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Formation of Saturn's small inner moons by collisions of similar-sized moonlets

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Abstract

The Cassini spacecraft revealed the spectacular, highly irregular shapes of the small inner moons of Saturn, ranging from the unique "ravioli-like" forms of Pan and Atlas to the highly elongated structure of Prometheus. Closest to Saturn, these bodies provide important clues regarding the formation process of small moons in close orbits around their host planet. By the means of N-body and Smooth Particle Hydrodynamics (SPH) simulations, we show that the range of shapes of these small moons is a natural byproduct of mergers of similar-sized moonlets, with impact parameters and velocities that are consistent the current orbits of the small moons.

1. Introduction

The small inner moons Atlas, Prometheus, Pandora, Janus, and Epimetheus are repelled by the rings of Saturn at a rate that is proportional to their mass and decreases with their distance [1,2]. It has thus been proposed that these moons were formed in a pyramidal regime (i.e. by a series of mergers of similar sized bodies) as they migrated away from the rings [2,3]. This scenario is supported by the observations of the small inner Saturnian satellites, as bodies with similar semi-major axis have comparable masses: $m_{Prometheus}/m_{Pandora}$~1.16 and $m_{Janus}/m_{Epimetheus}$ ~3.6 (JPL SSD, not accounting for error bars), and the mass of these bodies increase with their distance to the rings. The pyramidal regime provides an alternative to the formation by gradual accretion of small aggregates of ring material onto a proto-moon. The later scenario would result in Roche ellipsoids [4,5], not consistent with the observed shapes of the small moons (see Figure 1). For instance, while Atlas and Pan require a mechanism that makes their shapes

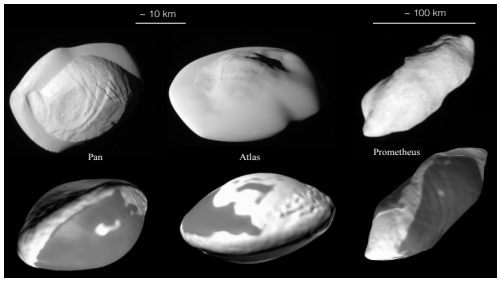

Figure 1: Top: Cassini observations (CREDIT: NASA/KPL-Caltech/Space Science Institute). Bottom: outcome of the simulations.

Flatter [5], Prometheus is over-elongated and its long axis extends beyond the Roche lobe [4].

2. Method

We developed a model for the late stages of the formation of the small inner moons of Saturn from Pan to Janus and Epimetheus, assuming that they formed in the pyramidal regime [2,3]. We investigate if the shapes resulting from the final collisional mergers are consistent with the current shapes of these moons. To this end, we combine N-body simulations to estimate the possible range of impact angles and velocities between the precursors of a given moon, and Smooth Particle Hydrodynamics (SPH) simulations to obtain the outcome of the collisions.

First, a general study of the evolution of the orbit of two moonlets was conducted, using 3-body integrations, taking into account the oblateness of Saturn, the effect of the rings and the presence of larger moons. From it, we derived likely impact

velocities and impact parameters for the collision. We then used SPH simulation to study these collisions, taking into account the Coriolis forces and tides raised by Saturn. Depending on the parameters of the impact, we identified two regimes: mergers, resulting in a variety of shapes, and hit-and-runs, where two distinct bodies resulted from the encounter.

Finally, we ran several populations of N-body simulations, using the prescriptions derived from the SPH simulations whenever a collision occurred. Integration stopped when a merger occurred, or when subsequent hit-and-run reduced the mass of the moonlet below a given threshold.

3. Results

The range of impact velocities and impact angles that are derived from the orbital evolution of the precursor of the moonlet leads to a range of shapes (Figure 1). Close to head-on impacts lead to flattened structures with large-scale ridges, resembling the observed shapes of Atlas and Pan. Another frequent type of resulting structures is elongated shapes with characteristics similar to Prometheus, which result from impact parameters close to the boundary between merging and merge-and-split collisions.

Several populations of similar-sized precursors were run with different distributions of initial eccentricities that were derived from the first steps of the study. Depending on the distribution, 20 to 50% of the systems result in flat or elongated moons. These results are consistent with the fraction of small moons possessing peculiar shapes: Pan, Atlas and Prometheus exhibit such features. The remaining of the systems underwent too many hit-and-run collision, that we assume lead to a phase of splat-like merging and re-accretion of ejecta, resulting in a randomized shape within the Roche lobe of the moonlet, as it is the case for Pandora, Janus and Epimetheus.

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