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Dust in Comet 103P/Hartley 2 coma during EPOXI mission ☆

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ABSTRACT

The *Deep Impact* spacecraft flew by Comet 103P/Hartley 2 on 4 November 2010 (EPOXI mission). In situ observations are complemented by a systematic ground- and space-based observation campaign. In the present work, imaging polarimetry is used to emphasize different dust regions in the coma and follow their evolution over a period including the EPOXI fly-by.

On the intensity images, the coma is asymmetric with an important tailward feature. Jets in the sunward direction are observed to present an extension that depends on the nucleus phase. The azimuthal integrated intensity presents a nominal radial decrease (-1 in log–log scale) for optocentric distances larger than a few hundred kilometers. Through cometary continuum narrow band filters, the aperture polarization decreases with the optocentric distance. On the polarization maps, the short sunward jets are more polarized than other parts of the coma. Intensity variations may be induced by large slow particles in the inner coma and possibly by their fragmentation into smaller particles, under ice sublimation processes. The decrease of linear polarization with increasing optocentric distance is correlated with intensity variations and may be induced by the same physical process.

The optical behavior of 103P/Hartley 2 is finally compared to those of other Jupiter-family comets such as Comet 9P/Tempel 1 impacted by the *Deep Impact* projectile in 2005 and Comet 67P/Churyumov–Gerasimenko, target of the *Rosetta* mission (2014–2015), since the polarimetric properties of both comets have been monitored remotely in the recent past.

1. Introduction

Comet 103P/Hartley 2 was discovered in 1976. Its orbit inclination is relatively small (about 14°). It had two close approaches with Jupiter in 1947 and 1971, which decreased its orbital period to a value of 6.47 years. The nucleus is small but very active. It was observed at each perihelion passage since its discovery. For the last passage (2010), the closest approach to Earth on October 20 was at 0.12 AU, making it easily observable.

The *Deep Impact* spacecraft flew by Comet 103P/Hartley 2, on 4 November 2010 as part of the extended mission EPOXI (A'Hearn et al., 2011). Amazing images of ice particles moving in the neighborhood of the nucleus were obtained with well-localized dust and gas jets emerging from the surface (Farnham et al., 2011). The small nucleus is very active with an outgassing dominated by CO_2, which drags off large pure ice particles from the sub-surface (Sunshine et al., 2011) and darker particles. The nucleus is bi-lobed with a 'waist' reminiscent in shape of Comet 19P/Borrelly (Boice et al., 2002). The relative abundances of volatiles ejected by the three parts of the nucleus are different (A'Hearn et al., 2011), showing a stronger water signal near the waist of the body and more CO_2 ejections and organics from the smaller lobe from which clustered jets are issued (Feaga et al., 2011). The dust jets are correlated with the CO_2 emissions. The large particles (chunks) that are found all around the nucleus and move slowly are possibly fluffy aggregates of micrometer-sized constituent grains consisting of water ice and dark refractory materials. From EPOXI observations, it is not expected that the water ice particles survive further than the innermost coma of the comet (<10^3 km; Lisse et al., 2011).

An important Earth- and space-based campaign using different techniques, including the study of light scattered by the ejected particles and its linear polarization has been developed in support of the EPOXI mission (Meech et al., 2011). An unusual CO_2-driven activity was observed near perihelion, which seemed to persist

☆ Based on observations made in part at Observatoire de Haute Provence (CNRS), France and in part at IUCAA Girawali Observatory, India.

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later on. An ice halo around the nucleus was inferred by fitting 103P/Hartley 2′ R-band light curve with a model of comet activity (Meech et al., 2011). The period of rotation of the nucleus increased with time from about 17.5 h in October to 18.8 h at the end of November (Samarasinha et al., 2011). A period of 18.34 h for the excited state of rotation was determined at encounter from the light curve (A'Hearn et al., 2011).

Jupiter family comets (hereafter JFCs) have the following observed general properties. The dust production rates estimated by coma observations in the visible is generally small; such comets are qualified as dust poor (low dust-to-gas ratio), requiring the use of narrow band filters to study the dust contribution, while avoiding possible contaminations by gas emissions. Hadamcik and Levasseur-Regourd (2009) reviewed the optical properties of dust in JFCs, as summarized below. The average geometric albedo of the nucleus (measured by EPOXI, 0.04) is lower than the one of the ejected dust particles (between 0.04 and 0.09 at zero degree phase, for dust particles in different JFCs). The observed light curves are usually similar from one apparition to the next, except when the nucleus suffers a major outburst or changes its orbit. Fans and jets are observed in the coma. If the physical properties of particles inside such structures are different from the surrounding dust coma, the fans and jets may be detected by color and/or linear polarization differences. Further away from the nucleus, the dust particles observed in trails are dark and may reach millimeter sizes. They can survive along the cometary orbit for several revolutions (Fernandez et al., 2009) but their number density is small; they are faint and not observable by polarimetry. Close to the nucleus, the number density of particles in the hundreds of micrometers to centimeters size range is more important due to their low velocity and their eventual fragmentation. They can then be detected by their linear polarization (Hadamcik et al., 2009 and Section 4.3 for experimental simulations showing the high polarization produced by large particles). Polarization imaging, through filters blocking gaseous emission lines, is necessary to correlate the intensity and polarization variations of dust through the coma. The correlation between intensity, color and polarization gives indications on the type of physical processes affecting the dust particles as they move away from the nucleus, probing for example their possible fragmentation. Fresh material, coming from inside JFC nuclei, as in the case of an outburst or the *Deep Impact* collision, seems to have properties similar to the ones of materials ejected in the well-focused jets observed in active comets originating from the Oort cloud such as Comet C/1995 O1 Hale–Bopp or Comet C/2001 Q4 NEAT (Hadamcik and Levasseur-Regourd, 2003a; Harker et al., 2007; Wooden et al., 2004).

