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Photometric determination of crater's depth on Enceladus

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1. Introduction

Enceladus, discovered by Herschel in 1789 is a small saturnian moon of 252km mean radius [13]. Since Voyager, we know that it has a heterogeneous old and young surface [12] leading to the idea that Enceladus still sustains a geological activity. The Cassini spacecraft has encountered Enceladus thirteen times since 2004, providing unprecedented high-resolution images. The Imaging Science Subsystem (ISS) cameras ([8]) revealed the existence of a plume of gas and icy particles above the south pole of the moon, confirming its geological activity and the genetic link of Enceladus with the E-ring, as it was previously suspected by [12]. [11], based on Cassini's observations and numerical simulations, proposed that, despite its small size, Enceladus is a differentiated body with a large rock-metal core of radius about 150 to 170 km surrounded by a liquid water-ice shell compatible with plume's observations. [14], based on the model of [11], showed that heterogeneity in viscosity, localized in the southern hemisphere and combined with deep liquid water layer, may explain the release of energy and the ejection of matter observed in the south pole. Nevertheless, these simulations need better knowledge of ground viscosity, thermal gradient or ground stratification. Various observational and numerical studies such as [10, 9, 15], show that craters morphologies, particularly the aspect ratio (depth/diameter), can bring constraints on ground properties.
We show here that it is possible to overcome the difficulty at determining the crater's depth of planetary bodies without radar or laser altimetry, by the use of the multi-angle geometry of imaging data. We present here for Enceladus the adaptation of a macroscopic surface roughness model, developed by [4] and well documented by [1,2]. This model allows reproducing the average photometric behavior of a crater and constraining its aspect ratio with a very good accuracy.

2. Data reduction

For our study, 36 ISS/NAC (Narrow Angle Camera) images recorded with the CLR+GRN filters combination (568±65 nm) were used. Images span over a time period from 2005 to 2008, which corresponds to the Cassini flybys of Enceladus E03 and E06. Each image is calibrated so as to give the I/F ratio for each pixel [7]. For each image, we compute a navigation cube composed of plans containing geometric information for the centre of each pixel: planetocentric longitude and latitude, resolution, incident angle 'i', emission angle 'e', phase angle 'α'. Knowing the diameter, central longitude and latitude for the 53 craters referenced by the USGS [6], we first calculate the precise geographic boundaries of each crater and then, if the crater is present in an image, extract its I/F ratio and geometric parameters averaged over the crater's area. We build its photometric curves by repeating this over the 36 ISS images, which span a great range of observing geometries.
In our model, the crater is simulated by a macroscopic parabolic hole of depth H with a circular opening of diameter D, covered by a layer of microscopic particles accounting for the regolith. To model the photometric behavior of the regolith, we use the Hapke formalism [5], which includes the treatment of the multiple and anisotropic scattering, and the opposition effect (Shadow Hiding Opposition Effect). Values of the compaction parameter h and the amplitude at zero phase angle B_0 have been fixed by taking the ones from [16]. We hence have three free parameters in our model: 1) one regarding the morphology, i.e. the aspect ratio q defined as H/D, and 2) two for the regolith, i.e. the asymmetry factor g and the single scattering albedo ω_0.

3. Results and discussion

We use a reduced χ^2 goodness function to determine the best fit between the data and our model. By setting a conservative minimum χ^2 threshold at 3σ during minimization between data and model, we reduce our crater sample to 32 craters, rejecting those whose photometric behavior is not sufficiently well reproduced by our model.

Best values of q, g and ω_0 for each crater show no regional heterogeneity on Enceladus surface (taking into account that the majority of our observations are within cratered terrains). Nevertheless, at global scales, these parameters, in particular q, can be used to extract information on the craterization processes (as did [9]) and bring global constraints on Enceladus's crust.

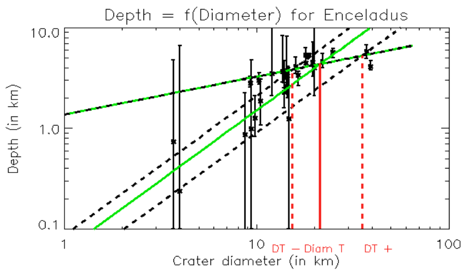

Figure 1: Crater's depth as a function of crater's diameter for 32 craters on Enceladus. Green and black dashed lines are respectively the best least square and 1-σ error fitting considering two H/D regimes. Red lines indicate the transition diameter (D_T) between the two regimes, along with its error bars (dashed red lines). We found $D_T = 21^{+14}_{-6}$ km.

Figure 1 shows the depth of craters as a function of their diameter. As suggested by [9] for the majority of cratered planetary bodies, two regimes seem to emerge for Enceladus. The intersection between these regimes defines the transition diameter D_T, which can be related to the crust properties of the body (like temperature gradient or viscosity [3]) and the craterization regime at which it has been submitted. Historically, this transition separates simple (bowl shape) and complex (rims, central pick, terraces) craters. For Enceladus, our results show that large crater are relatively shallower than small crater (for $D \lesssim 20$km).

[9] presents a diagram of transition diameters versus surface gravity for various body in the solar system. This diagram is updated with Enceladus' new value that is inferred from our study (Figure 2). In this diagram, Enceladus, as well as Mimas, seems to diverge from the empirical law for icy bodies. This may reveal that craterization processes are distinct at low surface gravity or that geological or external mechanisms have changed the shape of craters making their relaxation more efficient.

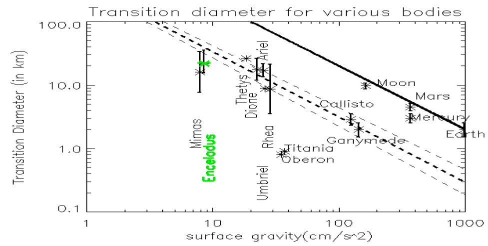

Figure 2: Transition diameters for various bodies in the solar system as a function of surface gravity (all values, except for Enceladus, Callisto and Ganymede, are taken from [9]). Full black line and dashed line indicate rocky and icy (without Mimas, Enceladus, Titania and Oberon) body regimes respectively. Values for Callisto and Ganymede come from [10].

5. Summary and Conclusions

Using a photometric model for macroscopic crater shape and regolith, we succeeded in deriving the depth of 32 craters on Enceladus. Using these depths, we find that the transition diameter for Enceladus seems to differ from the empirical law for icy bodies, as Mimas does. This could reveal singular craterization behavior and/or post impact relaxation particularly efficiency for these bodies.

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