REEXAMINATION OF THE LARGE SMOOTH PATCH ON COMET 9P/TEMPEL 1 AS OBSERVED BY THE DEEP IMPACT AND STARDUST MISSIONS.

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Introduction: 9P/Tempel 1 (T1) is a ~6 km diameter periodic Jupiter-family comet (JFC) (q=1.5, Q=4.7, i=10.4°) discovered in 1867. It was first visited by the Deep Impact (DI) mission in 2005 [1], and one-orbit later by the Stardust-NExT (SDN) mission in 2011 [2]. Because it is the only comet that has been visited twice on separate apparitions, it is a unique opportunity to document changes on the surface and study its physical properties and evolution over a full orbital period (5.56 yr.) [2].

T1 images acquired by both spacecraft covered ~70% of the surface and revealed a morphologically diverse body made up of rough, pitted terrain and, in two observed cases, regions of smooth terrain that appear distinct from their surroundings [3]. These km-scale smooth patches are not observed on any of the other cometary nuclei visited by spacecraft and may be key to further understanding how comets evolve.

In this work, we focus on the largest smooth patch, located at the south pole of T1, surrounded by rough terrain and embedded in a cliff (Fig. 1).

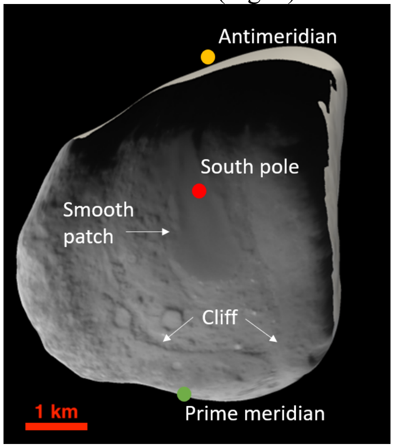

Fig. 1. SDN image 30036 projected on the new shape model [4] showing the south face of T1. The low albedo region in the center is the smooth patch on which we focus in this work, surrounded by a cliff and rugged terrain.

The origin of this large smooth patch and its surroundings remains a mystery. Since its identification, several ideas for its origin have been proposed: the smooth patch is comprised of primitive layers exhumed by sublimation [5], deposition of ice grains released in a collimated ejection during a massive outburst of gas [6], or results from complex subsurface fluidization production mechanism [7]. However, none of these approaches can either explain the observed cliff surrounding this patch or connect it to features such a second smooth patch in the equatorial face, or residual eroded features on the north face [8].

Data: We re-examined the DI and SDN images and spectral data taking advantage of an updated stereophotoclinometry-based shape model [4], which provides ~20x improvement in resolution (3,145,734 facets, ground sample distance up to 8 m) over previous work [3, 8]. This allows us to project the images acquired by both missions with better precision, and thus make higher-fidelity measurements to identify changes between the two encounters.

Results: Using the shape model and photogrammetry techniques, we compute the area and thickness of the largest smooth patch and the cliff that borders it. The lateral shadow lengths and the incidence angle of the Sun lead to a thickness of ~25 meters for this feature. Direct measurements on the shape model indicate an average cliff height of ~50 m. The cliff region that embeds the smooth patch has an area of 7.14 km^2. The smooth patch occupies a total of 1.72 km^2.

Through blinked images covering the same area by the two spacecraft, we can see differences in features obtained ~1 orbit apart. These differences can be organized into two main groups: (1) pairs of bright spots, which were seen by both DI and SDN but are spatially offset, and (2) a heterogeneous group of morphological changes caused by sublimation. The most prominent is a portion of the smooth patch edge (Fig. 2) in which an area of ~0.04 km^2 has sublimated away. Since the thickness of this feature is 0.025 km, we can establish a sublimation rate of at least 10^6 m^3 per period, larger than previous estimations [8].

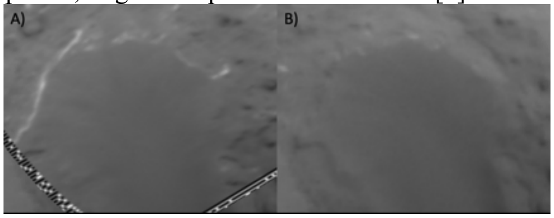

Fig. 2. Sublimation of the smooth patch edge. A) 5070405_9000673 DI ITS image. B) SDN image 30035. The volume of sublimated material constrains a minimum sublimation rate of 10^6 m^3/period.

Using the enhanced shape model to calculate the gravitational potential on the surface, we simulate the path that an ice flow would follow under various starting seeds area across the surface. We find that by placing the origin of the flow on the antemeridian region, the flow occupies the zone where the smooth patch is currently located and the rest of the eroded area. Surprisingly, it also allows us to establish a connection with the second smooth patch located in the equatorial face (Fig. 3A). Moreover, the flow also extends onto the north face where an apparently eroded flow is visible (Fig. 3D) [8].

