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RADAR OBSERVATIONS OF COMET 103P/HARTLEY 2

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ABSTRACT

Comets rarely come close enough to be studied intensively with Earth-based radar. The most recent such occurrence was when Comet 103P/Hartley 2 passed within 0.12 AU in late 2010 October, less than two weeks before the *EPOXI* flyby. This offered a unique opportunity to improve pre-encounter trajectory knowledge and obtain complementary physical data for a spacecraft-targeted comet. 103P/Hartley 2 is only the fourth comet nucleus to be imaged with radar and already the second to be identified as an elongated, bilobate object based on its delay-Doppler signature. The images show the dominant spin mode to be a rotation about the short axis with a period of 18.2 hr. The nucleus has a low radar albedo consistent with a surface density of 0.5–1.0 g cm^{-3}. A separate echo component was detected from large (>cm) grains ejected anisotropically with velocities of several to tens of meters per second. Radar shows that, in terms of large-grain production, 103P/Hartley 2 is an unusually active comet for its size.

Key words: comets: general – comets: individual (103P/Hartley 2) – techniques: radar astronomy

1. INTRODUCTION

Earth-based radar offers a powerful technique for remotely probing comet nuclei and the populations of large ejected grains that often accompany them. Unfortunately, good cometary radar observing opportunities are rare owing to the infrequency of close Earth approaches. Nevertheless, the inventory of comet radar detections has steadily increased, with a total of 14 objects having been detected since 1980. An important development of the past five years has been the advent of delay-Doppler radar imaging of comet nuclei. The most recent cometary radar imaging opportunity came with the close (0.12 AU) passage of the Jupiter-family comet 103P/Hartley 2 (henceforth referred to here simply as "Hartley") in late 2010 October. Hartley was also the target of a flyby by the *EPOXI* spacecraft on 2010 November 4. In this paper, we report pre-flyby observations of Comet Hartley made with the Arecibo Observatory planetary radar, emphasizing those results that complement the *EPOXI* data.

2. OBSERVATIONS

We observed Hartley with the Arecibo S-band (2380 MHz; $\lambda = 12.6$ cm) radar on eight dates over the period 2010 October 23–31. Our initial priority was to obtain astrometric delay-Doppler measurements useful for planning final course corrections for the *EPOXI* spacecraft flyby of November 4. The first measurements on October 24 corrected the comet position by +70 km and −120 mm s^{-1} in Earth range and range rate, respectively, relative to ground-based optical trajectory solution no. 128 then in use by *EPOXI*. We then continued to observe the comet every day (except October 28) through the end of October to monitor nucleus rotation and activity and to obtain follow-up astrometry for *EPOXI*.

We transmitted a 750 kW, circularly polarized wave and received the echo in both the opposite-circular (OC) and same-circular (SC) polarization senses. We used two different observing modes based on different transmission schemes. The larger portion of observing time was devoted to phase-coded observations designed to obtain images of the nucleus using the delay-Doppler technique. All of the imaging observations after October 24 were done with a "baud" (phase-flip interval) of 1 μs, which gave a range resolution of 150 m. The images were averaged in blocks of four transmit/receive cycles, each block representing 8 minutes of receive integration time over a span of 15 minutes. A total of 20 image blocks was obtained over six dates during October 25–31.

We supplemented the delay-Doppler observations with continuous-wave (CW) measurements of the echo Doppler spectrum. Although CW observations provide no delay discrimination and hence no images, they are useful for measuring accurate radar cross sections and polarization ratios and for identifying any separate echo component from particulates. Figure 1 shows the Doppler spectrum averaged over all of the CW observations. This spectrum shows a narrowband echo from the nucleus and the characteristic broadband echo expected from a population of large ejected grains in the inner coma (the so-called grain coma). Comet Hartley is the seventh of the 14 radar-detected comets to show such a two-component echo. Not only are the two echo components easily distinguishable in the Doppler spectra, but radar grain comae have been shown (Harmon et al. 2004) to be optically thin and to contribute negligible obscuration of the nucleus. This enables us to evaluate the nucleus and grain-coma echoes separately.

