crystalline H$_2$O with high precision. The results demonstrate that this method is useful for an effective survey of the crystalline ice abundance over a large number of TNOs.

2. OBSERVATIONS AND DATA REDUCTION

Our observation was carried out on 2013 April 7 with the Multi-Object InfraRed Camera and Spectrograph (MOIRCS: Ichikawa et al. 2006; Suzuki et al. 2008) mounted on the 8.2 m
Figure 1. Near-infrared reflectance spectra of H$_2$O ice in crystalline (solid line) and amorphous (gray line) states (from Mastrapa et al. 2008). The dashed and dotted curves show transmission curves of the H-band and NB1657 filters installed in MOIRCS, respectively.

Subaru telescope. MOIRCS consists of two 2048 \times 2048 arrays with a pixel scale of 0.′′117, each of which covers a field of view 4′ × 3′.5. We performed near-infrared imaging using the H band and the narrow-band filter NB1657. The NB1657, with a center wavelength of 1.657 \mu m and a bandwidth of 0.019 \mu m (Koyama et al. 2014), is suitable for diagnosing the absorption of crystalline H$_2$O ice at 1.65 \mu m (see Figure 1). The sky condition was photometric, with a seeing size of mostly 0.′′6–0.′′8.

Our target objects consist of the seven TNOs listed in Table 1. These objects have been reported to contain H$_2$O ice. The observational circumstances are shown in Table 2. Every image was taken with exposures of 42–80 s in the H band and 90–180 s in the NB1657 under sidereal tracking. The sky motion within the exposure time is sufficiently small than the seeing size that each target object can be treated as a point source. The NB1657 data were obtained between just before and just after H-band imagings so as to reduce color uncertainty caused by variation in rotational brightness.

Data reduction was conducted using IRAF produced by the National Optical Astronomy Observatories (NOAO) and MCSRED$^5$ (Tanaka et al. 2011) with standard processes: linearity correction, flat-fielding, sky subtraction, and distortion correction. Images with each band were shifted according to the sky motion of a target object and were combined. Position-matched composite images were also created for determining the point-spread function (PSF) from the field stars. We adopted aperture photometry for flux measurement using the IRAF/APPHOT package. The aperture correction technique has been applied to increase signal-to-noise ratio. Summed pixel counts within a small aperture with radius of \sim 0.5–0.8 arcsec were converted into total flux based on the flux ratio computed from the PSF profile given by the field stars. Haumea is an exception because of a lack of field stars and thus its flux was directly measured with a large aperture (2.2 arcsec in radius). The H-band magnitude and H–NB1657 index were calibrated with a G2V star, 2MASS J06430376-0117471 (H = 13.630 ± 0.031 mag) or 2MASS J16375427+4052592 (H = 13.161 ± 0.027 mag), taken within 2.5 hr of target data acquisition. \( \Delta (H– NB1657) \) is defined as the residual after subtracting the Sun’s color from the measured H–NB1657 index.

The results of photometry are shown in Table 3. Most of the H–NB1657 indexes have been determined with an uncertainty of \sim 0.02 mag or less, allowing us to estimate the abundance of crystalline H$_2$O ice on the surface of the target objects. Unfortunately, however, Ceto contains a large photometric error because of the insufficient exposure time (500 s with the H band and 720 s with the NB1657 filters) due to restriction of the observation time. We exclude Ceto from the sample for the following analysis.

3. RESULTS

3.1. Model Spectra

From the measured H–NB1657 index, we obtain the fraction of the crystalline phase in the H$_2$O ice spectrum, hereinafter called the “crystallinity factor” (f$_{\text{crys}}$). In this paper, the reflectance spectrum of phase-mixed H$_2$O ice, S$_{\text{H}_2\text{O}}(\lambda)$ (\lambda is wavelength in \mu m), is represented by a linear sum of the crystalline and amorphous spectra (S$_{\text{crys}}(\lambda)$ and S$_{\text{amor}}(\lambda)$, respectively) as defined in Newman et al. (2008), i.e.,

\[
S_{\text{H}_2\text{O}}(\lambda) = f_{\text{crys}} S_{\text{crys}}(\lambda) + (1 - f_{\text{crys}}) S_{\text{amor}}(\lambda). \tag{1}
\]

Modeling reflectance spectra of the target objects is required to convert the 1.65 \mu m absorption strength derived from \( \Delta (H– NB1657) \) into the crystallinity factor.

We assume that near-infrared spectra of those bodies are represented by a simple model consisting of the H$_2$O ice spectrum and a linear continuum presented by Brown et al. (2012). The model spectrum, \( S(\lambda) \), is given as

\[
S(\lambda) = f_{\text{H}_2\text{O}} S_{\text{H}_2\text{O}}(\lambda) + (1 - f_{\text{H}_2\text{O}}) \times [m_{\text{cont}}(\lambda - 1.74 \mu m) + 0.49], \tag{2}
\]

where \( f_{\text{H}_2\text{O}} \) is the spectral fraction of H$_2$O ice and \( m_{\text{cont}} \) is a continuum slope. The H$_2$O ice spectra were generated from the geometric albedo \( A_p \), described by the radiative transfer model of Hapke (1993) as

\[
A_p \approx r_0 \left( \frac{1}{2} + \frac{1}{6} r_0 \right) + \frac{w}{8} [(1 + B_0)p(0) - 1], \tag{3}
\]

where \( w \) is the single-scattering albedo given from the optical constants and grain size, \( r_0 \) is the diffuse reflectance given by \( \frac{1 - \sqrt{1 - w}}{1 + \sqrt{1 - w}} \), \( B_0 \) is the total amplitude of the opposition surge, and \( p(0) \) is the phase function at zero phase angle. We used \( B_0 = 0.67 \), a typical value among icy satellites (Verbiscer & Helfenstein 1998, p. 157) as in Merlin et al. (2009), and isotopic scattering, i.e., \( p(0) = 1.0 \). The optical constants of amorphous and crystalline H$_2$O ices were derived from the laboratory data provided by Mastrapa et al. (2008), Mastrapa (2012).

