The Astrophysical Journal, 601:L191–L194, 2004 February 1

EVIDENCE OF ICY GRAINS IN COMET C/2002 T7 (LINEAR) AT 3.52 AU

Hideyo Kawakita
Gunma Astronomical Observatory, 6860-86 Nakayama, Takayama, Gunma 377-0702, Japan; kawakita@astron.pref.gunma.jp
Jun-ichi Watanabe and Takafumi Ootsubo
National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
Ryosuke Nakamura
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sengen 2-1-1, Tsukuba 305-8505, Japan
Tetsuharu Fuse and Naruhisa Takato
Subaru Telescope, National Astronomical Observatory of Japan, 650 North A‘ohoku Place, Hilo, HI 96720
and
Sho Sasaki and Takanori Sasaki
Department of Earth and Planetary Science, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
Received 2003 October 14; accepted 2003 December 16; published 2004 January 27

ABSTRACT

We present evidence of icy grains in the coma of comet C/2002 T7 (LINEAR) at 3.52 AU from the Sun. This comet will approach the Sun in the spring of 2004, and it is expected to be very bright near its perihelion passage. The comet was observed using the Subaru Telescope with the Cooled Infrared Spectrograph and Camera for OHS (CISCO) on 2003 September 14.6 (UT). The near-infrared (J, H, K) spectrum was extracted from the near-nucleus region (1250 km × 1250 km at the comet), and it showed clear absorption features at 1.5 and 2.05 μm that originated from water ice grains. The calculated reflectance spectrum, based on the intimate mixture model for water ice grains and astronomical silicate grains (the diameters are 5 and 0.5 μm, respectively), can reproduce the observed reflectance spectrum of the comet up to 2.1 μm. The poor fit for the wavelength region longer than 2.1 μm is probably indicative of other grain species to be included in the model. Furthermore, the absence of the 1.65 μm feature of crystalline water ice may indicate that the water ice was in an amorphous state during the observation.

Subject headings: comets: general — comets: individual (C/2002 T7 (LINEAR)) — solar system: formation

1. INTRODUCTION

The existence of an icy grain halo in the cometary coma has been debated for a long time. Since the icy grains are considered to be dirty ice particles (not pure water ice) and can absorb the incident solar flux, the icy grains evaporate and vanish in a short time around 1 AU from the Sun (Hanner 1981; Mukai 1986; Mukai et al. 1989). It is difficult to detect water ice absorption features in the reflectance spectrum of the coma when a comet is near 1 AU. In order to detect water ice features, we need to observe the comet at farther than ~2.5 AU (Hanner 1981), where H_2O ice does not evaporate significantly and where the sublimation of highly volatile species like CO can drive the coma activity. Furthermore, the size of the icy grain halo is expected to be spatially small, so we should extract the reflectance spectra within small region close to the nucleus. Thus, the high spatial resolution and the high signal-to-noise ratio are required for the detection of the icy grain halo.

Water ice has spectral features near 1.5, 2.05, and 3 μm in the near-infrared region (e.g., Lellouch et al. 1998; Davies et al. 1997). Because the 3 μm feature is strongest among these features, this band feature was the target for searching water ice features in early attempts (Campins, Rieke, & Lebofsky 1983; Hanner 1984). Campins et al. (1983) showed that the reflectivity near 3.25 μm was lower than expected from the solar spectrum in comet Bowell at 3.4–3.5 AU from the Sun. A similar result was obtained by Hanner (1984) in comet Cernis at 3.3 AU. However, 1.5 and 2.05 μm features were not detected, and other molecular ices might have contributed to the 3 μm absorption feature (C−O, O−H, and N−H groups all have fundamental vibration absorption features in the wavelength range 2.5–3.5 μm). Furthermore, A’Hearn, Dwek, & Tokunaga (1984) pointed out that the 3 μm absorption feature in comet Bowell was inconsistent with model calculations for water ice grains. Thus, previous searches for the water ice feature around 3 μm might be inconclusive. The first secure detection of water ice absorption features at 1.5 and 2.05 μm was reported by Davies et al. (1997) in comet Hale-Bopp at 7 AU from the Sun. Although, these near-infrared features could not be detected in the same comet at 4.6 AU, the *Infrared Space Observatory* (*ISO*) could detect the emission band features originating from water ice near 44 and 65 μm in comet Hale-Bopp at 2.9 AU with the long wavelength spectrometer (Lellouc et al. 1998). Lellouch et al. (1998) also reported a possible absorption feature near 3 μm. The 65 μm feature of crystalline water ice was also detected by *ISO* with ISOPHOT in comet Hale-Bopp at 4.6–4.9 AU from the Sun (Grün et al. 2001).