3. NUCLEUS

The Hartley nucleus was clearly visible and resolved in each of the 20 delay-Doppler images. A selection of 10 of these images is shown in Figure 2(a). Although image quality and resolution was obviously too low to show fine detail, it sufficed for determining gross nucleus form and estimating rotation parameters. It was immediately clear from our first images that the Hartley nucleus is an elongated, bilobate body (Harmon et al. 2010b, 2010c). Such a shape had not been anticipated from earlier optical observations, although light curves from 2009 did suggest some asphericity (Meech et al. 2009). We found we could roughly reproduce the delay-Doppler images using an idealized shape model consisting of two prolate spheroidal lobes of unequal size connected by a thick neck. This basic "peanut" shape was essentially confirmed (and superseded) by the *EPOXI* flyby imagery. In Figure 2(b), we show a modified

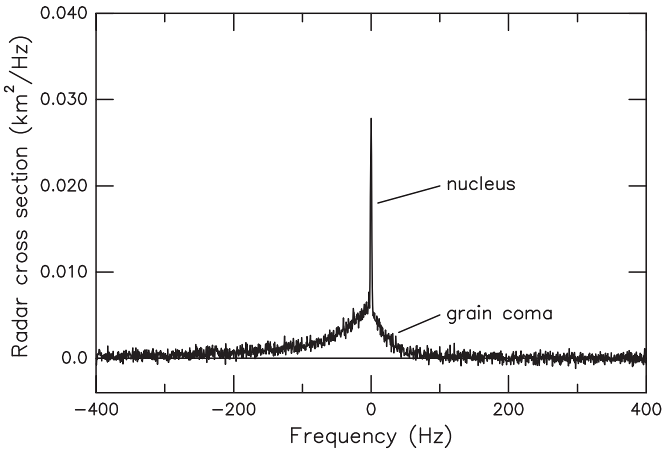

Figure 1. Radar Doppler spectrum (OC polarization) of Comet 103P/Hartley, with the narrow nucleus and broad grain-coma components denoted. This is an average of the spectra from CW observations on six dates during 2010 October 24–30.

shape model that is close to our provisional pre-flyby model but with the width of the connecting neck increased slightly to conform to the *EPOXI* results. Though Hartley is only the fourth comet to be imaged with radar, it is already the second to show a bilobate shape. Comet 8P/Tuttle, to which we also applied a bilobate spheroidal shape model (see Figure 2(c)), was even more strongly bifurcated than Hartley and is considered a strong candidate for a contact binary (Harmon et al. 2010a). The thick-necked Hartley more closely resembles the peanut-shaped Comet 19P/Borrelly, although that comet too has been suggested to be two fragments in contact (Oberst et al. 2004).

To estimate Hartley's rotation parameters we fit our modified shape model to the entire ensemble of 20 images, varying the synodic rotation period P, the rotation phase, and the long-axis length L as free parameters. The fits produced estimates of $P = 18.198 \pm 0.010$ hr and $L = 2.76 \pm 0.10$ km. (Our L value is about 15% larger than the average *EPOXI*-based value, which may be partly due to modeling bias related to the fact that the *EPOXI* images show the ends of the nucleus to be blunter than in our model.) To set the Earthward spin inclination angle, our model assumed a prograde spin pole of 17° R.A., +47° decl. (M. J. S. Belton 2011, private communication), which gave nucleus sub-Earth latitudes changing from −28° to −13° during October 25–31. Using this pole direction and our synodic period, we estimate the true (sidereal) rotation period to be 18.223 ± 0.010 hr. Our rotation period is longer than the 16.6 hr period inferred from light curves in mid-2009 (Meech et al. 2009) and from coma jets in 2010 August (Knight et al. 2010). It falls between the 17.1 to 17.6 hr periods inferred from coma jets during 2010 September 1 to October 4 (Samarasinha & Mueller 2010) and the 18.2 to 19 hr periods inferred from light curves during October 29 to December 7 (Jehin et al. 2010). Our radar-based period, which is effectively an average for the last week of October, might be consistent with the various optical-based values if the rotation was changing rapidly around perihelion, as was observed for Comet 9P/Tempel 1 (Belton et al. 2011). However, including the implied $\dot{P} = +0.021$ hr day^{-1} spin-down in our model did not reduce the fit chi-square, so we can claim no evidence for a changing period based on the radar data alone.

