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Surface ages of mid-size saturnian satellites

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ABSTRACT

The observations of the surfaces of the mid-sized saturnian satellites made by Cassini–Huygens mission have shown a variety of features that allows study of the processes that took place and are taking place on those worlds. Research of the saturnian satellite surfaces has clear implications not only for Saturn's history and Saturn's surroundings, but also for the Solar System. Crater counting from high definition images is very important and could serve for the determination of the age of the surfaces. In a recent paper, we have calculated the production of craters on the mid-sized saturnian satellites by Centaur objects considering the current configuration of the Solar System. Also, we have compared our results with crater counts from Cassini images by other authors and we have noted that the number of observed small craters is less than our calculated theoretical number. In this paper we estimate the age of the surface for each observed terrain on each mid-sized satellite of Saturn. All the surfaces analyzed appear to be old with the exception of Enceladus. However, we have noticed that since there are less observed small craters than calculated (except on Iapetus), this results in younger ages than expected. This could be the result of efficient endogenous or exogenous process(es) for erasing small craters and/or crater saturation at those sizes. The size limit from which the observed number of smaller craters is less than the calculated is different for each satellite, possibly indicating processes that are unique to each, but other potential common explanations for this paucity of small craters would be crater saturation and/or deposition of E-ring particles. These processes are also suggested by the findings that the smaller craters are being preferentially removed, and the erasure process is gradual.

On Enceladus, only mid and high latitude plains have remnants of old terrains; the other regions could be young. In particular, the regions near the South Polar Terrain could be as young as 50 Myr old. On the contrary for Iapetus, all the surface is old and it notably registers a primordial source of craters. As the crater size is decreased, it would be perceived to approach saturation until $D \lesssim 2$ km-craters, where saturation is complete.

1. Introduction

The surfaces of mid-sized saturnian satellites are a kind of laboratory where it is possible to observe and investigate the physical and dynamic processes that have been taking place around Saturn and also throughout the Solar System. The study of impact craters on the satellite surfaces allows us to better understand what could be happening in the Saturn environment to produce these craters. The saturnian satellite system was observed and studied in the past by Pioneer 11 and Voyager 1 and 2 spacecrafts, greatly increasing the knowledge of the Saturn system. Voyager images revealed diverse satellite surfaces (Smith et al., 1981, 1982). Crater counts on those images indicated that saturnian satellites have been variably cratered, which suggest different geologic histories (Plescia and Boyce, 1982, 1983, 1985). At present, the Cassini–Huygens mission is visiting the Saturn system, and the detailed observations it renders provide us with new paradigms and physical processes to understand and interpret.

The mid-sized icy satellites of Saturn are Mimas, Enceladus, Tethys, Dione, Rhea, and Iapetus. They are regular satellites, mainly composed of water ice and in synchronous rotation. The Cassini–Huygens mission has observed all of them in detail allowing scientists to obtain accurate information on the shapes, mean radii and densities (Thomas, 2010) and gravity fields (Jacobson et al., 2006). Furthermore, some of these satellites show traces of physical activity and renovation, possibly due to recent geological processes. The geologic activity could include endogenous activity such as viscous relaxation, volcanism, and/or tectonic or even

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atmospheric processes. Cratering itself is a potential process in which the formation of large craters could remove small craters by ejecta emplacement and seismic shaking. Also, exogenous processes, such as in fall from the E-ring or debris rings, could erase surface features.

Those physical processes would renew the satellite surfaces, erasing old or young surface features such as craters. The most striking case is Enceladus whose surface differs markedly from region to region and has present active geysers emanating from four parallel fractures in the south polar region, called "tiger stripes" (Porco et al., 2006). This region is a very active one where the surface is modified, erasing the craters (totally or partially). On Dione, in turn, Cassini observations reveal two different surfaces: the cratered plains (cp), heavily cratered, and the smoother plains (sp), with a lower cratering suggesting a younger surface. On Rhea, measurements by Cassini spacecraft detected a tenuous atmosphere of oxygen and carbon dioxide (Teolis et al., 2010). Iapetus is the opposite case of Enceladus as it has heavily cratered plains with large degraded basins, which indicates that its surface is ancient. What is more, the count of small craters showed a size distribution indicative of crater saturation (Denk et al., 2010).

Kirchoff and Schenk (2009, 2010), hereafter KS09 and KS10, analyzed high-resolution Cassini images and obtained the number and size–frequency distribution (SFD) of craters for the mid-sized icy satellites. With their observed number of craters and the previous cratering rate estimations by Zahnle et al. (2003), they calculated the surface ages of each satellite for some crater diameters.