The grain size is one of the most sensitive parameters for determining the reflectance spectrum but still unknown. We tentatively assumed uniform grain particles with a diameter of \( d = 50 \mu m \) as in Brown et al. (2012). The uncertainty due to the dependence on grain size is discussed in Section 3.3.

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$^5$ www.naoj.org/staff/ichi/MCSRED/mcsred.html
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Table 1
Properties of observed objects

| Object         | a (au) | e   | i (deg) | \( \mu \) (mag) | D (km) | \( f_{\text{H}_2\text{O}} \) | \( m_{\text{cont}} \) |
|----------------|--------|-----|---------|-----------------|--------|-----------------|-----------------|
| (38628) Huya   | 39.41  | 0.276 | 15.5    | 4.9             | 458 ± 9a | 0.08 ± 0.02 | −0.09 ± 0.00   |
| (42355) Typhon | 38.11  | 0.540 | 2.4     | 7.5             | 115 ± 7b | 0.31 ± 0.17 | 0.05 ± 0.10    |
| (50000) Quaoar | 43.22  | 0.035 | 8.0     | 2.4             | 1074 ± 38a | 0.29 ± 0.01 | 0.07 ± 0.00    |
| (65489) Ceto   | 101.91 | 0.825 | 22.3    | 6.4             | 281 ± 11b | 0.17 ± 0.28 | −0.10 ± 0.17   |
| (90482) Orcus  | 39.44  | 0.219 | 20.5    | 2.2             | 958 ± 23a | 0.44 ± 0.01 | −0.36 ± 0.03   |
| (136108) Haumea| 43.17  | 0.192 | 28.2    | 0.1             | 124σ  | 0.66 ± 0.00 | −0.40 ± 0.00   |
| (315530) 2008 AP129 | 42.07 | 0.143 | 27.4    | 4.9             | 471σ  | 0.14 ± 0.09 | 0.04 ± 0.05    |

Note. Properties shown are the orbital elements (semimajor axis, \( a \), eccentricity, \( e \), and inclination, \( i \)), absolute visual magnitude (\( \mu \)), diameter (\( D \)), and spectral parameters (amount of \( \text{H}_2\text{O} \) ice, \( f_{\text{H}_2\text{O}} \), and slope of the continuum, \( m_{\text{cont}} \)). Brown et al. 2012.

\( a \) Fornsasier et al. (2013).

\( b \) Santos-Sanz et al. (2012).

\( c \) Estimated from \( \mu \) assuming a geometric albedo of 0.09 ± 0.04, the average value of TNOs from Santos-Sanz et al. (2012).

Table 2
Observational Circumstances

| Object         | UT     | Airmass (arcsec) | Seeing\(^a\) | \( H^p \) (s) | NB1657\(^c\) (s) |
|----------------|--------|-----------------|--------------|--------------|------------------|
| (90482) Orcus  | 07:28–08:28 | 1.13–1.19       | 0.64         | 880          | 1260             |
| (315530)       | 08:34–09:38 | 1.20–1.38       | 0.64         | 840          | 1440             |
| 2008 AP129     |         |                 |              |              |                  |
| (42355) Typhon | 10:08–11:12 | 1.10–1.17       | 0.75         | 780          | 1440             |
| (65489) Ceto   | 11:53–12:29 | 1.34–1.46       | 0.64         | 500          | 720              |
| (136108)       | 12:34–13:24 | 1.06–1.16       | 0.66         | 600          | 810              |
| Haumea         |         |                 |              |              |                  |
| (38628) Huya   | 13:50–14:53 | 1.14–1.27       | 0.76         | 840          | 1440             |
| (50000) Quaoar | 14:57–15:42 | 1.22–1.25       | 0.78         | 450          | 1080             |

Notes.

\( a \) Typical full width at half maximum of point sources.

\( b \) Total exposure time in the \( H \) filter.

\( c \) Total exposure time in the NB1657 filter.

Table 3
Results of Photometry

| Object         | \( H^p \) (mag) | \( \Delta(H - \text{NB1657})^c \) (mag) |
|----------------|-----------------|-----------------------------------------|
| (90482) Orcus  | 17.89 ± 0.03    | −0.045 ± 0.010                          |
| (315530)       | 19.19 ± 0.03    | −0.031 ± 0.024                          |
| 2008 AP129     |                 |                                          |
| (42355) Typhon | 18.24 ± 0.03    | −0.030 ± 0.017                          |
| (65489) Ceto   | 18.85 ± 0.03    | +0.033 ± 0.032                          |
| (136108) Haumea| 16.37 ± 0.03    | −0.109 ± 0.011                          |
| (38628) Huya   | 17.57 ± 0.03    | −0.016 ± 0.016                          |
| (50000) Quaoar | 16.74 ± 0.03    | −0.040 ± 0.012                          |

Note.

\( a \) The errors show the \( 1 \sigma \) uncertainty.

The absorption spectrum of \( \text{H}_2\text{O} \) ice, especially the 1.56 \( \mu \)m and 1.65 \( \mu \)m bands in crystalline \( \text{H}_2\text{O} \) ice, varies with temperature (e.g., Grundy & Schmitt 1998). The surface temperature of airless solid bodies depends on the solar flux, rotation, and surface properties. Stansberry et al. (2008, p. 161) presented temperatures of 49 TNOs/Centaurs derived from 24 \( \mu \)m and 70 \( \mu \)m flux data collected by the Spitzer Space Telescope. Figure 2 shows the color temperatures as a function of target distance from the Sun at the time of the observations.