For our fits we assumed a principal-axis rotation state with the spin vector perpendicular to the nucleus long axis ($\theta = 90°$). When we tested this assumption by redoing the fits with θ as

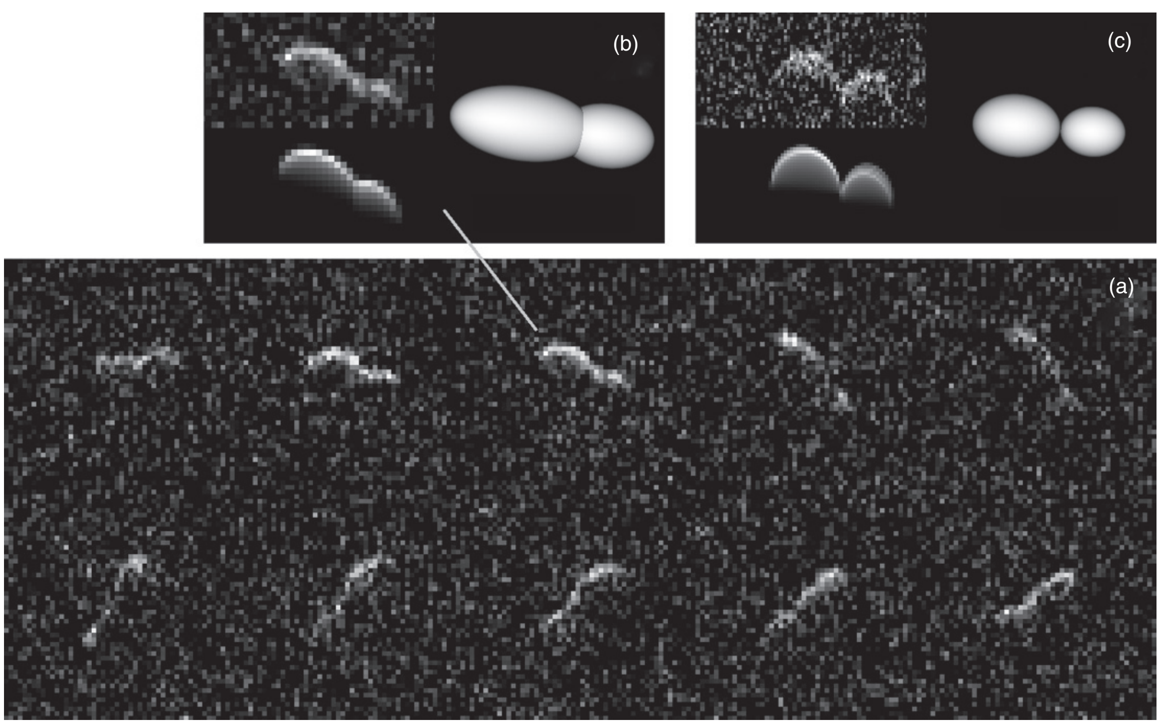

Figure 2. (a) Selection of 10 of the delay-Doppler images from 2010 October 25 to 31, showing two sides of the Hartley nucleus. The images are ordered by rotation phase, with the upper five images spanning phases 347°.9–42°.6 and the lower five spanning 131°.0–157°.6. (Our convention defines zero phase as when the nucleus is broadside and with the larger lobe approaching.) Delay is the vertical axis and Doppler is the horizontal axis. Delay and Doppler increase downward and leftward, respectively, so the rotation sense is clockwise. Each pixel measures 0.5 μs × 0.18 Hz. (b) Delay-Doppler image (upper left), best-fit model delay-Doppler image (lower left), and corresponding plane-of-sky model figure (right) for the third Hartley imaging epoch in (a); the rotation phase is 16°.9. (c) Similar to (b), but from Arecibo radar observations of Comet 8P/Tuttle on 2008 January 3; the rotation phase is 12°.9.

a free parameter, we found θ solutions converging to within a degree of 90°. This indicates that Hartley's dominant spin mode is consistent with principal-axis rotation about the short axis, although it does not rule out an oscillation or roll about the long axis.