There are a number of factors that must be taken into account in the analysis of the age of a satellite area. First, all possible impactor populations should be considered. The analysis of the images obtained by Voyager (Smith et al., 1981, 1982) implied that the satellites were struck by two different impactor populations: Population I, which produced a greater number of large craters (bigger than 20 km), and Population II, which produced a greater number of smaller craters (smaller than 20 km) (Smith et al., 1982). The origin or even the existence of both populations is disputed. Smith et al. (1981, 1982) suggested that Population I was the tail-off of a postaccretional heavy bombardment, while Population II has the form expected for collisional debris from the satellites or other orbiting debris. Horedt and Neukum (1984) concluded that cratering on saturnian satellites is produced by heliocentric objects as well as by planetocentric impactors. On the other hand, Hartmann (1984) noted that crater densities on heavily cratered surfaces throughout the Solar System are all similar due to a "saturation equilibrium". He argued that only one single population of heliocentric planetesimals and their fragments had been recorded. Dobrovolskis and Lissauer (2004) studied the fate of ejecta from the irregularly shaped satellite, Hyperion, suggesting that it does contribute to Population II craters on the inner satellites of Saturn. However, those particles would produce craters with a different morphology than those produced by a heliocentric source.

Moreover, consideration of the primordial situation is important for the study of the origin of craters. It is believed that the mass of the primordial trans-Neptunian zone, the source of Centaurs, was ~100 times higher than the present one (Morbidelli et al., 2008). This mass might have been depleted by a strong dynamical excitation of the trans-Neptunian region. There were several models that described the mass depletion; for example, in the "Nice Model" and its subsequent versions, the interaction between the migrating planets and planetesimals destabilized the planetesimal disk and scattered the planetesimals all over the Solar System before the time of the LHB (Tsiganis et al., 2005; Levison et al., 2008). Accordingly, there was much primordial mass that struck the planets and their satellites very early in the Solar System history. It would be expected that this event marked the surfaces of the satellites, mainly producing a great number of larger craters than at present. Those craters are probably the larger ones that can be observed on the satellites. Moreover, there are papers (Nesvorný et al., 2003, 2007) that argue in favor of more primordial irregular satellites and a more active primordial collisional activity around the major planets. There would even be populations of large irregular satellites and debris of catastrophically disrupted satellites that may have played important roles in the history of the Saturn system (Dones et al., 2009).

A primordial crater contribution to the Saturn system could also be connected with the crater saturation observed on some of the saturnian satellites. The formation of craters, especially the larger ones, is a process that is effective in erasing small craters, not only through crater formation, but also by the ejecta blanket and seismic shaking. When a surface is so heavily bombarded that the formation of craters is equaled by the obliteration of craters, it reaches a crater saturation equilibrium. In this case, the density of craters on a surface does not change proportionally. This process is then critical to the determination of the source of impactors, geological processes, ages, etc. (Hartmann and Gaskell, 1997). Crater saturation equilibrium finally causes a distinctive cumulative size frequency distribution (SFD) of craters. Gault (1970) obtained a -2 power-law, from a model based on first principles and laboratory experiments. Hartmann (1984) fitted a -1.83 power-law for the cumulative SFD to crater count data of the surface of various Solar System objects. Richardson (2009) developed a detailed cratered terrain evolution model and observed the way in which crater densities attain equilibrium conditions. He found that if the impactor population has a cumulative power-law slope of <-2, crater densities reach a cumulative power-law of about -2; and if the impactor population has a cumulative power-law slope of >-2, crater density equilibrium values follow the shape of the production population. Squyres et al. (1997) argued that cratering on a surface is a random process and as crater obliteration becomes more important, the spatial distribution of craters tends to be uniform. They used both the spatial distribution and size–frequency distribution of craters to study, with statistical techniques, how a cratered surface approaches saturation. They found that at least 25% of the craters on Rhea and Callisto were destroyed by subsequent obliteration. Therefore, crater saturation is especially important on highly cratered surfaces that are in general old.

In the supposedly young surfaces, as in the case of Enceladus for example, geological processes are erasing craters. However, such processes compete with possible exogenous processes, like particle deposition on the surface that can fill in the craters, finally removing them. Mid-sized saturnian satellites with the exception of Iapetus are embedded in the Saturn E-ring; therefore their particles cross the orbits of the satellites with some probability of impact. Enceladus's plumes are thought to be the source and maintenance of E-ring material (Hamilton and Burns, 1994; Kempf et al., 2010). A fraction of the plume particles escape to populate the E-ring but other fraction returns to Enceladus hitting its surface (Kempf et al., 2010). Ingersoll and Ewald (2011) estimated $(12 \pm 5.5)10^8$ kg for the mass of particles in the E-ring and a particle lifetime in the E-ring of about 8 years. This material could be an exogenous source causing erasure of craters in the mid-sized saturnian satellites.

In a recent paper, Di Sisto and Zanardi (2013), hereafter DZ13, calculated the production of craters on the mid-sized saturnian satellites produced by current Centaur objects coming from the Scattered Disk (SD) and plutinos, in the trans-Neptunian region, and compared these calculations with the Cassini observations made by KS09 and KS10. Also obtained was the current cratering rate on each satellite. In that paper, the authors concluded that since the number of observed small craters is lower than their