2. Observations and data reduction

This work is part of a French-Indian collaboration. Two telescopes in Cassegrain mode are used. A short description of the instruments and data reduction is given below, more details can be found in Hadamcik et al. (2010).

The intensity and polarization state of a beam of light scattered by irregular particles can be entirely expressed by the four Stokes parameters: *I, Q, U, V* (van de Hulst, 1957). These quantities can be calculated from the observed polarized intensities. In the present work four polarized images are recorded with their polarization axis at 45° from each other. If the polarization axis of the images can be oriented relatively to the scattering plane, the total intensity I and the linear polarization are I and $P_r = -\frac{Q}{I}$ respectively

$$I = I_{\perp} + I_{//} \tag{1}$$

$$P_r = \frac{I_{\perp} - I_{//}}{I_{\perp} + I_{//}} \tag{2}$$

where $I_{\perp}$ and $I_{//}$ are the polarized components perpendicular and parallel to the scattering plane respectively. The third Stokes parameter $\frac{U}{I}$ equals zero in that case, while $\frac{V}{I}$ allows to calculate the circular polarization, equal to 0 for irregular randomly oriented particles.

The polarization of the scattered light by solid particles is a dimensionless ratio (Eq. (2)), which makes it unnecessary to normalize the fluxes as a function of distance or of the number density of particles.

2.1. Observatory of Haute-Provence (OHP) instrumentation

The telescope has a diameter of 0.8 m with *f* ratio of 15. The resolution on the camera is 0.21 arcsec diameter by pixel. A pixel binning of 4 pixels × 4 pixels is used to increase the signal-to-noise ratio. The total field of view is 7 arcmin × 7 arcmin. The sky background is measured at more than 2 arcmin from the optocenter, in regions without stars.

Four Polaroid filters are mounted on a rotating wheel. The continuum ESA narrow band blue (CB) and red (CR) filters, the broadband red Gunn (R) and infrared Gunn (I) filters, installed on a second wheel, avoid or considerably reduce contaminations by the gaseous species (see Table 1 for their bandwidth). With a star-tracking mode, series of 10–20 short exposure time images (typically 30 s depending on the filter and date, up to 240 s for the very narrow blue cometary filter) are added to increase the signal-to-noise ratio.

2.2. Girawali IUCAA Observatory (IGO) instrumentation

The telescope has a diameter of 2 m with *f* ratio of 10. The resolution on the camera is 0.307 arcsec diameter by pixel. A rotating half-wave plate (HWP) and a Wollaston prism allow to measure the polarization (Sen and Tandon, 1994). The total field of view for polarization imaging has a 4 arcmin diameter.

With the Wollaston, two perpendicularly polarized images are recorded at the same time on the same CCD frame; their separation on the image is about 1 arcmin. This limits the size of one polarized image to less than 0.5 arcmin. The non-overlapping of the two images is controlled by intensity profiles and compared to the value of the sky background measured at more than 1.5 arcmin from the optocenters. Specific formulas for the calculation can be found in Ramaprakash et al. (1998) and Hadamcik et al. (2010). To build the polarization maps, it is in the end necessary to separate the two components and re-center them. In this work, the general formulas with four polarized components are considered (Eqs. (3)–(7)). Like at OHP, ESA blue (CB) and red (CR) narrow-band continuum cometary filters and a Bessel red (Rb) broadband filter reduce the gaseous emission contaminations (Table 1). The telescope tracks the comet with a typical exposure time of 900 s per filter.

2.3. Observations procedure

During each night, polarized and unpolarized stars are observed to estimate the residual instrumental polarization and to determine the origin of the instrumental reference system θ_0 (Table 2). θ_0 corresponds to the position angle of the polarization axis of one polarized filter or of the rotating HWP.

The four images are polarized at 45° from one another. The intensity, the measured polarization degree P, the measured position angle θ, the position angle of the polarization plane and finally the values of the polarization P_r and of the position angle θ_r in the coordinate system referring to the scattering plane are calculated by the following expressions:

$$I = I_0 + I_{90} = I_{45} + I_{135} \tag{3}$$