The CW observations gave a total radar cross section $\sigma \equiv \sigma_{\rm oc} + \sigma_{\rm sc}$ for the nucleus of 0.061 km^2, averaged over all CW epochs. Dividing the radar cross section by the projected area of the nucleus gives an estimate of the radar albedo, a measure of the absolute radar reflectivity of the surface. We estimate the nucleus albedo to be 0.041, averaged over all epochs, or 0.034 if only the three most broadside epochs are used. If the shorter *EPOXI*-based dimensions are used, then the corresponding values are 0.054 and 0.045, respectively. These albedos imply a bulk density for the top few meters of about 1.0 g cm^{-3}, assuming a dusty composition, or about half that density for ice (Harmon et al. 2004). These low albedos and inferred densities are similar to the low values estimated for most other radar-detected comets (Harmon et al. 2004; Harmon & Nolan 2005; Harmon et al. 2006). Comets typically have only about one-third the radar albedo of the average asteroid and hence only about half the surface density (Harmon et al. 2004). The Hartley radar albedo is important in this regard as it is based on a direct nucleus size measurement rather than an indirectly inferred size as with most other comets. Curiously, Comet Tuttle, for which we also have a direct radar-based size, gave a radar albedo of 0.15 (Harmon et al. 2010a) and thus showed that not all comets have such low-density surfaces. Finally, we measured a circular polarization ratio $\mu_{\rm c} \equiv \sigma_{\rm sc}/\sigma_{\rm oc}$ of 0.37 for the nucleus, which places Hartley in the middle of the $\mu_{\rm c}$ range (0.10–0.59) for comet nuclei and, hence, intermediate in terms of decimeter-scale surface roughness.

4. LARGE-GRAIN COMA

The detection of a grain-coma echo from this comet is not surprising, given that Hartley is the 10th of the 14 radar-detected comets to show such a component. Also, earlier modeling of Hartley's infrared dust coma and tail had suggested the presence of cm size grains (Epifani et al. 2001) and the *Spitzer Space Telescope* more recently detected an infrared dust trail presumably associated with millimeter size debris (Lisse et al. 2009). Although radar backscatter-efficiency and mass-loss considerations (Harmon et al. 2004) require that the radar grain coma be dominated by large (>cm) grains, our radar polarization results provide even more direct evidence for this. In Figure 3, we show the grain-coma CW spectra (with nucleus echo subtracted) for the OC and SC polarization senses. The presence of a substantial depolarized (SC) echo ($\mu_{\rm c} = 0.34$) indicates that the largest grains have radii a exceeding the Rayleigh transition size $a = \lambda/2\pi$ or 2 cm (Harmon et al. 2004; Nolan et al. 2006). In fact, Hartley exhibits the highest grain-coma depolarization yet measured reliably for a comet, which suggests that the grain size distribution included a significant population at decimeter sizes or even larger.

The characteristic "peak-and-wings" shape and asymmetry of the grain-coma spectrum (Figures 1 and 3) is similar to that of other comets and diagnostic of grains ejected into free trajectories rather than circum-nuclear orbits. The 65 Hz bandwidth (FWHM) corresponds to a characteristic grain velocity dispersion of 4 m s^{-1}, although the broad wings indicate that the fastest grains are moving at tens of meters per second. In Figure 3, we show a model fit to the OC spectrum based on a grain ejection fan with an $a^{-3.5}$ grain production size distribution and a grain velocity $V(a) \propto a^{-1/2}$, where $V = 30$ m s^{-1} for $a = 2$ cm. Accelerating centimeter size grains to these velocities requires surface gas mass fluxes of 1×10^{-3} g cm^{-2} s^{-1}, which is sufficient to lift meter size and larger boulders off the nucleus (Harmon et al. 2004; Nolan et al. 2006; Molina 2010). The preferential redshift of the grains indicates that their ejection was skewed toward the anti-Earthward direction. We could reproduce the spectral asymmetry by concentrating the grain ejection in a 90° wide cone with a centroid aimed 110° away from the comet-Earth line. Since the Sun-comet-Earth angle averaged 58° during the radar observations, the fan centroid must have been directed at least 52° away from the Sun.

