Icarus 222 (2013) 453–466

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

The nucleus of Comet 9P/Tempel 1: Shape and geology from two flybys

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ARTICLE INFO

Article history:
Available online 7 March 2012

Keywords:
Comet Tempel 1
Comets, Nucleus
Geological processes

ABSTRACT

The nucleus of comet Tempel 1 has been investigated at close range during two spacecraft missions separated by one comet orbit of the Sun, 5½ years. The combined imaging covers ~70% of the surface of this object which has a mean radius of 2.83 ± 0.1 km. The surface can be divided into two terrain types: rough, pitted terrain and smoother regions of varying local topography. The rough surface has round depressions from resolution limits (~10 m/pixel) up to ~1 km across, spanning forms from crisp steep-walled pits, to subtle albedo rings, to topographic rings, with all ranges of morphologic gradation. Three gravitationally low regions of the comet have smoother terrain, parts of which appear to be deposits from minimally modified flows, with other parts likely to be heavily eroded portions of multiple layer piles. Changes observed between the two missions are primarily due to backwasting of scarps bounding one of these probable flow deposits. This style of erosion is also suggested by remnant mesa forms in other areas of smoother terrain. The two distinct terrains suggest either an evolutionary change in processes, topographically-controlled processes, or a continuing interaction of erosion and deposition.

1. Introduction

The February 2011 flyby of comet Tempel 1 by the Stardust spacecraft as the Stardust-NExT mission (SDN) constituted the first revisit of a comet by a spacecraft (Veverka et al., 2012). The Deep Impact mission (DI) in 2005 provided image coverage of ~40% of the surface, determined many physical properties, and showed a surprisingly complex array of surface forms, including smooth regions thought to be the result of flows depositing materials on the surface (A'Hearn et al., 2005a,b; Belton and Melosh, 2009). Given the restricted image coverage, it was not clear what the truly typical topography and dominant surface processes of the comet were, and how distinct Tempel 1 really was from the only other comet seen with anywhere nearly comparable resolution, Wild 2 (Brownlee et al., 2004). The DI images hinted at thick layering in the body of the comet along with more superficial, possibly flow-related layers (Thomas et al., 2007; Belton et al., 2007), but how pervasive these were remained uncertain. The revisit to Tempel 1 allowed more of the nucleus to be mapped providing a much better assessment of the types of terrain as well as detection of changes during one solar orbit, presumably formed during one perihelion passage.

This paper presents the basic image maps, shape, short descriptions of the geological features, and a brief interpretation of the history of the comet's surface including estimates of rates of surface modification by erosion and deposition.

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http://dx.doi.org/10.1016/j.icarus.2012.02.037

2. Data and methods

Data are from the DI and SDN missions. The DI spacecraft and its instruments are described in A'Hearn et al. (2005a) and Hampton et al. (2005); the flyby is summarized in A'Hearn et al. (2005b). Most DI work reported here is done with the Medium Resolution Instrument (MRI) data, which had a pixel scale of 7 m at the closest approach of ~700 km, and the nearly identical Impactor Targeting Sensor (ITS), which obtained higher resolution, but smaller, windowed images just before impact. Most useful data were taken within 1500 km and spanned phase angles of 63–70°. The High Resolution Instrument (HRI), which has nominally five times better resolution than MRI, was determined to be out of focus after launch (Klaasen et al., 2008). Deconvolution (Lindler et al., 2012) can render some of these images suitable for detecting smaller forms than are visible in the MRI data, but this processing often introduces artifacts such that considerable care is required in interpreting these data.

The SDN data are from the NAVCAM instrument (Brownlee et al., 2004; Newburn et al., 2003; Klaasen et al., 2012). The flyby of Tempel 1 is discussed in Veverka et al. (2012). Closest approach images from ~180 km have pixel scales of 11 m. Phase angles of the best data cover 15–60°. Navigation data in the form of "SPICE" kernels (Semenov et al., 2004; Semenov and Acton, 2006) are the basis for all geometric work on the comet.

Determination of the shape and accurate relative positioning of the images relies upon stereo control points (Fig. 1) with the usual image pointing adjustments (Thomas et al., 2002). There are 480 manually measured points in the ~70% of the comet that is well observed. Residuals (predicted image location vs. actual image location) have rms values of 0.42 pixels, or typically ~6 m.