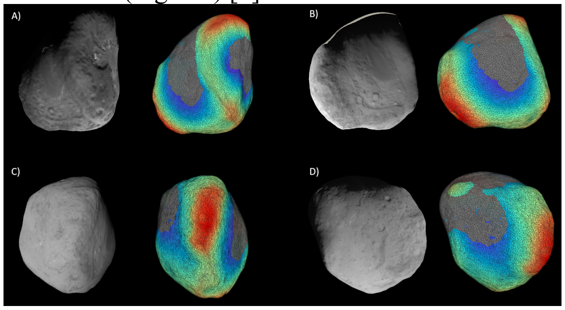

Fig. 3. Blue-red (low-high) color scale facets represents the gravitational potential. Gray facets represent the simulated flow. Next to each figure, we place a real image to facilitate the interpretation.

By stretching and zooming DI and SN images, we observe lineaments [3] which resemble glacial moraines (Fig. 4A), and a u-shaped —lateral edges higher than the central area— smooth patch (Fig. 4B). All these features are compatible with a gravitational ice flow.

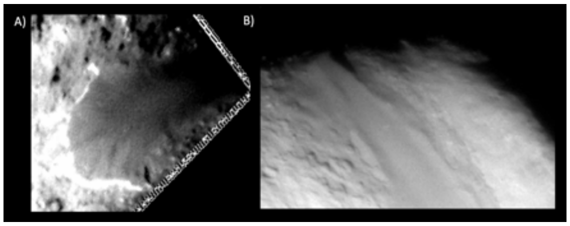

Fig. 4. A) Stretched ITS image showing lineaments on the smooth patch edges. B) SDN image 30035 including what could be the smooth patch origin.

Combining DI flyby, DI impactor, and SDN images, we create 3D stereo-images, which provide additional information about tridimensional surface morphology (Fig. 5). The large smooth patch can be described as a lobate u-shape, with a less wide extension near the pole, which spreads out as we move towards the meridian.

Finally we calculate the cumulative solar irradiance and thermal contribution throughout one orbital period of T1 using its orbital parameters and the relative position and orientation to the Sun. The smooth patch face presents a more intense insolation towards the meridian than towards central and antimeridian regions. This may explain why the smooth patch would have been completely sublimated over the edge of the cliff.

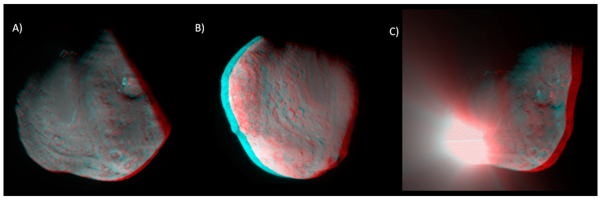

Fig. 5. Anaglyph (A) is composed of the 5070405_9000639 DI ITS image (cyan) together with the deconvolved 9000904 DI HRI image (red), (B) using 30034 (cyan) and 30035 (red) SDN images, and (C) using the DI MRI post-impact images 5070405_9000999 (cyan) plus 5070405_9001012 (red).

Conclusions: Since the smooth patch was observed on T1, several hypotheses for its origin have been proposed [3,5,6,7]. Only those with flow of material are consistent with the features described above for both the smooth patch and the surroundings.

Our results suggest that the smooth patch is compatible with a gravitational ice flow that began in the equatorial antemeridian region. The mass moved towards the meridian region, causing a drag of the previous surface that, after sublimation, exposes a cliff and a sunken region.

Flow origin: However, this raises an intriguing question: which phenomenon triggered this flow? Considering that the sublimation rate is >0.04 km^2/period, that the cliff area is 7.14 km^2, and assuming a constant sublimation rate, this event was produced <~1000 years ago.

We propose three main scenarios for the large T1 smooth patch: (1) it is melted material deposited by an external source after an impact, however there is little evidence for impact craters on cometary nuclei; (2) it is material that emerged from the interior after an unknown mechanism [7], but this should be more common and appear on at least some other nuclei; or (3) T1 experienced a splitting event after a close approach to Jupiter, in which a fraction of the energy released caused the melting of the newly exposed surface. Although scenarios (1) and (2) cannot be completely ruled out, we consider (3) as the most likely given that according to [9], JFCs may split thousands of times during their lifetime.

References: [1] A'Hearn et. al. (2005) Space Sci. Rev. 117, 137–160. [2] Veverka et al. (2013) Icarus 222, 424-435. [3] Thomas et al. (2007) Icarus 187, 4–15. [4] Ernst et al. (2019) 50th Lunar and Planetary Science Conference 2019. [5] Belton et al. (2007) Icarus 190, 655–659. [6] Bar-Nun et al. (2008) Icarus 197, 164–168. [7] Belton et al. (2009) Icarus 200, 280–290. [8] Thomas et al. (2013) Icarus 222, 453–466. [9] Chen and Jewitt (1994) Icarus, 108, 265–27.