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Giant Impacts Around Saturn

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Abstract

We revisit a scenario for the formation of Saturn's middle-sized moons. Saturn would begin with a Jupiter-like system of 'galilean' moons that underwent dynamical collapse, with the collisional mergers ultimately forming Titan. The middle-sized moons formed by the release of ice-rich material in the spiral arms that form in the immediate aftermath of the collisions. We aim at improving the realism of similar-sized collisions in the vicinity of another massive body by including the tidal forces in the collision simulation. This puts a constraint on the location where the impact occurred. Moreover, the inclusion of friction influences the formation of the spiral arms, and the sizes and morphologies of clumps.

1. Background

The origin of the Saturnian satellites is an evolving mystery. Titan, orbiting at $a = 20.3\ R_♄$, is about equal in mass to all the satellites of Jupiter combined, when normalized to the planet's mass. The origin and evolution of its high orbital eccentricity ($e = 0.0288$) is a classic problem in planetary science, as is its remarkably active geology compared to Ganymede and Callisto, two jovian satellites of approximately the same size and density, especially the existence of an almost Earthlike atmospheric/cryo-hydrologic cycle. Titan's periapsis is closer to Saturn than its apoapsis by $1.2\ R_♄$, causing a strong non-equilibrium tide; in the absence of forcing, Titan's orbit should have circularized within a few billion years [6] due to the dissipation of tidal energy. It would appear that either Titan was formed with significantly greater eccentricity than it has today, or its orbital eccentricity has been acquired more recently or is forced, with no obvious options for either (see however [2]).

The middle-sized moons (Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, Iapetus) are a connected mystery, beginning with their extraordinary compositional diversity. Radar observations [5] reveal considerable variations in their near-surface properties. Compositionally and geologically they are highly diverse. Innermost Mimas, 400 km diameter, is an inactive world of mostly ice ($\rho = 1.15\ \mathrm{g/cm^3}$), but its neighbor Enceladus (500 km diameter) is about half rock ($1.61\ \mathrm{g/cm^3}$) and is one of the most active satellites in the Solar System. Tethys ($0.98\ \mathrm{g/cm^3}$) and Mimas, the ice-dominated inner MSMs, are in a 2:1 mean motion orbital resonance, and so are the two rockiest, Enceladus and Dione ($\rho = 1.43\ \mathrm{g/cm^3}$). To add to the complexity of the system, Tethys and Dione are the only moons in the Solar System to have co-orbital satellites at their Lagrange points, and Hyperion is in 4:3 mean motion resonance with Titan. And to round out the picture, the two largest (Rhea, $1.24\ \mathrm{g/cm^3}$, and Dione) are of average bulk composition, while the three smallest, Mimas, Enceladus and Hyperion, could hardly be more dissimilar.

To address these two issues, the unique characteristics of Titan and the diversity of the middle-sized moons (MSMs), Asphaug and Reufer (2013) [1] developed a scenario where Saturn began with a 'galilean' system of moons comparable to Jupiter's, that underwent dynamical collapse, with collisional mergers ultimately forming Titan. The collisional accretion of Titan through a series of giant impacts has the benefit of leaving behind a finished satellite with substantial eccentricity (~ 0.1) that would decrease with tidal evolution. Moreover the frictional and accretionary (gravitational binding) energy released in the merger might explain the geological uniqueness of this large moon. Mergers liberate ice-rich spiral arms around the merged body in their simulations; these self-gravitate into escaping clumps resembling MSMs in size and compositional diversity. [1] reasoned that MSMs were spawned in a series of giant collisional mergers around Saturn, while Jupiter's original satellites stayed locked in resonance. They considered various causes for the dynamical collapse, but focused mainly on the clump-producing SPH simulations of these collisions, that are capable of producing tens of clumps, fragments from each merger that maintained unique identities as satellites around Saturn for some time. An open question is whether these satellites, which in SPH simulations have characteristics that are surprisingly comparable to the MSMs in size and compositional diversity, can survive to long time and avoid ultimately being accreted by the larger bodies in the system. If dozens of clumps were produced by this series of mergers, then a fraction of those clumps must survive. To study that aspect of the problem requires attention to the realism of similar-sized collisions and mergers and attempted mergers when the colliding bodies are in the strong gravitational influence of a central planet.

2. Giant impacts around a central body

We begin with the basic problem of improving the realism of the giant impacts. To our knowledge there are no studies of the physics of giant impacts happening well inside of a central body's gravitational field, so we are performing suites of simulations to reproduce the simulations of [1] but at various radii from Saturn. The threshold for clumps escaping from a given merger is lower, so that more MSMs will be produced. But also, the dynamics of a graze and merge collision are transformed considerably, in our pilot calculations, so that what would be a graze and merge collisions becomes a hit and run, and what may be a simple accretion becoming graze and merge, or a so-called hit and run return [3].

Moreover, the proposed satellite-forming giant impacts would have occurred well inside the regime where friction will matter during giant impacts [4]. So we have explicitly included the influence of solid friction in our studies, which may strongly influence the dynamics leading to clump formation. It should be noted that the proposed collisional mergers, at or around the escape velocity of Titan, $\sim 2\,\mathrm{km/s}$, are overall subsonic so that there will be little or no shock melting, although there may be considerable frictional heating. In this velocity range it appears that the most common outcome is graze and merge, when considering all impact angles. The typical sequence for shallow impacts $\theta > 60^\circ$ involves two to three collisions until the impactor is finally accreted. The first collision captures the impactor, which subsequently ranges to roughly $10\,\mathrm{R_S}$ before the second collision occurs. The second and third collisions then produce spiral arms, from which the smaller clumps are formed.

The presence the central planet will affect the whole process in two ways: the return trajectory of the impactor and the clump formation in the spiral arms. With Saturn and Titan's bulk densities, the Hill radius is $R_\mathrm{H} = a_\mathrm{S}(M_\mathrm{S}/3M_{♄})^{1/3} \sim R_\mathrm{S} \cdot a_\mathrm{S}/R_{♄}$. In case the collision happens at the current location of Titan, all the collision remain well within the Hill sphere. However if the impact occurred closer in then the distances will become comparable to the Hill radius. To asses the effect of Saturn on the formation of the MSMs, we are including in our simulations an additional force to represent the differential tidal effects of the presence of a third massive body. This adds another layer of complexity to the problem, as now the distance and directions of that body are now parameters. The inclusion of friction also influences the formation of the spiral arms, and the sizes and morphologies of clumps.

To first order, when the 'bouncing' impactor strays beyond the Hill radius in a graze and merge collision, this usually implies its loss, although that limit is not precise. This implies that if the impact takes place closer in than about $10\,\mathrm{R}_{♄}$, then the impact is not graze and merge, but hit and run. This would prevent the formation of the MSMs with the original scenario, but also, it would leave two projectiles that are likely to collide again sometime in the near future, several thousand orbits later. Before we can further consider the detailed dynamical evolution of this scenario using an *N*-body formalism, our goal is to obtain a comprehensive understanding of the unique nature of satellite-forming giant impacts.

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