Mapping of features and projection of images is enabled by image cubes that store latitude, longitude, radius, incidence, and emission angles at each pixel. Line and sample coordinates of features that have been individually marked or the original image data can then be arbitrarily projected.

Quantities such as gravity and slope are calculated using an assumed uniform density of 400 kg/m^{-3} for the nucleus (Richardson et al., 2007) and calculated rotation vectors. The slowly varying spin period of ~40 h (Belton et al., 2011) imposes relatively small additional accelerations on the surface gravity field. These relatively small rotational accelerations mean that uncertainties in the mean density have little effect on calculations of relative potential energy across the surface. In this paper we use a single spin period of 40.7374 h for analysis of the data from both DI and SDN. This is an arbitrary value useful only in the synchronization of partial rotations. "Topography" is calculated as dynamic height, the surface potential energy divided by an average acceleration (Vanicek and Krakiwsky, 1986, p. 369; Thomas, 1993). "Slope" is the angle between surface normal and the local acceleration vectors.

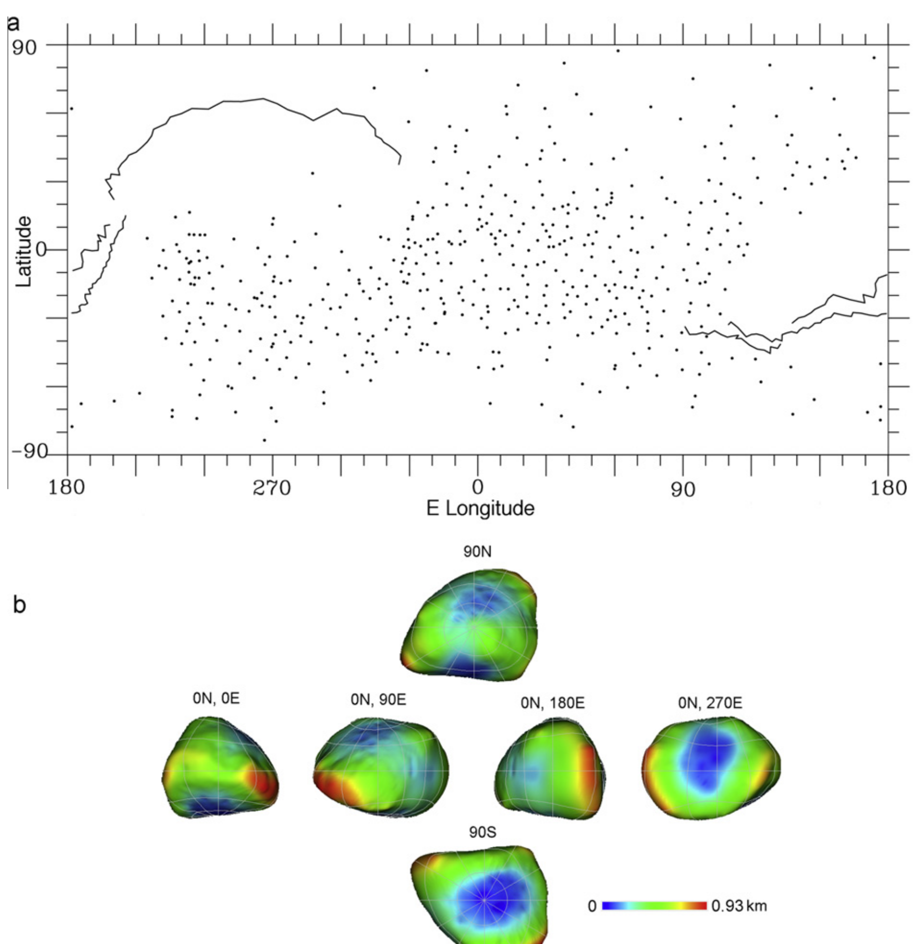

Fig. 1. Shape of Tempel 1 nucleus. (A) Location of limbs and control points restricting the shape model of Tempel 1. Simple cylindrical projection. Jagged nature of limb lines originates from small errors with projection at ~90° emission. Limb locations involve ambiguity along the line-of-sight, so these locations do not give the rigorous control of stereo points; they do limit the shape, however. (B) Model of the shape of Tempel 1 from different perspectives with gravitational heights projected on the surface.