In this Letter, we report the firm detection of near-infrared water ice absorption features at 1.5 and 2.05 μm in comet C/2002 T7 (LINEAR) at 3.52 AU from the Sun. This comet will be close to the Sun in the spring of 2004, and this apparition is considered to be the first travel from the Oort Cloud to the inner solar system (Marsden 2003). This comet is expected to be very bright near its perihelion passage.

2. OBSERVATION AND DATA ANALYSIS

A near-infrared spectroscopic observation of comet C/2002 T7 (LINEAR) was performed using the 8 m Subaru Telescope with Cooled Infrared Spectrograph and Camera for OHS (CISCO; Motohara et al. 2002) on 2002 September 14.6 (UT).

TABLE 1
Observational Parameters

UT Date	Object	Total Integration (s)	r^a (AU)	Δ^b (AU)	Air Mass	Grism
2003 Sep 14.61 ……	C/LINEAR	1200	3.52	3.45	1.13	*JH*
2003 Sep 14.62 ……	C/LINEAR	1200	3.52	3.45	1.10	w*K*
2003 Sep 14.65 ……	SAO 59433	80	…	…	1.14	*JH*
	SAO 59433	80	…	…	1.16	w*K*

[a] Heliocentric distance.
[b] Geocentric distance.

The heliocentric and geocentric distances of the comet were 3.52 and 3.45 AU, respectively.

In order to obtain a wide-range spectrum in the near-infrared region, the grisms named "*JH*" and "w*K*"(wide-*K*) were used. At the *JH* grism setting, both *J* and *H* bands (1.05–1.8 μm) were covered simultaneously, and a part of the *H* band and all of the *K* band (1.8–2.45 μm) were covered in a single exposure at the w*K* grism setting. The slit size was 108″ × 0″.5 in our observation ,and it corresponds to the spectral resolving power of $R = 400$ at the *JH* setting and $R = 600$ at the w*K* setting. The typical seeing size at the observation was about 0″.3 in the *K* band.

The total integration time for C/LINEAR was 1200 s for each (*JH* or w*K*) setting. We put the comet on the slit at two different positions (A and B) to subtract sky background emissions by the (A-B) operation. The nodding angle was 20″ for the comet observations. For the cancellation of telluric absorption features, an A0 star (SAO 59433) was observed just after the cometary observation. The difference in the air mass during the observations of the comet and the reference star was smaller than 0.1 for each grism setting. The reference star was also observed at the A and B positions (the nodding angle was 10″). Observational parameters are listed in Table 1.

We used the NOAO IRAF astronomical software package to reduce the near-infrared spectra obtained by CISCO. The TWODSPEC package was used for the reduction. First of all, dark subtraction and flat-fielding were applied to all frames. The OH sky emission lines were used for the wavelength calibration. We extracted the cometary spectra within the area of 0″.5 × 0″.5 near the nucleus because icy grains in the coma rapidly evaporated after they ejected from the nucleus. A sensitivity calibration was done as follows. First, the cometary spectra were divided by spectra of the reference star to cancel the telluric absorption features. Then the ratio spectra was multiplied by the model spectrum of the A0 star and finally divided by the synthesized solar spectrum (Kurucz 1994). Thus, we can get the near-infrared spectrum of the reflectance (or albedo) in comet C/LINEAR. Note that the albedo obtained here is just a relative value. Since the wavelength ranges of the *JH* and the w*K* spectra are slightly overlapped near 1.8 μm (by ~0.02 μm), we finally scaled these spectra to be consistent with each other in the overlapped wavelength region.

