GIANT IMPACTS AROUND SATURN.

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Introduction. We revisit a formation scenario [1] for Titan and the icy middle-size moons (MSMs) of Saturn, by explicitly modeling the dynamical influence of Saturn on the collision process and its aftermath. In this "late origin" hypothesis, the Saturn system consisted originally of a few major satellites the size of Europa, that accreted in a series of relatively low-velocity giant impacts to form 5,000-km diameter Titan and diverse, ice-rich remainders that would become the MSMs.

In a new set of giant impact simulations we include Saturn as a central massive body. For collisions among massive bodies orbiting Saturn, we find that the outcome depends sensitively on the orientation of the collision relative to the orbital plane, and on the orbital radius. The general trend is to turn simple merging giant impacts into graze-and-merge collisions, and to turn graze-and-merge collisions into hit-and-run collisions, and so on. Keplerian shear further disperses the remnants away from the accreted body, increasing the likelihood of MSM formation by this mechanism.

Background. The initial study [1] treated collisions using smoothed particle hydrodynamics (SPH) in the two-body frame, but did not include Saturn. Satellite-satellite collisions tend to occur around the mutual escape velocity of the pair, $\sim$2 km/s for a Titan-forming merger. This is lower than the sound speed in the materials, so although impact heating was seen in the simulations, shock vaporization did not occur. As a result the aftermath of these relativvely slow giant impacts is characterized by gravitational dynamics of condensed phases.

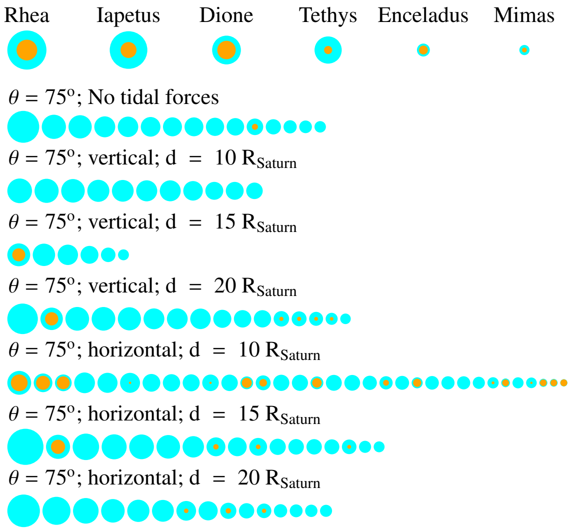

Figure 1: Comparison between actual Saturn's middle-sized moons (MSMs), clumps ejected from one SPH simulation without tidal forces, and six with the same progenitor bodies and impact angle but different orientations.

For off-axis collisions the combined angular momentum is often greater than a self-gravitating body can sustain, causing the outer layers of each parent body to contribute to spiral arms and streamers. When an arm escapes past the Roche limit of the merging satellite, it collapses gravitationally into clumps. Pulled out from the water-rich upper mantle and crust, down to the rocky outer mantle of the Europa-sized progenitors, these clumps end up, in simulations, to strongly resemble MSMs in terms of size and compositional diversity (Fig. 1), with rockier MSMs (e.g. Enceladus) deriving from large hydrostatic pressure inside their parent body.

Sometimes there is only one escaping clump, a hit and run collision. The 'runner' is still bound to the planet and can come back for a second collision [2], which can in turn be a graze and merge collision, and so on. Therefore, here we are limited to studying single occurrences of a larger collisional-dynamical process.

Influence of Saturn. While this scenario can explain key aspects of Saturn's moons (and the dynamical excitation of the system including Titan and possibly Iapetus [1]) the initial study left major questions on the table. For one thing, how did the proposed original system evolve into a state of collisional mergers? For another thing, do any of the escaping clumps survive for sufficiently long time to evolve into stable orbits? At minimum a half-dozen MSMs must have done so; and moreover they would evolve further via later mutual collisions [3], so the clumps produced in these simulations should be regarded as proto-MSMs.

