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Photometric properties of the nucleus of Comet 103P/Hartley 2

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ABSTRACT

We have studied the photometric properties of the nucleus of a hyperactive comet, 103P/Hartley 2, at visible wavelengths using the DIXI flyby images with both disk-integrated and disk-resolved analyses. The disk-integrated phase function of the nucleus has a linear slope of 0.046 ± 0.002 mag/deg and an absolute magnitude of 18.4 ± 0.1 at *V*-band. The nucleus displays an overall linear, featureless spectrum between 400 nm and 850 nm. The linear spectral slope is 7.6 ± 3.6% per 100 nm, corresponding to broadband solar-illuminated color indices *B*–*V* of 0.75 ± 0.05 and *V*–*R* of 0.43 ± 0.04. Disk-resolved photometric analysis with a Hapke model returns a best-fit single-scattering albedo of 0.036 ± 0.006, an asymmetry factor of the Henyey–Greenstein single-particle phase function of −0.46 ± 0.06, and a photometric roughness of 15 ± 10°. The model yields a geometric albedo of 0.045 ± 0.009 and a Bond albedo of 0.012 ± 0.002. The overall photometric variations of the nucleus are small, with an equivalent albedo variation of 15% FWHM, and a color variation of 12% FWHM. Some areas near the terminator visible in the inbound images show an albedo of more than twice the global average value, and a much bluer color than the average nucleus. The overall photometric properties and variations of the nucleus of Hartley 2 are similar to those of the nuclei of Comets Wild 2 and Tempel 1 as studied from previous spacecraft flyby missions at similar resolutions.

1. Introduction

Disk-resolved photometry of cometary nuclei has been enabled by recent spacecraft explorations of comets. Before the flyby of Comet 103P/Hartley 2, three cometary nuclei had been analyzed photometrically in great detail from high-resolution images returned by spacecraft, including 9P/Tempel 1 (Li et al., 2007a), 19P/Borrelly (Li et al., 2007b), and 81P/Wild 2 (Li et al., 2009), with Tempel 1 visited twice in two consecutive apparitions (Li et al., 2012). All of the nuclei display similar disk-averaged photometric properties, with geometric albedos of 0.04–0.07, a linear phase slope of 0.04–0.05 mag/deg. However, Borrelly shows extremely large photometric variations (Buratti et al., 2004; Nelson et al., 2004; Kirk et al., 2004; Oberst et al., 2004; Li et al., 2007b), while the other two only display 10–20% (FWHM) photometric variations on their surfaces.

The surface morphology of these three comets varies greatly (Britt et al., 2004; Brownlee et al., 2004; Thomas et al., 2007, 2012a). These variations may be related to their different dynamical ages in the inner Solar System: Wild 2 is the most recent visitor, having resided in its current orbit close to the Sun for only a few apparitions (Sekanina and Yeomans, 1985); the other two comets have been stable in their inner Solar System orbits for considerably longer time (Carusi et al., 1985; Yeomans et al., 2005).

Despite the different dynamical ages and appearances, the activity levels for the three previously measured comets were all relatively low, with active areas less than a few percent of the total nuclear surface area, and similar dust and gas production rates (Schleicher et al., 2003; Farnham and Schleicher, 2005; Lisse et al., 2005). Although there was some early evidence suggesting that photometric properties were correlated to cometary activity on the surface of Borrelly (Buratti et al., 2004; Li et al., 2007b), a similar correlation was not found on the other two comets. The comparative study of photometric properties among cometary nuclei is limited by the similar and weak activity levels of the three comets.

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Comet Hartley 2, on the other hand, is a hyperactive comet (A'Hearn et al., 2011). It has a total water production rate similar to that of Tempel 1 (Crovisier et al., 1999; Colangeli et al., 1999), but its much smaller size, an equivalent radius of ~0.57 km, means that it must be emitting gas over an active area ~100% of the nucleus surface area (Groussin et al., 2004; Lisse et al., 2009). The Deep Impact eXtended Investigation (DIXI) retargeted the Deep Impact flyby (DI) spacecraft to fly by Hartley 2 in November 2010 to study this highly different comet, and thus probe the diversity among comets (A'Hearn et al., 2011). Two cameras onboard the spacecraft, the High-Resolution Instrument (HRI) and Medium-Resolution Instrument (MRI) collected disk-resolved images of the nucleus of this comet throughout the encounter, once again enabling disk-resolved photometric study of a cometary nucleus, but a very different one from any ever measured before. Strong and bright jets are obvious in all flyby images of Hartley 2, and for the first time from an *in situ* flyby, many jets can be easily traced back to their source areas on the surface of the nucleus (Bruck Syal et al., 2013). The geology of this comet shows some correlations with its jet activity. Whether the much stronger activity of Hartley 2 compared to that of an ordinary comet results in any detectable effects on its surface photometric properties, such as large photometric variations or correlations between photometric properties with jet activity, is the focus of this study.