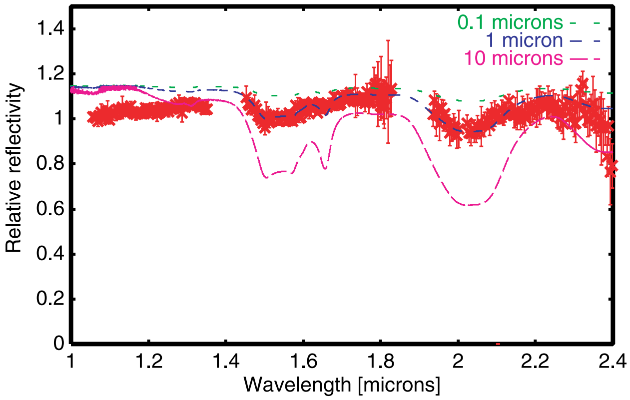

Fig. 1.—Spectrum of comet C/2002 T7 (LINEAR) along with synthesized spectra for pure H_2O crystalline icy grains (0.1, 1.0, and 10.0 μm, in diameter). The absorption by H_2O ice is clearly shown in the cometary spectrum. However, the agreement between the cometary spectrum and the pure H_2O spectrum is not good in the *J* band.

3. DISCUSSION

Figure 1 shows the relative reflectance spectrum of C/LINEAR on 2003 September 14.6 (UT). The cometary spectrum is normalized to unity at the shortest wavelength. In this figure, data points were averaged for each of the 5 pixels (nearly the same as the spectral resolving element), and the spectrum is plotted with $\pm 3\ \sigma$ error bars. The data are removed in the wavelength range where the telluric absorptions were strong and where the error bars are large. Our spectrum is quite similar to that observed in comet Hale-Bopp at 7 AU (Davies et al. 1997). Both 1.5 and 2.05 μm absorption features of water ice are recognized, and the reflectance (where $\lambda > 2.2$ μm) decreases for longer wavelength.

The synthesized reflectance spectra of pure crystalline water ice grains are overplotted in the same figure. The grain sizes are 0.1, 1, and 10 μm in diameter. These spectra were produced by Hapke's bidirectional reflectance model (Hapke 1993), which was also used in Davies et al. (1997) to model the reflectance spectrum of the icy grains in comet Hale-Bopp. The optical constants of the crystalline water ice are from Quirico, Douté, & Schmitt (1999). These water ice reflectance spectra were scaled appropriately to compare with the observation. If we consider *H* and *K* bands only, the pure water ice grains with 1 μm size can reasonably explain the observation. However, the color in the *J* band must be slightly reddish, and this wavelength dependence cannot be explained by the pure water ice. This fact demonstrates the importance of the *J*-band spectrum for investigating the dirty materials in icy grains. In the case of comet Hale-Bopp, unfortunately, Davies et al. (1997) observed only *H*- and *K*-band spectra. If there was a *J*-band spectrum of comet Hale-Bopp in addition to the *H*- and *K*-band spectra, it would give stronger constraints to the dirty materials in icy grains.

Figure 2 shows the synthesized spectrum produced by the intimate mixtures of water ice grains and astronomical silicate grains (Draine 1985). In the intimate mixtures, individual components exist as separate grains that are in turn thoroughly mixed at the granular scale (Davies et al. 1997). Davies et al. also used the spatial mixture model, in which the total reflectance is modeled by a linear combination of the reflectance of each component weighted by its spatial extent. The spatial mixture model represents a surface having distinctive albedo

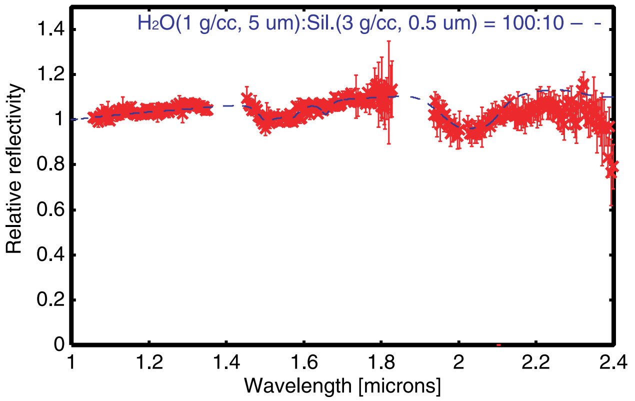

FIG. 2.—Spectrum of comet C/2002 T7 (LINEAR) along with a synthesized spectrum for the intimate mixture of water ice and astronomical silicate grains. The mass ratio is assumed to be 100 : 10. The size of the icy grain is 5 μm, while the size of silicate dust is 0.5 μm. The color of the cometary grains in the *J* band is illustrated well by the synthesized spectrum. However, the shallow absorption near 2.2 μm is not understood well.

