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Investigating the combined effects of shape, density, and rotation on small body surface slopes and erosion rates

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ABSTRACT

Based upon observational evidence and the derived shape-models from seven small Solar System bodies (Comets 103P Hartley 2 and 9P Tempel 1; Asteroids 433 Eros, 243 Ida, 951 Gaspra, and 25143 Itokawa; and the martian moon Phobos) we explore the existence of a self-correcting (negative-feedback) system in which disturbance-triggered downslope regolith flow is constantly working to erode the local surface topography of rotating, irregularly shaped, small bodies towards that of a flat, equipotential surface. This process is driven by the fact that erosion rates are very non-linear with respect to slope: becoming quite high as slopes approach the angle-of-repose, but also quite low when slopes are small. Four conditions are required for this system: (1) the mean rotational force is a significant fraction of the mean gravitational force; (2) a sufficiently thick, low cohesion, mobile regolith layer exists over most of the body's surface; (3) a downslope flow disturbance source is present, such as volatile activity on comets or impact-induced seismic shaking; and (4) a sufficient amount of time has occurred since the body's last major surface alteration. When these conditions are met, then the magnitude of the gravitational force for the body (and hence its bulk density) can be estimated by assuming that the body has reached an erosional 'saddle-point' in which either increasing or decreasing the body's rotation rate will increase erosion rates and drive the surface topography back towards a low-slope state. This technique yields bulk density estimates of 220 (140–520) kg m^{-3} for Comet 103P Hartley 2, and 1400 (930–2800) kg m^{-3} for Asteroid 951 Gaspra, neither of which have accurate density measurements via other means.

1. Motivation

On November 4, 2010, the Deep Impact spacecraft conducted a flyby of Comet 103P Hartley 2 as part of its extended (EPOXI) mission (A'Hearn et al., 2011). The images returned of the comet nucleus, taken from a closest-approach range of 695 km, revealed an asymmetrical, bilobal nucleus structure, rather like a bowling pin in shape (see Fig. 1), and comprised of two, relatively coarse-terrained lobes connected by a very smooth, 'neck' region between them. This smooth neck region may have a common origin with the smooth flows observed on Comet 9P Tempel 1 during Deep Impact's initial mission (A'Hearn et al., 2005), which have been hypothesized to have formed by the nearly frictionless, fluidized, cryovolcanic flow of solid particulate in a percolating, gas-rich environment (Belton and Melosh, 2009). This region also resembles the smooth ponds observed on Asteroid 433 Eros, which are believed to have been formed by the frictionless flow of electrostatically levitated, small regolith particles (Robinson et al., 2001; Colwell et al., 2005; Richardson et al., 2005b).

Regardless of exact formation mechanism, if we assume that the smooth neck region on Hartley 2 formed via some form of fluidized, near-frictionless particulate flow, then this region should be very low-sloped (flat) and lie coincident with a potential energy equipotential surface with regard to the combined accelerations due to gravity and rotation. The density of the nucleus can therefore be estimated by fitting potential contours to the observed, gently curving, neck geometry. When provided with a shape model for Hartley 2 (Thomas et al., 2013) and a measured rotation period of 18.34 h (which contains a small non-principal axis rotation component), the remaining free parameter for performing this fit becomes an assumed homogeneous density for the body, which determines the magnitude of the gravitational potential component.

As described in A'Hearn et al. (2011), the net potential as a function of body density was calculated for each surface element of the comet's polygon shape model, using the method developed in Werner (1994). The variance in net potential within the neck region is minimized when the observed surface best approximates

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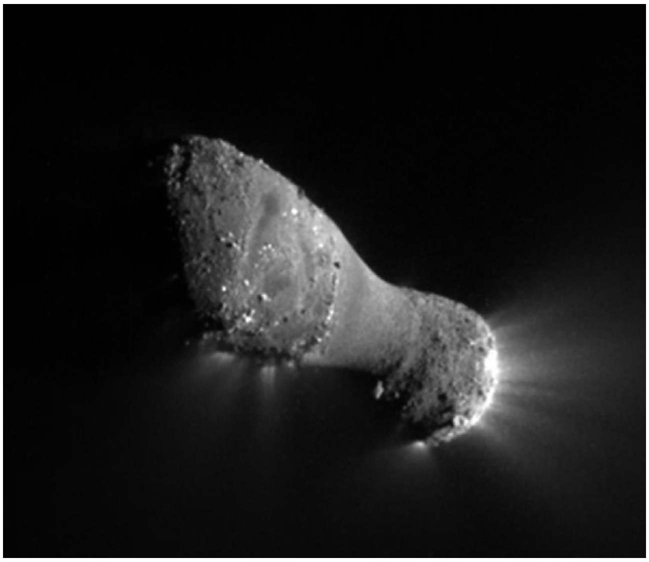

Fig. 1. Comet Hartley 2 as imaged by the Deep Impact spacecraft's Medium Resolution Instrument (MRI) near the point of closest approach (695 km) as part of the EPOXI mission on November 4, 2010. The bilobal structure of the nucleus includes a smooth-surfaced 'neck' region which connects the two rougher-surfaced major lobes. If this smooth neck formed under conditions of extremely low friction, then it should denote a 'flat' surface, lying along a potential energy equipotential with regard to the combined accelerations due to gravity and rotation.

a constant equipotential surface. The metric used for the minimization was weighted to account for uneven spatial distribution of surface elements, and a systematic increase in variance as the assumed bulk density is increased, thus producing a fractional or normalized variance measure (top panel of Fig. 2). This initial analysis was constrained to the region of the neck that was directly imaged and well illuminated during the encounter, and produces a best fit equipotential at a bulk density of $\rho = 220$ (140–520) kg m^{-3}, which corresponds to a comet mass of $m = 1.84$ (1.17–4.35) $\times 10^{11}$ kg.