The plot is well approximated by the equation

\[
T = (389 \pm 14) r_h^{-1/2} + (−7.1 \pm 3.3),
\]

where \( T \) and \( r_h \) are the temperature in kelvin and the heliocentric distance in au, respectively. Here, we consider the thermal temperatures derived from this equation assuming isothermal blackbodies to be their ice temperatures. The appropriateness of this is assessed below. Mastrapa’s data set contains the optical constants of crystalline \( \text{H}_2\text{O} \) ice at temperatures from 20–150 K every 10 K and those of amorphous \( \text{H}_2\text{O} \) ice at temperatures higher/lower than 70 K. Based on the estimated temperatures, we drew the spectral reflectance of crystalline/amorphous ices from the optimum optical constant data for each target object as shown in Table 4. The model spectra of the target objects were generated from Equation (2) with the synthetic spectra of \( \text{H}_2\text{O} \) ice as mixtures of crystalline and amorphous phases given by Equation (1).

The spectral fraction of \( \text{H}_2\text{O} \) ice \( f_{\text{H}_2\text{O}} \) and the continuum slope \( m_{\text{cont}} \) were assumed to be those suggested by Brown et al. (2012) as listed in Table 1. Note that these parameters have been estimated from simple modeling with the optical constants.

![Figure 2](image-url)
of fully crystallized ice. We evaluated the variability of $f_{\text{H}_2\text{O}}$ determined through the model depending on crystallinity. The synthetic spectra from Equation (2) were compared between pure crystalline ice and amorphous-dominated/mixed ice by least-squares optimization under the same conditions as Brown et al. (2012), i.e., temperatures of 50 K, grain size of 50 $\mu$m, and wavelength ranges of 1.45–1.80 $\mu$m and 1.95–2.30 $\mu$m. Table 5 shows the best-fit $f_{\text{H}_2\text{O}}$ values for the spectra created with $f_{\text{crys}}$ of 0.00, 0.25, and 0.50. Since there are only small differences from the given values for any $f_{\text{crys}}$, one can see that $f_{\text{H}_2\text{O}}$ has little dependence on crystallinity. This indicates the validity of our crystallinity measurement based on the published $f_{\text{H}_2\text{O}}$ values.

To compare with the photometric data, the model spectra were converted into $\Delta(H - \text{NB1657})$ using

$$\Delta(H - \text{NB1657}) = 2.5 \times \log \left[ \frac{\int R_{\text{NB}}(\lambda) S(\lambda) \lambda F_{\lambda,\text{c}}(\lambda) d\lambda}{\int R_{\text{H}}(\lambda) S(\lambda) \lambda F_{\lambda,\text{c}}(\lambda) d\lambda} \right]$$

(5)

where $R_{\text{H}}(\lambda)$ and $R_{\text{NB}}(\lambda)$ are the response functions for the $H$ and NB1657 bands, respectively. $F_{\lambda,\text{c}}(\lambda)$ is the wavelength flux density of the Sun. The response functions include atmospheric transmission at the summit of Maunakea generated by ATRAN modeling software (Lord 1992) assuming an airmass of 1.0 and water vapor column of 1.0 mm. We used the solar reference spectrum distributed by STScI Calibration Database System.\(^7\)

### Table 4

| Object       | $\text{H}_2\text{O}$ Ice Spectra\(^c\) | Crystallinity Factor\(^d\) |
|--------------|----------------------------------------|----------------------------|
| (90482) Orcus | crys_50K, amorph_low 0.53$^{+0.08}_{-0.09}$ |                            |
| (315530) 2008 AP\(_{129}\) | crys_60K, amorph_low 1.00$^{+0.10}_{-0.09}$ |                            |
| (423555) Typhon | crys_80K, amorph_high 0.79$^{+0.01}_{-0.27}$ |                            |
| (136108) Haumea | crys_50K, amorph_low 0.77$^{+0.07}_{-0.05}$ |                            |
| (38628) Huya | crys_70K, amorph_low 0.93$^{+0.03}_{-0.03}$ |                            |
| (50000) Quaoar | crys_50K, amorph_low 0.82$^{+0.15}_{-0.15}$ |                            |

### Notes.

\(^a\) Heliocentric distance at the time of observation.

\(^b\) Thermal temperature from Equation (4).

\(^c\) The optical constant data set derived from laboratory spectra provided by Mastrapa et al. (2008).

\(^d\) The errors show the 1$\sigma$ uncertainty.

3.2. Crystallinity

By comparing the obtained $\Delta(H - \text{NB1657})$ index with the model spectra, we determined the crystallinity factors of H$_2$O ice for each target object. Figure 3 shows $\Delta(H - \text{NB1657})$ derived from our observation and modeling with respect to the crystallinity factor. The point where the model curve intersects with the measured value represents a plausible crystallinity factor. The resulting crystallinity factors are listed in Table 4. The accuracy of determination depends on photometric precision and the slope of the model curve given by the abundance of H$_2$O ice. For bright objects including Orcus, Haumea, and Quaoar, the crystallinity factor has been fixed

\(^7\) [www.stsci.edu/hst/observatory/crds/calspec.html](http://www.stsci.edu/hst/observatory/crds/calspec.html)

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### Table 5

| Given $f_{\text{crys}}$ | 1.00 | 0.70 | 0.50 | 0.30 | 0.10 |
|------------------------|------|------|------|------|------|
| Best fit               | 0.50 | 0.69 | 0.50 | 0.30 | 0.10 |
| 0.25                   | 0.69 | 0.49 | 0.29 | 0.10 |
| 0.00                   | 0.68 | 0.48 | 0.29 | 0.10 |

