A recent impact origin of Saturn's rings and mid-sized moons

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Summary: Saturn's rings appear to be remarkably young, ∼100 Myr old, ruling out most previous hypotheses for their origin and incentivising new explanations [1]. This could include a recent formation also for at least some of Saturn's mid-sized icy moons [2, 3]. We present high-resolution SPH simulations that reveal how a range of collision scenarios driven by recent resonant instabilities in a precursor satellite system can scatter large masses of fragments and debris throughout the system that could evolve to both form the rings and reaccrete into present-day moons [4].

Introduction: Saturn's rings used to be thought of as primordial or ancient, perhaps formed from a disrupted moon or comet [2]. However, their age has now been constrained to be less than a few 100 Myr, with a similar remaining lifetime, by observations made over the course of the Cassini mission. These include their low mass (∼0.4 Mimas) [1], low non-icy fraction (∼1%) [5], and the extrinsic micrometeroid flux [6], prompting new hypotheses for recent ring formation [7, 8].

This also raises the question of whether Saturn's mid-sized moons (interior to Titan) might also be young, as young rings could be tricky to reconcile with old moons. Ćuk et al. (2016) [4, hereafter Ć16] demonstrated that if the present-day system were ancient, then recent evolution through dynamical resonances would have excited the moons' orbits beyond what is seen today. In particular, Rhea's present inclination is an order of magnitude lower than if it had survived crossing an evection resonance, and such inclinations are not readily damped [9]. This implies a similarly recent and thus perhaps shared formation for these moons as the rings. Alternatively, the tidal evolution rate could be very slow, but this conflicts with the apparent intense tidal heating of Enceladus [10].

Furthermore, any pair of precursor moons with masses and orbits loosely comparable with present-day Dione and Rhea will be suddenly excited when the Rhea analogue encounters evection during migration [4], leading to high-velocity collisions due to their significant eccentricities (∼0.1–0.2) and inclinations of several degrees. Fragments and debris ejected by the impact could then both reaccrete into the present-day moons and deliver material inside Saturn's Roche limit to form rings.

Some aspects of this Ć16 scenario were investigated using smoothed particle hydrodynamics (SPH) simulations of two colliding Rhea-mass moons [11], with results that suggested the debris would rapidly reaccrete into a satellite without forming rings. However, this conclusion was premature for a few reasons, including: the simulations used a low resolution of 2×10^5 SPH particles; the subsequent evolution assumed a simplified hard-sphere and coefficient-of-restitution model for the reaccretion of fragments; and the presence of and potential cascade interactions with the other precursor moons that are expected in the system were neglected.

Methods: Here, we examine the collision of Dione- and Rhea-like precursor moons with 3D SPH simulations, where materials are represented by particles that evolve under gravity and pressure forces. With the open-source code SWIFT, we use over two orders of magnitude higher resolution than [11] with $10^{7.5}$ particles to examine the consequences of these impacts in detail.

We take two example outcomes of Ć16 numerical integrations, which result in collisions with relative velocities of 2 and 3 km s^{-1} (∼3 and 5 times the mutual escape speed). For each of these speeds, we simulate collisions at nine impact angles from nearly head-on (5°) to highly grazing (85°) in steps of 10°. The impact simulations are evolved from 1 h before contact to 8 h after. As this is only a modest fraction of the orbital period (∼82 h), we initially neglect the effects of Saturn's gravity. The outcomes of the SPH simulations are then placed in the context of the Saturnian system to compute the trajectory of the debris.

Results and discussion: For head-on to mid-angle impacts, a significant amount of ice and rock material is ejected from both bodies, as illustrated by Fig. 1 and the linked animation. The ice is mostly dispersed into relatively diffuse debris, while the rock remains or more rapidly reaccretes into a large number of cohesive fragments. Material is sent far throughout the Saturnian system, as shown in Fig. 2. It is likely that a precursor satellite system would have a broadly similar mass and architecture to the present one – perhaps with a somewhat larger total mass – whether it formed from a gaseous circumplanetary disk or primordial rings [12–14]. Large amounts of impact debris and fragments are placed onto orbits that would intersect with other satellites around the locations of those in the present-day system, as well as deep into the Roche limit.