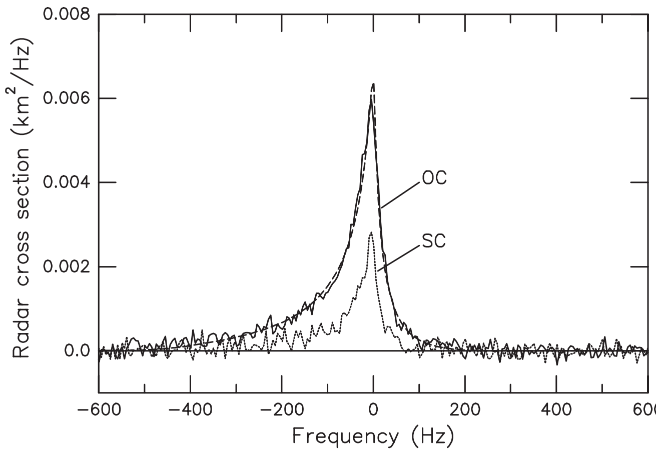

Figure 3. Doppler spectrum of the Hartley grain-coma echo, averaged over all CW observations from 2010 October 24 to 30. The nucleus has been subtracted from this spectrum by interpolation. Shown are both circular polarization components: OC (solid) and SC (dotted). The spectra have been smoothed and decimated to 5 Hz resolution. Also shown is model fit (dashed) to the OC spectrum based on a 90° wide grain-ejection fan (see the text).

The radar cross section of the grain coma averaged 0.89 km^2. Both cross section and spectral shape remained fairly steady over the week, the most noticeable change being a 29% dip in cross section on October 25. Although the radar cross section of the grain coma was not especially high in an absolute sense, the fact that it was 15 times higher than the nucleus cross section (the highest such ratio yet measured) indicates that, for its size, Hartley is an unusually prolific source of large grains. We estimate, from simple grain ejection models (Harmon et al. 2004), that Hartley would need to eject about 3×10^5 g s^{-1} of material to produce the observed grain-coma echo. This is a factor of 3–7 times larger than the perihelion dust mass-loss rates quoted in earlier Hartley studies (Epifani et al. 2001; Fomenkova et al. 1999) and a respectable grain production rate for a comet of any size. Also, our grain production rate is comparable with the 2×10^5 g s^{-1} water production rate estimated for Hartley's 2010 perihelion passage (Biver et al. 2010; Bonev 2010). Hence, if the radar grain coma includes icy grains, then our observations would support a recent suggestion (A'Hearn et al. 2011) that sublimating grains may account for much of Hartley's high gas production. Grain sublimation might also explain the even higher gas production rates (and extremely high inferred nucleus active fractions) measured at previous Hartley apparitions (Groussin et al. 2004).

5. CONCLUSION

Our Hartley campaign represents an important addition to the limited inventory of comet radar observations and the first radar study of a comet nucleus that was also a spacecraft flyby target. Among the nucleus results complementing the *EPOXI* mission are the measurement of an accurate rotation period and the estimation of a reliable radar albedo and corresponding surface density. Hartley is only the fourth comet nucleus to be imaged with radar, but already the second to be identified as an elongated, bilobate object based on its delay-Doppler signature. Although radar imagery can never rival spacecraft imagery for revealing detailed shape and surface features, our recent Hartley and Tuttle observations have demonstrated its capability as a remote means of identifying bilobate comets. It is significant to note that, if one includes Comet 1P/Halley (Keller et al. 2004), fully half of the eight comets imaged by spacecraft and/or radar have been found to have bilobate shapes. It is becoming increasingly clear that binary and bilobate objects are common constituents of the various minor-planet populations, with contact-binaries alone estimated to constitute 10%–20% of all near-Earth asteroids, Jupiter Trojans, and Kuiper Belt objects. Recent theories for the formation of such objects have been developed based on collisions, mutual capture, and rotational fission. There is good reason to believe that these same mechanisms may have operated on the comet population as well. Based on this, and prompted by the Comet Tuttle results, Harmon et al. (2010a) suggested that bilobate or contact-binary objects might be as common in the comet population as in the other minor-planet populations. The discovery of yet another bilobate comet, Hartley, provides additional support for this notion. It will be interesting, then, to see if future Earth-based and space-based comet observations turn up more such objects.

Our observations have added Hartley to the growing list of comets with radar-detectable grain comae, which provides further support for the notion that large-grain ejection is a common property of comets and can account for a significant or dominant fraction of a comet's total mass loss. Although Hartley's radar grain coma is similar to others that we have seen, this comet stands out as the most active in terms of large-grain production, for its size. Also, the strong depolarization of the grain-coma echo suggests that Hartley's grains tend to be larger than those from some other comets that we have observed. Our results support other evidence that Hartley is a significant producer of debris during its perihelion passage.

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