### Figure 3

Figure 3. Relative $H - \text{NB1657}$ indexes of the observed objects (solid lines) and 1$\sigma$ errors of photometry (dashed lines). The gray lines show the relation between $H - \text{NB1657}$ index and crystallinity factor estimated from the model spectra. The width of the gray lines represents the uncertainty of the model parameters (see Table 1).
Figure 4. Model spectra of Haumea (left) and Quaoar (right) with the determined fractions of crystalline H₂O ice (gray lines). The dots show the published spectral data for comparison.

with an accuracy of ~0.1. Huya is also bright, but the error is very large due to low \( f_{\text{H}_2\text{O}} \) (0.08 ± 0.02) causing little variation in \( \Delta(H-NB1657) \) with crystallinity factor. This implies that \( f_{\text{H}_2\text{O}} \sim 0.1 \) is the limit of application of this technique for TNOs in Subaru/MOIRCS observation.

Under hypothetical ice conditions with a temperature based on thermal flux and a grain size of 50 \( \mu \text{m} \), the model matching indicates abundant crystalline H₂O ice on the surfaces of Haumea and Quaoar, as well as a moderate amount of the crystalline phase on Orcus. This result agrees with previous spectroscopic works showing a significant feature of the 1.65 \( \mu \text{m} \) absorption on those objects (e.g., Jewitt & Luu 2004; de Bergh et al. 2005; Trujillo et al. 2007). Typhon also shows high crystallinity, consistent with the spectral model presented by Guilbert et al. (2009) (5% crystalline and 0% amorphous).

We evaluated the validity of this technique through comparison with published near-infrared spectra of Haumea and Quaoar obtained with Keck/NIRC² (Barkume et al. 2008). Figure 4 shows those spectra as well as the spectral models generated from Equation (2) with the crystallinities measured by this work. The models reproduce the observed spectra well, including the 1.65 \( \mu \text{m} \) feature in both objects. This supports the idea that our photometric method is useful in constraining the ratio of crystalline to amorphous phases for an icy small body whose \( f_{\text{H}_2\text{O}} \) is known. The effect of the assumed ice properties, i.e., temperature and grain size, on the determination of the crystallinity factor is examined in the following section.

3.3. Ice Temperature and Grain Size

The depth and center wavelength of the 1.65 \( \mu \text{m} \) band vary sensitively with temperature and grain size (Fink & Larson 1975; Clark 1981; Grundy & Schmitt 1998; Taffin et al. 2012); the two parameters were given as the thermal temperature estimated from Equation (4) and \( d = 50 \mu \text{m} \), respectively, in the above modeling. Grundy et al. (1999) presented disk-averaged H₂O ice temperatures of Jovian, Saturnian, and Uranian satellites derived from their near-infrared spectra. They pointed out that the ice temperature is generally lower than the brightness temperature derived from thermal emission, which is sensitive to warm regions on the surface with a typical difference of ~10 K. The target objects could actually have a lower surface temperature.

We conducted additional modeling with the same processes as presented in Section 3.1 but using the optical constant data of crystalline H₂O ice at temperatures 10 K lower than those in Table 4. The results, shown in Table 6, indicate no significant change in the obtained crystallinity factor compared with the original model spectrum in any objects. Such a difference in the given temperature causes a systematic error of no more than ~10% for our crystallinity measurements.

On the other hand, grain size can induce considerable uncertainty in the modeling. Although the dominant size of the ice grains on the surface layer of TNOs is still unknown, Barucci et al. (2011) reported models of the surface composition of 12 TNOs/Centaur based on their near-infrared spectroscopy data, showing that most of their surfaces contain H₂O ice (in crystalline and/or amorphous states) with particle diameters of ~10–200 \( \mu \text{m} \). Many of the previous studies of TNO/Centaur spectra showed the best-matched grain sizes to be in this range. Note that H₂O ice with larger grains enhances the absorption coefficients, but the enhancement saturates at the diameter of ~1000 \( \mu \text{m} \). In contrast, if the grains are smaller than ~10 \( \mu \text{m} \), the absorptions are too weak to measure the 1.65 \( \mu \text{m} \) feature via the \( \Delta(H-NB1657) \) index. Thus, our technique is applicable to objects whose surfaces are dominated by H₂O ice with grain sizes of ~10–1000 \( \mu \text{m} \).

We examined the variation in crystallinity factor for our observed objects among the spectral models with grain sizes from 10 to 200 \( \mu \text{m} \) in diameter (see Figure 5). A uniform size between the crystalline and amorphous particles was assumed in each pattern. The results are shown in Figure 6. One can see that the crystallinity factor decreases monotonically with increasing grain size. This is because of the optical characteristic of H₂O ice whereby larger grains increase the amount of 1.65 \( \mu \text{m} \) absorption rather than that of the entire absorption covered by the \( H \) band, as pointed out in Grundy & Schmitt (1998). Although the crystallinity factor varies greatly between the smallest and largest grain sizes, it remains larger than ~0.5 to within the error in Haumea, Quaoar, Typhon, and 2008 AP₁₂⁹. Orcus has a slightly lower crystallinity in the case of the largest grain sizes, but definitely contains a certain level of crystalline ice. This result indicates that all of the five objects whose crystallinity has been precisely determined are likely to be covered by a surface containing crystalline-dominant H₂O ice or one comparable to it.