In this paper we report a detailed study of the photometric properties of the nucleus of Hartley 2 using the disk-resolved images collected during the DIXI flyby of this comet. Section 2 summarizes the data we used and the basic data reduction and photometric measurement techniques. Section 3 describes the disk-integrated properties of this nucleus, including its phase function and color. Section 4 provides the disk-resolved photometric modeling with Hapke photometric model. Section 5 studies the photometric variations on Hartley 2's nucleus based on a disk-resolved photometric model. Section 6 discusses the limitations and caveats of our modeling process and results, and compares the photometric properties of the nucleus of Hartley 2 with those of other comets previously studied. The general conclusions are summarized in Section 7.

2. Data

The DI spacecraft approached Hartley 2 at a phase angle of ~84°, and flew past the comet going from south of its orbital plane to north of it at a closest-encounter distance of 694 km. The spacecraft continuously tracked the comet and acquired data during the encounter with all onboard instruments. The minimum achieved pixel size on the nucleus was ~7 m for MRI and ~1.4 m for HRI. The phase angle coverage was from 79° right before the closest encounter to 95° at departure. While most flyby images of the nucleus were obtained through the broadband clear filter, several full sets of color images were taken from both cameras, symmetrically positioned on both inbound and outbound legs of the flyby trajectory. The pixel sizes of color images used in our study (taken at ~7000 km distance) are ~70 m for MRI, and ~14 m for HRI. All images are calibrated to I/F units, where I is the scattered intensity from the comet, and πF is the incident solar flux. Both instruments have been carefully calibrated initially with the DI mission (Klaasen et al., 2008), and then continuously monitored and improved over the course EPOXI mission (Klaasen et al., in preparation, 2012). The absolute photometric calibration is good to ±5% for HRI filters except for the 950-nm one, which is good to ±10%, and good to ±10% for MRI filters except for the narrow band UV filters, which are good to ±20%.

For disk-integrated photometry of the nucleus, we did not use HRI images because of two reasons. First, HRI images are out of focus (Klaasen et al., 2008, in preparation, 2012), and the boundary of the nucleus is >10 pixels wide, complicating the estimate of foreground coma from the immediate vicinity of the nucleus. Second, many HRI images near close encounter either only cover part of the nucleus or completely lost the nucleus out of field-of-view (FOV). For MRI images, we used those with pixel size less than 40 m/pix, and discarded all other images with lower resolutions. The phase angles of the MRI images we used start at 84°, decreasing to a minimum of 79° at closest encounter, then increasing to 92°. We measured the total flux by integrating the flux within the boundary of the nucleus, which is calculated from the shape model (Thomas et al., 2012b) coupled with the flyby geometry (Semenov and Acton, 2009), in order to avoid including ambient coma. For most images, the shape model matches the outline of the nucleus well except for occasional small discrepancies along the limb caused by uncertainties in the shape model, which can cause an uncertainty in the total flux measurement of up to 2%.

For disk-resolved analysis, we used both HRI images and MRI images with pixel sizes less than 10 m/pix. The phase angle coverage is from 79° to 85° for MRI, slightly smaller than that for disk-integrated analysis. Although the best pixel scale for HRI images is 2.8 m, better than that for MRI images by more than a factor of two, the out-of-focus point spread function (PSF) of HRI and the partial nucleus within the FOV, as mentioned earlier, make the HRI images not particularly useful for studying the photometry of the nucleus. Therefore we focused on the MRI images for the disk-resolved modeling, and only used the HRI images to check the consistency of photometric models in a different instrument.

One difficulty in studying the photometry of the nucleus of Hartley 2 is the obvious contamination from the relatively bright coma compared to all previously studied comets (Li et al., 2007a,b, 2009, 2012). The bright jets near the terminator obscure part of the boundary of the nucleus and possibly affect the foreground coma along the line-of-sight of the cameras. It is impossible for us to precisely remove the foreground coma by modeling the complicated jets in the ambient coma. Instead, we could only estimate the brightness of the foreground coma to subtract from the nucleus, and we include this process in the estimate of measurement uncertainties.

The brightness of the foreground coma was estimated with two extremely simplified models. For the first model, we measured the averaged surface brightness of the ambient coma within a five-pixel-wide annulus immediately surrounding the nucleus along the boundary. The foreground coma is taken as a half of the measurement from the ambient coma. Since jets on Hartley 2 appear to concentrate in several isolated areas along the limb and terminator, this method probably underestimates the coma brightness. This method yields a total flux from the foreground coma equaling ~10% of that of the nucleus for the closest approach images. The second model is a 2-D foreground coma model, constructed for each image by a bilinear interpolation based on the same annulus as used for the first model. The foreground coma is taken as a half of the 2-D model. This method tends to overestimate foreground coma, because whenever jets happen to be on both left and right sides (or top and bottom) of the nucleus, this model will impose foreground coma that is very likely greater than the real foreground coma across the whole nucleus. But as a 2-D model, it partially accounts for the highly non-uniform distribution of jets on the nucleus. This method results in a total foreground coma flux that is 2.5× higher than that from the first method for images taken at 1000 km distance from the nucleus, and about 1.5× higher for the closest approach images. We consider that the true brightness of the foreground coma must be somewhere between the estimates derived from the two models, between 10% and 20% of the average nucleus brightness, and will discuss the coma model we used and the implications in the corresponding measurements in later sections.