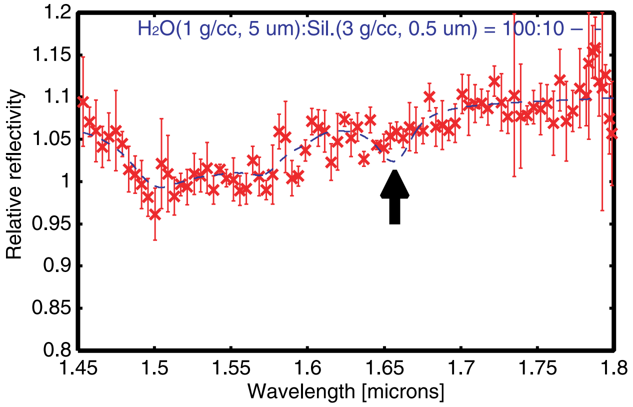

FIG. 3.—Close-up of Fig. 2 in the *H* band. The absence of the 1.65 μm absorption feature of crystalline ice may indicate that the cometary ice was in an amorphous state.

areas existing on a scale smaller than the spatial resolution of the observations. We consider that the intimate mixture model is better for modeling cometary dust comae because a real cometary grain seems to consist of silicate grains together with some kinds of ices and seems to be mixed at the granular scale. Therefore, only the intimate mixture model is used here.

We simply assumed that the mass ratio between the water ice and the astronomical silicate is 100 : 10 and that the sizes of grains are 5 and 0.5 μm in diameter, respectively. The resultant spectra can explain the observation well up to ∼2.1 μm. The observed albedo, where $\lambda > 2.1$ μm, is lower than the modeled spectrum, and a 2.2 μm shallow absorption feature exists. Again, we note that Davies et al. (1997) found the comparable solutions for both intimate and spatial mixtures in comet Hale-Bopp, and the spatial mixture also showed the poor fitting for $\lambda > 2.2$ μm.

Some additional materials seem to be necessary to explain the lower reflectance at $\lambda > 2.1$ μm. Even if we tried to fit the observation to the model by considering ammonia, methanol, methane, or ethane ice grains, our attempts would have failed in the above Hapke's model. However, with respect to the shallow absorption at 2.2 μm, it may be attributed to the ammonia hydrate ices (not pure ammonia ice) as demonstrated by Brown & Calvin (2000) for Pluto's satellite Charon (unfortunately, the refractive indexes of ammonia hydrate ice at the relevant wavelengths are not presently available). A more sophisticated grain model (with a more complicated grain size distribution and grain composition) and the optical constants for various kinds of ices at the relevant wavelength region seem to be required to reproduce the observation. Regarding the lower reflectivity at $\lambda > 2.1$ μm, it may be possible to explain the observed low reflectance by hydrate silicates. Recently, Kanno et al. (2003) found a 3 μm absorption of hydrated silicates on the D-type asteroid Irmintraud. It is well known that bare cometary nuclei are classified as D-type asteroids with their dark and reddish spectra in the visible and near-infrared wavelengths (e.g., Licandro et al. 2003). While comets are generally supposed to have anhydrous compositions as a result of low temperatures, we cannot rule out the possibility that hydrated silicates are responsible for the observed feature beyond 2.1 μm.

Anyway, our simple model is enough to demonstrate the existence of water ice grains in the coma of C/LINEAR at 3.52 AU. The size of water ice grains is assumed to be 5 μm in our model. Is this size reasonable? We can check the validity of the grain size obtained from the model independently by comparing the lifetime of the grain in the coma at 3.52 AU with the aperture size used here. The lifetime of the icy grain for the sublimation should be longer than the traveling time of icy grains from the nucleus to the edge of the aperture used (0″.5 × 0″.5 at the sky). According to the heterogeneous icy grain model (Mukai 1986), the 5 μm sized dirty ice grain (80% of water ice, 10% of magnetite, and 10% of silicate) has a lifetime of $\sim 3 \times 10^4$ s at 3.5 AU from the Sun. Of course, if the grains consist of pure water ice, the lifetime of the grains is much longer than the lifetime of the dirty icy grains (i.e., the lifetime is about 10^8 s for 5 μm sized pure water ice grains even at 1 AU). If we assume an expansion speed of 100 m s^{-1} for the icy grains, the size of the icy grain halo is expected to be about 6000 km. Because the observed spectrum was extracted from an aperture of 1250 km × 1250 km at the comet, the 5 μm sized icy grains could easily survive in the area within the aperture (on the other hand, the size of the halo of 1 μm sized dirty ice grains is about a few tens of kilometers only). This estimation is consistent with our detection of the icy grains.