3.4. Impurities

The model spectrum given by Equation (2) approximates the surface reflectance spectrum of the target objects as a combination of H₂O ice and other materials for which the total spectrum shows a continuum with a linear slope and no absorption feature. For the \( H \)-band data, this assumption seems to be reasonable because most non-H₂O ices that potentially exist on the TNOs’ surface, e.g., CH₃OH, CO, CO₂, N₂, and NH₃, have no or only slight absorptions over the wavelength range (Cruikshank et al. 1984); Gerakines et al. 2005. However, CH₄ ice could be influential in determining H₂O ice crystallinity because it exhibits several absorption features from 1.5 \( \mu \text{m} \) to 1.8 \( \mu \text{m} \) (Pearl et al. 1991). In particular, the strong absorption band at 1.67 \( \mu \text{m} \) possibly makes a significant negative contribution to the \( \Delta(H-NB1657) \) index.

Various near-infrared spectroscopic studies suggest the presence of CH₄ ice on several TNOs with an H₂O ice-rich surface including Quaoar (Schaller & Brown 2007; Dalle Ore

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8 http://web.gps.caltech.edu/~pa/data/kbo_info.html
CH$_4$ ice (stable between 20 K and 90 K) presented by Grundy et al. (2002). The synthetic model spectra were generated from Equation (2) by replacing the reflectance spectrum of H$_2$O ice, $S_{H_2O}$, with that of mixed ices of H$_2$O and CH$_4$ derived from the intimate mixture model developed by Hapke (1993). The grain size of H$_2$O ice was fixed to $d = 50 \mu m$.

The results are shown in Figure 7. If CH$_4$ ice grains are of equal size to or smaller than H$_2$O ice grains, the H$_2$O ice crystallinity factors are larger than 0.50 for Quaoar and 0.25 for Orcus. The situation is similar if CH$_4$/H$_2$O $\lesssim 0.05$. In contrast, the absorption due to the larger-grain CH$_4$ ice on the surface with CH$_4$/H$_2$O $\gtrsim 0.1$ dominates at $\sim 1.65 \mu m$ and could cause great uncertainty in the H$_2$O ice crystallinity.

We recognize that Dalle Ore et al. (2009) and Carry et al. (2011) provide the most reliable spectral modeling for Quaoar and Orcus, respectively, among the published works. The former suggests that Quaoar’s surface contains fine CH$_4$ ice grains of $d \sim 10 \mu m$ with a slightly high fraction of CH$_4$/H$_2$O $\sim 0.3$. The latter suggests that Orcus’s surface contains coarse CH$_4$ ice grains of $d \sim 100 \mu m$ with a tiny fraction of CH$_4$/H$_2$O $< 0.03$. If those parameters are simply applied to our modeling, they indicate that the potential presence of CH$_4$ ice is unlikely to induce significant overestimation of H$_2$O ice crystallinity in Quaoar and Orcus.

4. DISCUSSION

Provided that the observed objects are coated by H$_2$O ice grain of $d \lesssim 50 \mu m$ with negligible contamination by other ices such as CH$_4$, our results suggest the following implications:

(i) It is not only Haumea and Quaoar that are known as large objects rich in crystalline H$_2$O ice, but smaller objects, Typhon and 2008 AP$_{129}$, also contain crystalline-dominated H$_2$O ice on their surfaces.

(ii) Orcus has a crystallinity comparable to 0.5, obviously lower than that of Haumea and Quaoar.

(iii) No objects with a low-crystallinity surface have been found in our well-measured TNO sample.

The initial state of H$_2$O ice in TNOs is likely to be amorphous if the bodies formed beyond $\sim 25$ au from the Sun (Kawakita et al. 2006). Such pristine ice could be heated and crystallized through thermal evolution after the formation. Based on the timescale to onset of crystallization (Jenniskens & Blake 1996) and the timescale to completion of crystallization (Kouchi et al. 1994), amorphous ice at $> 70$ K would be non-crySTALLine.

Table 6

| Object          | $T^a$ (K) | H$_2$O Ice Spectra$^b$  | Crystallinity Factor$^c$ |
|-----------------|-----------|-------------------------|--------------------------|
| (90482) Orcus   | 42        | crys.40K, amorph_low    | 0.51±0.09                |
| (315530) 2008 AP$_{129}$ | 48        | crys.50K, amorph_low    | 1.00±0.07                |
| (42355) Typhon  | 70        | crys.70K, amorph_high   | 0.72±0.24                |
| (136108) Haumea | 41        | crys.40K, amorph_low    | 0.75±0.06                |
| (38628) Huya    | 56        | crys.60K, amorph_low    | 0.89±0.09                |
| (500000) Quaoar | 44        | crys.40K, amorph_low    | 0.80±0.15                |

Notes.

$^a$ Reduced thermal temperature (see text).

$^b$ The optical constant data set derived from laboratory spectra provided by Mastrapa et al. (2008).

$^c$ The errors show the 1σ uncertainty.

Figure 5. The relations between H–NB1657 index and crystallinity factor estimated from the model spectra with a grain size of 10 $\mu m$ (dotted lines), 50 $\mu m$ (solid lines), and 200 $\mu m$ (dashed lines).

Figure 6. Estimated Crystallinity Factors with Lower Temperatures

Table 6

| Object          | $T^a$ (K) | H$_2$O Ice Spectra$^b$  | Crystallinity Factor$^c$ |
|-----------------|-----------|-------------------------|--------------------------|
| (90482) Orcus   | 42        | crys.40K, amorph_low    | 0.51±0.09                |
| (315530) 2008 AP$_{129}$ | 48        | crys.50K, amorph_low    | 1.00±0.07                |
| (42355) Typhon  | 70        | crys.70K, amorph_high   | 0.72±0.24                |
| (136108) Haumea | 41        | crys.40K, amorph_low    | 0.75±0.06                |
| (38628) Huya    | 56        | crys.60K, amorph_low    | 0.89±0.09                |
| (500000) Quaoar | 44        | crys.40K, amorph_low    | 0.80±0.15                |

Notes.