In the absence of other perturbations, the most likely fate of any MSM that is born in this manner is to become accreted by merging satellite that spawned it. We find, through *N*-body dynamical modeling, that if there are no other major satellites present, and ignoring disk-driven migration and tides, then most of these clumps get swept up, as expected. Satellite orbital migrations would have to outpace this rate of sweep-up by the major moon. Accretions and binary-exchanges among the multiple clumps might also put them onto a new orbit. Given the complexity and lossiness of giant impact accretion, it is straightforward to come up with scenarios that over-produce MSMs, allowing for combination and attrition into a stable set of dynamically interconnected moons. However, to maintain their compositional diversity, any follow-on collisional evolution must be limited in scope, otherwise it would homogenize their compositions, and break down their regular size distribution to include more smaller bodies.

The presence of the central planet has, until now, been neglected in giant impacts. At much smaller scale, Saturn's gravitational influence has been explored and found to have a pronounced effect for collisions in the gravity-friction regime involving the small 'ravioli moons' Pan and Atlas [4]. With the inclusion of Saturn in the giant impact phase, we find that"runners", clumps, and spiral arms can evolve well outside the Hill radius $r_\mathrm{H} = r\sqrt{M/3M_\mathrm{p}}$, where M_p is the mass of the planet. Inserting parameters for Saturn and satellites the mass of Titan, the Hill radius is approximately $r_\mathrm{H} \approx ar_\mathrm{Titan}$ where a is the semi-major axis in Saturn radii. So the present Hill sphere around Titan is 20 Titan radii; for bodies closer to where the MSMs are now, the Hill radius is smaller.

For the 'best case' graze and merge simulation identified in [1] the projectile 'bounces' almost ten target radii before it comes back for the merger. For collisions occurring around the orbits of the present MSMs, much of the giant impact ejecta that returns in the 2-body scenario would be in orbit around Saturn.

Modeling. We bring greater realism to this study in three ways. **First** we directly model giant impact accretions in orbit around Saturn, represented as a central mass. This requires longer simulation time but is overall straightforward. **Second** we identify the clumps produced during the giant impacts, and evolve them by means of N-body dynamical modeling. This opens up a substantial parameter space so at present we consider a few examples. **Third** we perform SPH simulations with and without material friction. These runs are more computatioally costly, so we again consider a few points of comparison. Because the remnants are largely fluidized, the major effect is to alter the collisional cross-section, by preventing tidal deformation of the bodies prior to their mechanical interaction.

Methods. Simulations are run using SPH [1, 5], which includes self-gravity by means of a hierarchical spatial tree [6] and the (M-)ANEOS equation of state [7, 8]. We choose a resolution so that the mass of Titan is represented by $\approx 2 \times 10^5$ particles. Clumps the size of Enceladus are $\sim$200 particles, the size of Dione and Rhea, a few thousand. We evolve the collision for 48–96 h until the process finishes either by accretion of the impactor and production of spiral arms, by capture of the impactor and circularization of its orbit around the target, or the escape of the impactor in a hit and run collision.

Results. The effects of the tidal forces on the giant impact, due to Saturn, greatly depend on the orientation of the collision relative to the satellites' orbits, and the distance of the impacting bodies to Saturn (Fig. 1). This is a large parameter space with many novel outcomes; also, the merging process takes also longer to execute, making the simulation more challenging to compute. So we present a subset of that. The overall trend is for effective mergers (in a 2-body collision) to become hit and run collisions, enhancing the production of collisional arms and clumps, and favoring the hypothesis.

The presence of Saturn changes the orientation of the bodies during the course of the collision, so that there is no straightforward link between the incoming orbit and the direction on which clumps are ejected. A systematic search is then needed to link the initial orientation with the final state, and if smaller clumps are formed, their orbital parameters. Such a study is unfeasible with SPH alone, due to the numerous models required. Hence, the first encounter, which results in the initial capture of the smaller body, is modelled with SPH, while the following orbit is modelled with a N-body until a subsequent collision is detected or the time limit has elapsed. This permits us to obtain a distribution of probable secondary collisions, to determine its properties (velocity, angle and orientation) and the likelihood to eject small clumps. The orientation of the second collision will determine how the small clumps will behave, i.e. if they can be sent on orbits that are not crossing one of the primary bodies (the larger bodies that are accreting to become Titan).

Further work. Depending on the thermal state of the bodies, the assumption of fluid bodies might not hold. Our initial results show that in the case of solid bodies, the main effect of friction is to work against tidal deformation during the first encounter. The effect is to make the capture process weaker, and the following orbit is then further affected by the presence of Saturn. Clump formation is also affected, the tendency being to generate more smaller-mass bodies, composed only of the upper regions of the bodies.

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