Finally, we note the absence of the 1.65 μm feature of the crystalline water ice in our observation (Fig. 3). The 1.65 μm feature was also absent in the near-infrared spectrum of comet Hale-Bopp at 7 AU (Davies et al. 1997). Davies et al. (1997) suggested that the absence of the 1.65 μm feature means that the water ice was in an amorphous state during their observation. The amorphous water ice changes its phase from amorphous to cubic at $T \sim 140$ K. Therefore, the absence of the 1.65 μm feature may indicate that the grain temperature was lower than 140 K. The equilibrated blackbody temperature at 3.52 AU from the Sun is 149 K, while the equilibrated temperature for the pure water ice grain (10 μm size) is estimated to be 70 K (Mukai et al. 1989) at the same heliocentric distance. Therefore, the icy grains observed here might have little dark materials, and their absolute reflectance in the visible wavelength region may be high enough to achieve an equilibrated temperature of lower than 140 K. Note that the change in the shapes of the absorption features between 1.0 and 2.7 μm was reported by Grundy & Schmitt (1998), although their report was for the hexagonal water ice (not the cubic water ice). With higher temperature, the shapes of the absorption features become more smoothed. However, if we take this effect into account, we consider that the 1.65 μm feature should be recognized in our spectrum in the case of an icy grain temperature of 149 K (the blackbody temperature) during our observation.

In future work, the development of a more sophisticated icy grain model will help us to reveal the composition of the ice, and a comparison between the near-nucleus spectrum and the off-nucleus spectra will provide us with information on the sublimation of icy grains (i.e., the change in the grain size), on the dynamical properties of grains, and so on.

The authors thank R. Furusho for her fruitful discussions and an anonymous referee for providing valuable comments that greatly improved the manuscript. This work is financially supported by the Ministry of Education, Science, and Culture of Japan under grants 15740127 (H. Kawakita) and 15654078 (J. Watanabe). This report is based on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

REFERENCES

A'Hearn, M. F., Dwek, E., & Tokunaga, A. T. 1984, ApJ, 282, 803
Brown, M. E., & Calvin, W. M. 2000, Science, 287, 107
Campins, H., Rieke, G. H., & Lebofsky, M. J. 1983, Nature, 302, 405
Davies, J. K., Roush, T. L., Cruikshank, D. P., Bartholomew, M. J., Geballe, T. R., Owen, T., & De Bergh, C. 1997, Icarus, 127, 238
Draine, B. T. 1985, ApJS, 57, 587
Grün, E., et al. 2001, A&A, 377, 1098
Grundy, W. M., & Schmitt, B. 1998, J. Geophys. Res., 103, 25809
Hanner, M. S. 1981, Icarus, 47, 342
———. 1984, ApJ, 277, L75
Hapke, B. 1993, Theory of Reflectance and Emittance Spectroscopy (Cambridge: Cambridge Univ. Press)
Kanno, A., et al. 2003, Geophys. Res. Lett., 30, 1909
Kurucz, R. L. 1994, in IAU Symp. 154, Infrared Solar Physics, ed. D. M. Rabin, J. T. Jefferies, & C. Lindsey (Dordrecht: Kluwer), 523
Lellouch, E., et al. 1998, A&A, 339, L9
Licandro, J., Campins, H., Hergenrother, C., & Lara, L. M. 2003, A&A, 398, L45
Marsden, B. G. 2003, Minor Planet Electronic Circ. 2003-R06
Motohara, K., et al. 2002, PASJ, 54, 315
Mukai, T. 1986, A&A, 164, 397
Mukai, T., Fechtig, H., Grün, E., & Giese, R. H. 1989, Icarus, 80, 254
Quirico, E., Douté, S., & Schmitt, B. 1999, Icarus, 139, 159