$^a$ Reduced thermal temperature (see text).

$^b$ The optical constant data set derived from laboratory spectra provided by Mastrapa et al. (2008).

$^c$ The errors show the 1σ uncertainty.
crystallized within the age of the solar system (Mastrapa et al. 2013, p. 371). Additionally, surface annealing due to micrometeorite impacts may also be effective in inducing ice crystallization. In this section, we discuss several possible mechanisms for crystallization of the surface H$_2$O ice of TNOs.

Note that crystalline H$_2$O ice can be amorphized by irradiation with UV photons as well as energetic particles such as protons and electrons from the solar wind and cosmic rays. Leto & Baratta (2003) and Leto et al. (2005) confirmed that UV photolysis induces amorphization at 16 and 90 K, respectively, through irradiation experiments. However, as Hudson et al. (2008, p. 507) pointed out, the UV penetration depth is much less than the optical depth in the near infrared ($\sim$350 $\mu$m). The effect of UV photolysis can be excluded in this observation. On the other hand, protons above $\sim$1 MeV and electrons above $\sim$0.1 MeV have stopping ranges larger than the optical depth for an H$_2$O ice target (Hudson et al. 2008, p. 507). Mastrapa & Brown (2006) presented the results of proton irradiation experiments, indicating that (i) amorphous ice was produced at low temperatures ($<40$ K), (ii) some crystalline ice persisted at 50 K after irradiation, and (iii) the crystalline spectrum showed only slight changes at $>70$ K.

Zheng et al. (2009) investigated the effect of electron irradiation on the near-infrared spectra and found that crystalline H$_2$O ice can be converted only partially to amorphous at 40 K or higher. According to measurements from the Geostationary Operational Environmental Satellites (GOES)$^9$, the fluence ratio of electrons to protons above 1 MeV from the solar wind is $10^3$--$10^7$. The interplanetary flux of protons from cosmic ray is $\sim10^2$ greater than that from the solar wind above 1 MeV at a heliocentric distance of 40 au (Cooper et al. 2003). Thus, electrons are likely to be the dominant component of energetic particle irradiance on surfaces of icy bodies in the main trans-neptunian region. Although there are a lot of discrepancies among previous experimental studies as mentioned in Mastrapa et al. (2013, p. 371), assuming the irradiation tolerance of crystalline H$_2$O ice based on the experimental results of Zheng et al. (2009), the amorphization process could be only limited. Here we ignore the effect of radiation-induced amorphization in the following discussion.

4.1. Insolation

Prior to discussions of the thermal evolution, we should confirm the variations in surface temperature of the target objects over an orbit. Amorphous ice would be crystallized on surfaces that have been much warmer than 70 K over the timescale of the age of the solar system or less (Kouchi et al. 1994; Jenniskens & Blake 1996). Even if there is no heat source except solar insolation, the transition from amorphous to crystalline occurs on the surface of bodies sufficiently close to the Sun. All the target objects other than Typhon have perihelion distances larger than 28.5 au, which are converted into surface temperatures of less than 66 K by Equation (4). Assuming that there has been no significant migration since their formation, their surfaces have been cold enough for amorphous ice to be continuously stable. However, Typhon has a high orbital eccentricity (0.54), allowing it to approach up to 17.5 au from the Sun. Around its perihelion, the sunward surface would be warmed up to $\sim$86 K, while the ordinary temperature is $\sim$50 K during most of its

$^9$ The data distributed by NOAA/National Centers for Environmental Information (ftp.ngdc.noaa.gov).
orbit. In the model of Jenniskens & Blake (1996), the time to onset of crystallization at that temperature is \( \sim 10^6 \) yr. The insolation heating can induce surface crystallization if Typhon has retained such an eccentric orbit over the age of the solar system and the intermittent contribution has accumulated monotonically.

### 4.2. Radiogenic Heating

The decay of radioactive isotopes contained in dust mixed with ice is the most important heat source for the internal thermal evolution of small icy bodies in the outer solar system. It allows the crystallization to proceed outward from the deep interior of the body.

In Prialnik & Podolak (1995), thermal evolutionary calculations of icy bodies larger than 40 km in diameter (\( D \)) with heat sources of \(^{26}\text{Al} \) and four long-lived radioactive isotopes indicate that \( \text{H}_2\text{O} \) ice on the outer layer seems to be left in the amorphous form. Choi et al. (2002) also reported that \(^{26}\text{Al} \) decay could not raise the surface temperature of TNOs with \( D = 20–1000 \) km higher than \( \sim 50 \) K and not induce \( \text{H}_2\text{O} \) ice crystallization at the surface layers. Those models cannot explain the surface crystallization of objects with \( D > 100 \) km.

However, assuming that the objects were formed closer to the Sun than their present orbits, radiogenic heating can potentially crystallize the surface ice because of fast accretional growth, and thus sufficient radiogenic heating by \(^{26}\text{Al} \). The simulations of Merk & Prialnik (2006) showed that icy bodies above \( D \sim 30 \) km originally located at around 20 au could be covered by a crystalline ice surface. McKinnon et al. (2008, p. 213) showed that if icy bodies formed at a heliocentric distance less than \( \sim 32 \) au, then the crystalline/amorphous ice boundary reaches the surface.

More recent work by Guilbert-Lepoutre et al. (2011) presented three-dimensional simulations to compute the thermal evolution of icy small bodies with heat sources of several short- and long-lived radioactive isotopes. Their results suggest:

1. When the growth advanced quickly (\( \sim 1 \) Myr) and short-lived isotope decay effectively contributes to the thermal evolution, objects with \( D > 100 \) km retain only a thin (\(< 2 \) km) layer of amorphous \( \text{H}_2\text{O} \) ice on their surface, which may possibly be removed by impact excavation. In addition, provided such objects are formed close enough to the Sun (10–15 au), crystallization would be triggered at the surface by insolation.