The eccentric, high-velocity fragments and debris could erode or even disrupt any inner moons analogous to Tethys, Enceladus, and Mimas in a collisional cascade to spread more material throughout the system and into the Roche limit [15]. The total mass crossing each orbit depends on the impact angle. For all angles up to ∼45°, a mass of material ranging from around that of Mimas to over that of Enceladus (order 10^{19}–10^{20} kg) reaches

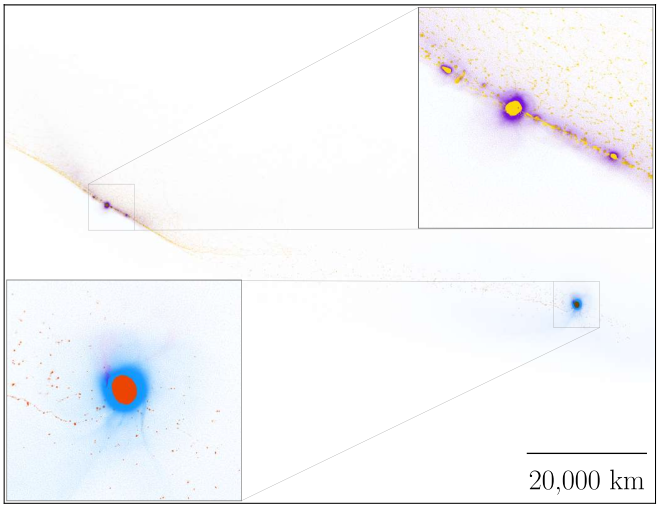

Figure 1: An illustrative cross-section of a snapshot from a simulation with $10^{7.5}$ SPH particles for an example 3 km s^{-1} impact at a middling impact angle of 35°. Orange and blue show particles of precursor(p)-Rhea's core-rock and mantle-ice material respectively, and yellow and purple the same for p-Dione. In this centre-of-mass frame, p-Dione came from the right, travelling left. An animation is available at icc.dur.ac.uk/giant_impacts/icy_moons_impact.mp4.

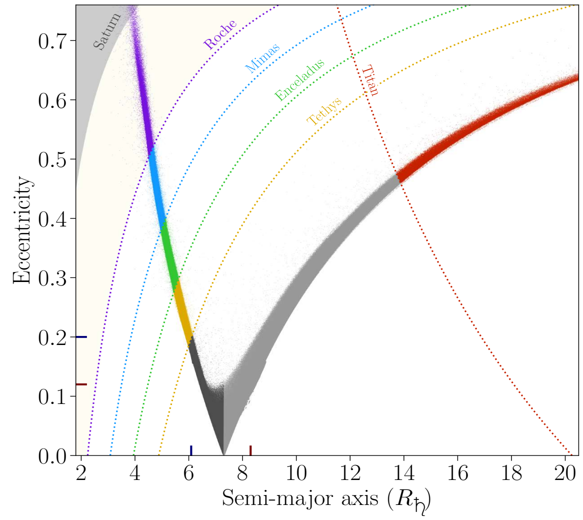

Figure 2: The eccentricities and semi-major axes of the debris in Fig. 1 orbiting in Saturn's frame. The dotted lines and corresponding particle colours indicate where an orbit crosses the Roche limit or other present-day moon locations. Grey and light grey indicate other semi-major axes either side of the impact point. The dark red and blue pairs of axis ticks indicate the orbits of the pre-impact moons.

Tethys, Enceladus, and even Mimas itself in some cases.

More than half the present-day total ring mass is immediately sent inside the Roche limit where it could tidally and collisionally evolve towards forming rings [16], even before considering further cascades and other material redistribution [4]. The Roche-entering material contains negligible rock, matching the present-day rings' nearly pure-ice composition [5], while the material that encounters Tethys and Enceladus can be several tens of percent rock by mass, depending on the scenario.

We also examine the comparable $\sim 10^{19}$–10^{20} kg mass of debris sent outwards to encounter Titan, which could open up new pathways for kickstarting its atmospheric evolution [17]. Finally, we compare the size distribution of fragments from our high-resolution simulations with the crater populations on Saturn's moons, which indicate a population of planeto- rather than heliocentric impactors [18].

For more grazing collisions, the pre-impact moons are incrementally less disrupted. Less ice and much less rock becomes ejected, particularly at angles for which the moons' cores do not intersect. However, in these same cases the remnant moons' orbits are also negligibly changed, so they will likely collide again in a future orbit [4], at perhaps more head-on angles.

Conclusions: Dynamical instabilities for precursor Saturnian moons can lead to high-velocity collisions that scatter fragments and debris throughout the system [4]. Fully testing this scenario is a multi-phased project that requires (1) improved understanding of the outcomes of icy-moon collisions; (2) following their dynamical evolution using N-body simulations; (3) determining the final outcomes for resulting satellite systems; and (4) quantifying the amount and composition of material that can evolve to form the rings, among other implications.

Here, we have addressed the first of these tasks with SPH simulations of impacts between icy moons, at over two orders of magnitude higher resolution than previous studies. We find that significant mass can be delivered directly into the Roche limit, with a ring-like composition of pure ice, across a range of plausible impact scenarios. Furthermore, over a Mimas mass of material – and even over an Enceladus mass in some cases – is placed onto crossing orbits with present-day Mimas, Enceladus, and Tethys (and Titan), facilitating the possibility of a collisional cascade to further distribute debris that could contribute to forming the rings and present-day moons.

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