Curiously, this same type of potential variance minimization yields a very similar bulk density of $\rho = 200$ (140–350) kg m^{-3} when performed for the entire shape model of Comet Hartly 2 as a whole (also shown in the top panel of Fig. 2). At first glance, this similar result would seem to invalidate the potential variance minimization performed for the carefully selected smooth neck region as a means for determining the body's most likely bulk density. However, as shown in Fig. 2, similar exercises performed for the Asteroids 243 Ida and 433 Eros also yield bulk densities close to the actual, spacecraft-measured densities for these two objects. For 433 Eros, the global potential variance minimization technique yields a best fit density of 2200 (1400–4000) kg m^{-3}, within 18% of the measured density of 2670 ± 30 kg m^{-3} (Thomas et al., 2002). For 243 Ida, the technique yields a best fit density of 2300 (1500–4800) kg m^{-3}, within 12% of the measured density of 2600 ± 500 kg m^{-3} (Thomas et al., 1996). Clearly, there is some phenomena at work here that causes the surfaces of small, rotating bodies to move towards and eventually achieve as small a potential energy variance over the surface as possible. This will be explored further in the following sections.

2. Approach

2.1. Background

Over the past two decades, the amount of collected data with regard the dimensions, shapes, and spin rates of small, irregular (non-spherical) Solar System bodies has increased dramatically. Whereas previously we had only some asteroid light curves and the Viking Orbiter observations of the martian moons Phobos and Deimos (Thomas, 1979), techniques were developed whereby ground-based radar 'images' and shape models of asteroids could be obtained (Ostro et al., 1988); robotic spacecraft began to conduct close flybys of small Solar System bodies, beginning with Asteroid 951 Gaspra (Belton et al., 1992); and spacecraft began to target and orbit (or orbit with) selected small bodies, beginning with the NEAR mission to Asteroid 433 Eros (Veverka et al., 2001). More recently, inversions techniques are being developed for the purpose of deriving asteroid shapes from optical light curve (photometric) observations (Durech et al., 2010).

Concurrent with this growing body of data has been a growing theoretical interest in the development, stability, and evolution of small body shapes and spins (types and rates). Such theoretical studies have a long history, wherein self-gravitating, rotating, cohesionless, and frictionless fluid bodies have been investigated by the likes of Newton, Maclaurin, Jacobi, Roche and others – see the histories and mathematical reviews in Chandrasekhar (1969) and Lebovitz (1998) for background and details. Isaac Newton investigated slightly oblate fluid spheres as a means to explain the Earth's shape. Maclaurin found combinations of body oblateness and spin that were in equilibrium and which are now called the "Maclaurin spheroids". Jacobi discovered certain equilibrium ellipsoids with axes of unequal length that are now called the "Jacobi ellipsoids". Roche introduced the effects of tidal forces from a larger body being orbited by the small body, and found that there is a limit to the orbital radius, the so-called "Roche limit", inside of which there are no equilibrium shape solutions for the smaller body.

With the advent of the Viking Orbiter images of the martian satellites, solid bodies began to be investigated. Dobrovolskis (1982) developed semi-analytical models of Phobos and Deimos as homogeneous, elastic triaxial ellipsoids subject to tidal, rotational, and self-gravitational stresses, thus bringing compressive strength into the picture. Slyuta and Voropaev (1997) generalized this elastic body modeling to investigate the 'failure limit' wherein gravitational forces in non-equilibrium figures produce differential, structural stresses above the body's yield strength, and thus the shape of the body will relax into an equilibrium, sphere-like figure. Working the problem both forward from an assumed material elastic yield strength and backwards from bodies of known shape and spin, Slyuta and Voropaev (1997) sought to find minimum yield strengths for each case.

Cohesionless, self-gravitating, rotating bodies possessing compressive strength and internal friction were investigated in Holsapple (2001) and Holsapple (2004), using a elastic–plastic constitutive material model with a Mohr–Coloumb yield criteria. In that work, a series of triaxial-ellipsoid body 'failure limit' curves were identified as a function of body aspect ratio (minor/major axis), spin rate, and internal fiction angle, which contain the Jacobi ellipsoids as a frictionless end-member. These results were tested and largely confirmed in two subsequent independent studies, the first using numerical models of "perfect" rubble piles consisting of hundreds of self-gravitating, spherical particles (Richardson et al., 2005a), and the second using an analytical approach which treated the body as a rigid-plastic, cohesionless material with a Drucker–Prager yield criterion (Sharma et al., 2009).

The most important finding from these studies, particularly Holsapple (2001, 2004), was that the great majority of observed asteroids (Near Earth, main belt, Trojan, and Centaur asteroids) fall well *below* the failure limit curves for cohesionless bodies possessing realistic values for the coefficient of friction. The implication from this result was that most asteroids seemed to be cohesionless 'rubble piles', a conclusion that has received wide acceptance.