2. When the thermal evolution is dominated by long-lived isotope decay, only large objects (\( D > 600 \) km) with a bulk density of at least 1.5 \( \text{g cm}^{-3} \) should contain crystalline \( \text{H}_2\text{O} \) ice close to the surface.

Our findings regarding the presence of crystalline \( \text{H}_2\text{O} \) ice on Typhon and 2008 AP\(_{129}\) agree with the first scenario. In contrast, Typhon and possibly 2008 AP\(_{129}\) (see Table 1) are inconsistent with the second scenario. Based on the model of Guilbert-Lepoutre et al. (2011), at least those small objects should have grown in a sufficiently short timescale for the surfaces to be heated up to the crystallization temperature by the decay of short-lived isotopes unless they were formed close to the Sun (10–15 au).

Such a rapid formation as to induce sufficient heating for surface ice crystallization due to the decay of short-lived isotopes can also occur at a smaller heliocentric distance than the current location. Actually, several theoretical studies support this model. Weidenschilling (2004, p. 97) presented coagulation simulations of planetesimal growth in the outer solar system and showed the formation of objects with \( D > 100 \) km only inside \( \sim 30 \) au. More recently, Kenyon & Bromley (2012) performed \( N \)-body coagulation calculations for the formation and evolution of TNOs, indicating that objects at 15–18 au grow up to 100 km in diameter within \( \sim 1 \) Myr at earliest, while it takes more than 10 Myr at 33–40 au. Outward transport of planetesimals from the inner regions via planetary migration has been believed to take place based on numerical simulations for the dynamical evolution of giant planets and TNOs (e.g., Gomes 2003; Levison & Morbidelli 2003; Hahn & Malhotra 2005; Levison et al. 2008). Rapid growth around 20 au from the Sun is a plausible mechanism for crystallization of surface ice from the early radioactive heating on TNOs as small as Typhon.

The thermal evolution model may also be able to explain the low fraction of crystalline ice on Orcus compared with Haumea and Quaoar. One of the important parameters that the heating rate depends on is the bulk density of the body. A higher density increases the abundance of dust materials containing radioactive isotopes and thus enhances the heating efficiency. The difference in bulk density possibly causes the variation in crystallinity among objects of comparable size. Guilbert-Lepoutre et al. (2011) suggest that a density of at least 1.5 \( \text{g cm}^{-3} \) is required for the presence of crystalline ice on the surface of objects with \( D \gtrsim 600 \) km. Haumea is well known to have a high density (\( \sim 2.6 \text{g cm}^{-3} \), Rabinowitz et al. 2006; Lacerda & Jewitt 2007). Quaoar’s density has also been estimated to be as high as \( 2.18^{+0.03}_{-0.02} \text{g cm}^{-3} \) from thermal flux (Fornasier et al. 2013) or \( 1.99 \pm 0.46 \text{g cm}^{-3} \) from occultation (Braga-Ribas et al. 2013). In contrast, Orcus exhibits an obviously lower density of \( \sim 1.5 \text{g cm}^{-3} \) (Brown et al. 2010), just about the same value as the criterion for surface ice crystallization shown by Guilbert-Lepoutre et al. (2011). This fact suggests the possibility that temperature of the upper layer of Orcus failed to rise sufficiently to crystallize most of the surface \( \text{H}_2\text{O} \) ice due to a deficiency in the amount of radioactive isotopes. The potential correlation between crystallinity and bulk density could support the hypothesis that radiogenic heating is the dominant effect on surface crystallization for TNOs.

### 4.3. Cryovolcanism

Some surface ice may not have been formed in situ but may have been supplied from the interior by geological activity of volcanic eruptions of ice, so-called cryovolcanism. Actually, atmospheric plumes have been seen on several icy satellites of giant planets, such as Triton (Smith et al. 1989; Kargel 1994), Enceladus (Porco et al. 2006; Spencer et al. 2009, p. 683), and Europa (Roth et al. 2014), as possible evidence of cryovolcanic events. The occurrence of a substantial flow of liquid \( \text{H}_2\text{O} \) to the surface requires some sort of continual heating process to melt the subsurface ice. For the satellites, tidal energy dissipation is likely to be a major heat source (e.g., Ruiz & Tejero 2000). Even though inclusion of \( \text{NH}_3 \) in \( \text{H}_2\text{O} \) ice allows the melting point to drop from 273 K to 176 K at minimum (Kargel et al. 1991) and decreases the thermal conductivity, it is still uncertain whether the cryovolcanic activity can be driven on TNOs primarily by long-lived radioactive isotopes without tidal heating.
Cook et al. (2007) suggested that a body with $D > 1200\ \text{km}$ composed of rock with a mass fraction $\geq 0.7$ (corresponding to a bulk density $\geq 1.8 \ \text{g cm}^{-3}$) and NH$_3$-rich H$_2$O ice ($\sim 0.15$ by weight) could develop cryovolcanism and be steadily resurfaced by crystalline H$_2$O ice at a sufficient rate to be detected at near-infrared wavelengths. Haumea, with a mean diameter of 1200–1300 km (Lellouch et al. 2010; Fornasier et al. 2013) and a density of 2.6 g cm$^{-3}$ (Lockwood et al. 2014), satisfies these conditions. Quaoar is slightly smaller than the required size ($\sim 1000$–1100 km) and has a high density (1.99 $\pm$ 0.46 g cm$^{-3}$; Braga-Ribas et al. 2013; 2.18$^{+0.41}_{-0.36}$ g cm$^{-3}$; Fornasier et al. 2013). Orcus is likely to be comparable in size to Quaoar ($\sim 850$–950 km; Brown et al. 2010; Lim et al. 2010; Fornasier et al. 2013), while its density is relatively low (1.53$^{+0.15}_{-0.13}$ g cm$^{-3}$; Fornasier et al. 2013). As pointed out by Desch et al. (2009), ice containing CH$_3$OH along with NH$_3$ freezes at a lower temperature (153 K; Kargel 1994) and therefore is likely to reduce the minimum diameter of a TNO that can retain liquid H$_2$O to 800–1000 km. Cryovolcanism may be active on Quaoar and Orcus if they consist of CH$_3$OH–NH$_3$–H$_2$O ice.

