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Water ice and dust in the innermost coma of comet 103P/Hartley 2

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ABSTRACT

On November 4th, 2010, the Deep Impact eXtended Investigation (DIXI) successfully encountered comet 103P/Hartley 2, when it was at a heliocentric distance of 1.06 AU. Spatially resolved near-IR spectra of comet Hartley 2 were acquired in the 1.05–4.83 μm wavelength range using the HRI-IR spectrometer. We present spectral maps of the inner ~10 km of the coma collected 7 min and 23 min after closest approach. The extracted reflectance spectra include well-defined absorption bands near 1.5, 2.0, and 3.0 μm consistent in position, bandwidth, and shape with the presence of water ice grains. Using Hapke's radiative transfer model, we characterize the type of mixing (areal vs. intimate), relative abundance, grain size, and spatial distribution of water ice and refractories. Our modeling suggests that the dust, which dominates the innermost coma of Hartley 2 and is at a temperature of 300 K, is thermally and physically decoupled from the fine-grained water ice particles, which are on the order of 1 μm in size. The strong correlation between the water ice, dust, and CO_2 spatial distribution supports the concept that CO_2 gas drags the water ice and dust grains from the nucleus. Once in the coma, the water ice begins subliming while the dust is in a constant outflow. The derived water ice scale-length is compatible with the lifetimes expected for 1-μm pure water ice grains at 1 AU, if velocities are near 0.5 m/s. Such velocities, about three order of magnitudes lower than the expansion velocities expected for isolated 1-μm water ice particles (Hanner, 1981; Whipple, 1951), suggest that the observed water ice grains are likely aggregates.

1. Introduction

Comets formed beyond the H_2O frost line, where ices can condense (*e.g.*, A'Hearn et al., 2012). A variety of processes have affected comets during their long storage in the Oort cloud and scattered disk (*e.g.*, irradiation by energetic particles, heating by passing stars, collisions). Similarly, repeated solar heating leads to evolution of short period comets during their many passages close to the Sun. However, because most of these processes affect only the outer layer of comets, the pristine nature of the bulk of the nucleus is preserved (Bockelée-Morvan et al., 2004; Mumma et al., 1993; Stern, 2003; Weissman and Stern, 1997). As such, comets are excellent laboratories to extend our understanding of the origin and evolution of the Solar System.

Given that comets contain the least processed primordial materials that formed the cores of the giant planets (A'Hearn et al., 2011), the analysis of the composition and physical state of cometary materials is critical to improve our understanding of the accretion processes that led to the formation of comet nuclei and ultimately the planets. Water is a key component of comets (Bockelée-Morvan et al., 2004; Bockelée-Morvan and Rickman, 1997; Feaga et al., 2007; Mumma and Charnley, 2011) and water ice has been observed from the ground and with *in situ* observations in the comae (Davies et al., 1997; Kawakita et al., 2004; Sunshine et al., 2011a; Yang et al., 2009), on the surfaces (Sunshine et al., 2006), and in the near-surface interiors (Sunshine et al., 2007) of comets. An example of addressing comet nuclei formation by means of water ice characteristics is given by Sunshine et al. (2007): the presence of very fine (~1 μm) water ice particles in the impact ejecta of comet Tempel 1, free of refractory impurities, led to question the interstellar dust grain model proposed by Greenberg (1998) and Greenberg and Li (1999). The

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basic idea of this model is that comets formed directly through coagulation of interstellar dust. As such, the morphological structure of comet nuclei is an aggregate of presolar interstellar dust grains, which consist of a core of silicates mantled first by a shell of organic refractory material and then by a mixture of water dominated ices, which are embedded with thousands of very small (1–10 nm) carbonaceous/large molecule particles. According to Sunshine et al. (2007), it is unlikely that water ice would segregate from the superfine particles in the impact ejecta. The model by Greenberg is only one of the several models proposed, describing the underlying structure of cometary nuclei (*e.g.*, the "fluffy aggregate" of Donn et al. (1985) and Donn and Hughes (1986), the "rubble pile model", either collisionally modified (Weissman et al., 2004) or primordial (Weissman, 1986), the "icy-glue" model of Gombosi and Houpis (1986), the "talps" or "layered pile" model by Belton et al. (2007)). All of these models consider different origins and/or evolutionary processes. Investigations of cometary nuclei at close range, which can only be achieved by space missions, are required to validate, disprove, or improve these various formation models.

On November 4th, 2010, the Deep Impact Flyby (DIF) spacecraft (A'Hearn et al., 2005; Hampton et al., 2005) successfully encountered comet 103P/Hartley 2 as part of its extended mission, the Deep Impact eXtended Investigation (DIXI) (A'Hearn et al., 2011). The DIF spacecraft employs two multi-spectral imagers (MRI-VIS, HRI-VIS) and a 1.05–4.83 μm near-infrared spectrometer (HRI-IR). Near-IR spectra of comet Hartley 2 were acquired for several weeks before and after closest approach (CA, at a range of 694 km, occurred on November 4th, 2010, at 13:59:47.31 UTC with a maximum HRI-IR spatial resolution of 7 m/pixel). DIXI observations revealed a bi-lobed, very small (maximum length of 2.33 km, (A'Hearn et al., 2011)), and highly active nucleus, with water ice distributed heterogeneously, in specific areas on the surface (Sunshine et al., 2011b) and in the coma (Protopapa et al., 2011; Sunshine et al., 2011a).