Unfortunately, our results cannot provide explicit constraints on the source of crystalline H$_2$O ice at the surfaces of Haumea, Quaoar, and Orcus. On the other hand, Typhon and 2008 AP$_{129}$ are likely to be too small to exhibit cryovolcanic activity even if antifreeze compounds such as NH$_3$ and CH$_3$OH are sufficiently mixed in the subsurface ice.

4.4. Other Mechanisms

Instead of the internal heat sources as mentioned above, H$_2$O ice crystallization on surfaces of airless bodies in the trans-neptunian region could be induced by impacts of meteorites such as interplanetary dust particles (IDPs). Cook et al. (2007) assessed possible mechanisms with micrometeorites to explain the presence of crystalline H$_2$O ice on Charon’s surface, namely, impact gardening and annealing. They approximated the mass flux of IDPs from Pioneer 10 observations as $2.4 \times 10^{-13}$ kg s$^{-1}$ m$^{-2}$ at 18 au and concluded that these mechanisms make little contribution to surface renewal on either Charon or other TNOs. In contrast, Porter et al. (2010) expected the IDP flux at Uranus to be $1.2 \times 10^{-10}$ kg s$^{-1}$ m$^{-2}$ and claimed that impact annealing could be effective for surface crystallization on TNOs.

As seen in Table 2 of Porter et al. (2010), the impact velocity of IDPs and required dust flux for annealing are similar among objects in the main trans-neptunian belt. Assuming a homogeneous IDP distribution over the region, the surface crystallinity would be almost uniform among TNOs if micrometeorite impacts are the primary factor. However, considering our result that indicates a low crystallinity of Orcus compared with Haumea and Quaoar, micrometeorite annealing seems not to be a major mechanism of surface crystallization, at least for icy objects as large as Orcus.

Finally, we focus on the unique situation of 2008 AP$_{129}$, which has an orbit consistent with the Haumea collisional family (Brown et al. 2007). The velocity relative to the estimated center of mass of the collision, $\sim 140$ m s$^{-1}$, also agrees with the velocity dispersion of the known family members ($50$–$300$ m s$^{-1}$), suggesting a dynamical association with the Haumea family (Volk & Malhotra 2012). The spectra of family members uniquely show significantly high fractions of H$_2$O ice as well as the crystalline feature (Barkume et al. 2008; Barucci et al. 2011; Brown et al. 2012). However, 2008 AP$_{129}$ contains only a minor fraction of H$_2$O ice ($f_{H_2O} = 0.14 \pm 0.09$; Brown et al. 2012), which prevents characterization of the membership. If 2008 AP$_{129}$ originates from a collisional fragment as an ice-poor family member, the presence of crystalline H$_2$O ice on the surface is natural because the body is likely to derive from the icy mantle of Haumea. The lack of ice could be explained by inhomogeneous compositions of the partial differentiation (Volk & Malhotra 2012) although the actuality is still unknown.

5. CONCLUSIONS

We have developed a new technique for measuring the crystallinity of H$_2$O ice on the surface of TNOs with near-infrared narrow-band photometry using Subaru/MOIRCS. The strength of the 1.65 $\mu$m absorption band for five objects has been obtained and converted into the fraction of crystalline ice by comparison with the model spectrum. The largest objects—Haumea, Quaoar, and Orcus—show a crystalline-rich icy surface as many previous spectroscopic studies have reported, while it is also found that their surfaces are likely to contain amorphous ice unless the grain size is smaller than $\sim 20$ $\mu$m. For Haumea and Quaoar, the model spectra based on the determined fractions of crystalline ice agree well with the published near-infrared spectra, indicating reasonable accuracy of our measurements.

The results indicate that H$_2$O ice on Haumea and Quaoar is highly dominated by the crystalline state, while Orcus shows a higher fraction of amorphous ice. Based on the model of thermal evolution due to radiative decay, the low bulk density of Orcus could cause suppression of the surface heating and stagnation in crystallization. It is of great significance to examine the possibility of a positive correlation between bulk density of the body, i.e., abundance of refractory inclusions, and surface crystallinity, providing a critical clue for understanding the crystallization mechanism.

We also found the presence of crystalline H$_2$O ice on Typhon and 2008 AP$_{129}$. Those objects are smaller than the expected critical size ($D \sim 600$ km) for surface crystallization, assuming that they were formed far enough from the Sun ($>15$ au) and the initial thermal evolution was dominated by the decay of long-lived isotopes (Guilbert-Lepourte et al. 2011). It is still uncertain which thermal or nonthermal process is the primary crystallization mechanism for midsize TNOs. Further investigations are required to determine whether the size of the body affects the production of crystalline H$_2$O ice at the surface layer.

We are grateful to Tadayuki Kodama who kindly provided the NB1657 filter to open-use observers. We thank Ichiro Tanaka for technically supporting our observation and data reduction, as well as Naruhi Takoto for fruitful comments on the manuscript. We also thank an anonymous referee for helpful comments and suggestions. This study is based on data collected at Subaru Telescope, National Astronomical Observatory of Japan.

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