In this paper, we present a detailed analysis of the composition and texture of water ice and refractories in the inner-most coma of Hartley 2, within a few kilometers of the surface, using DI HRI-IR data. We investigate the physical makeup of the water ice grains, with the goal of providing more observational constraints to help us have a better understanding of the accretion process that led to the formation of comet nuclei. We investigate the role of the gas in delivering the water ice and dust to the coma of Hartley 2 and how the emitted material evolves after it leaves the nucleus.

2. Observations

Spatially resolved near-IR spectra of comet Hartley 2 were acquired in the 1.05–4.83 μm wavelength range using the HRI-IR spectrometer (Hampton et al., 2005). HRI-IR data were collected from 01 October 2010 to 26 November 2010. In this paper, only a subset of data is analyzed. In particular, we present HRI-IR spatially resolved scans of comet Hartley 2 collected 7 (ID 5006000) and 23 (ID 5007002) minutes post-CA. Table 1 lists the main characteristics of these two scans.

The IR data are calibrated using the DI science data pipeline (Klaasen et al., 2008, 2013) and are available in the NASA Planetary Data System (PDS) archive (McLaughlin et al., 2013). The standard steps of the pipeline processing include linearization, dark subtraction, flat fielding, conversion from DN to radiance units (W m^{-2} sr^{-1} μm^{-1}), and bad pixel masking. These data have been recalibrated since the work by A'Hearn et al. (2011), although the differences are not dramatic. The 5006000 and 5007002 radiance maps are shown in panels (a) and (b) of Fig. 1, respectively, compared with the HRI-VIS and MRI-VIS context images (with characteristics given in Table 2). Because the HRI-IR instrument is a scanning slit spectrometer, reconstructed spatial information is susceptible to errors from jumps in spacecraft attitude due to impacting particles or autonomous operations. A mismatch in the nucleus shape between the IR scan acquired 7 min post-CA and the corresponding visible context images was observed, possibly caused by very small grains hitting the spacecraft at high speed. We have corrected this mismatch by shifting the bottom 14 rows of the 56-row IR scan by 1 pixel to the left and the top 21 rows by 1 pixel toward the right and bottom (with respect to the orientation of Fig. 1).

Both the 5006000 and 5007002 scans contain the nucleus of Hartley 2 and the surrounding coma. The nucleus is in roughly the same orientation in the two scans. The precession of the long axis of the nucleus around the angular momentum vector has a period of 18.4 h at encounter (A'Hearn et al., 2011; Belton et al., 2013); therefore in 16 min separating the two scans, the rotation of the nucleus is negligible with regards to coma studies, as is the change of the spacecraft line of sight. In both scans, there are jets off the end of the smaller lobe of the nucleus and beyond the terminator along the lower edge of the larger lobe (Fig. 1).

The nucleus of Hartley 2 needs to be masked in order to focus our analysis on the water ice and refractories in the inner-most coma. The dashed red line in Fig. 1 outlines the illuminated portion of the cometary nucleus, including the scattered light near the limb, that is excluded from our analysis. This mask was defined at long wavelengths ($\lambda \geqslant 3.5$ μm), where the thermal emission of the nucleus dominates over the signal from the dust in the coma, allowing the nucleus and coma to be disentangled. The nucleus contour is defined by radiance values in the 450 channel (~4.1 μm) greater than 0.16 W m^{-2} sr^{-1} μm^{-1} in order to match the nucleus as seen in the HRI-VIS and MRI-VIS images acquired at the same time as the IR data.

Table 1
Characteristics of the HRI-IR scans analyzed in this paper.

Exposure ID	5006000	5007002
Time at mid-scan at spacecraft	2010-11-04 14:07:08	2010-11-04 14:23:10
Time after CA (min)	7	23
Number of Commanded Frames	56	30
Mode name	ALTFF[a]	ALTFF
Total integration time per frame (ms)	1441	1441
Spatial resolution at mid-scan (m/pixel)	55	173
Phase angle (deg)	92	93
Spacecraft–comet distance (km)	5478	17295

[a] The alternating binned full frame (ALTFF) stores the image in 512 × 256 pixels (spectral × spatial).

3. Spectral modeling

3.1. Reflectance

Once the flux is calibrated into radiance, *I*, from the pipeline, we can convert it into reflectance, *R*, by

$$R(\lambda) = \frac{\pi I(\lambda) r^2}{F_{\odot}(\lambda)} \quad (1)$$

where $F_{\odot}(\lambda)$ is the solar flux at 1 AU, and *r* is the heliocentric distance, in our case 1.06 AU. The solar spectrum we use is a synthesized spectrum from various sources (Berk et al., 2006; Kurucz, 1995), available at the MODTRAN web site http://rredc.nrel.gov/solar/spectra/am0/other_spectra.html.