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

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Fig. 1: The outcome of an example 2 km s^{-1} high-resolution impact simulation between two icy moons analogous to Dione and Rhea, using $10^{7.5}$ SPH particles, 9 hours after impact, rendered in 3D using the Houdini VFX program and Redshift.

Fig. 1b: The colliding moons shortly after contact.

Full video

youtu.be/OWaMeUF4enU

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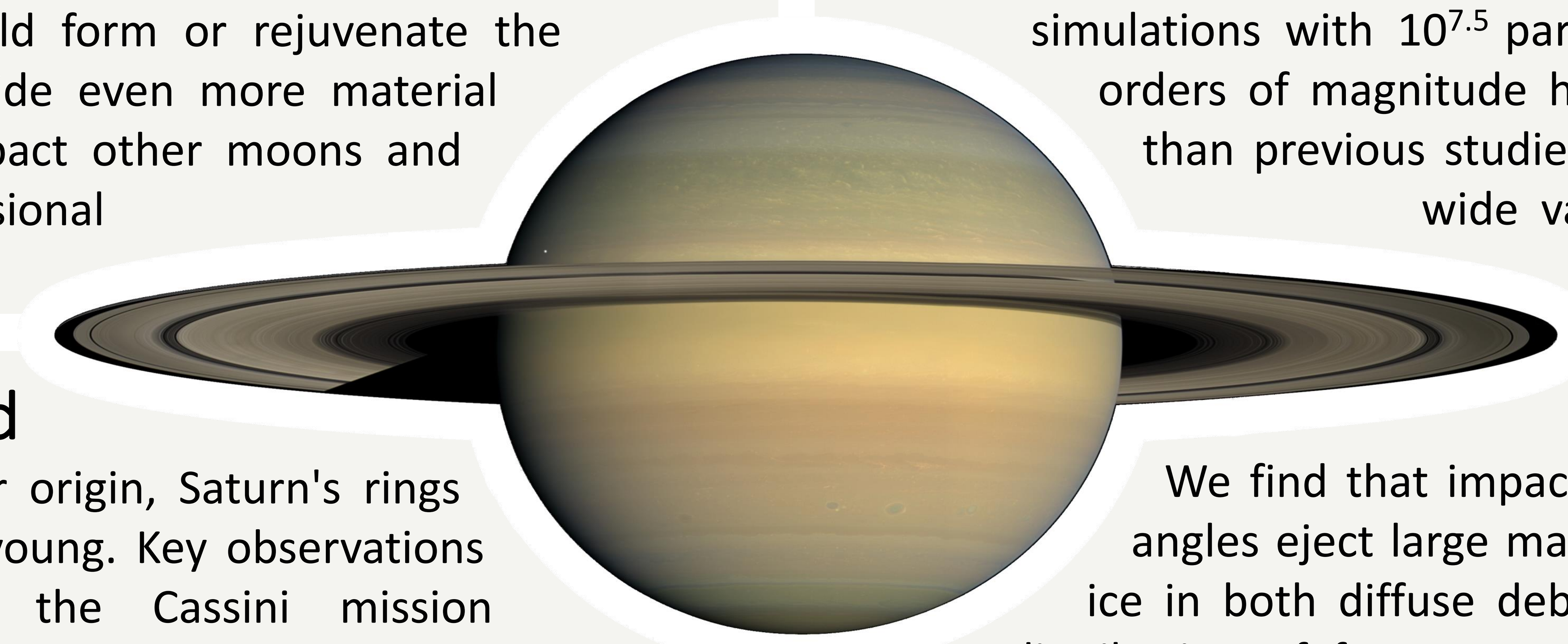
Teodoro & Kegerreis et al. (2023), ApJ 955:137.

Overview

Saturn's rings appear to have formed remarkably recently, ~100 Myr ago, ruling out most previous hypotheses for their origin. We have modelled the violent collision of two icy moons as a potential mechanism for delivering ring-forming material. Such an event could have been triggered a few hundred million years ago by resonant instabilities in a precursor satellite system. We find that large masses of debris can be scattered throughout the system, including the direct placement of pure-ice ejecta onto orbits that enter Saturn's Roche limit. This could form or rejuvenate the rings – alongside even more material that could impact other moons and initiate a collisional cascade.

Methods

Smoothed particle hydrodynamics (SPH) is a widely used method for simulating planetary impacts, where the materials are represented by many points or "particles". The more particles, the higher the resolution. Recent work has shown that standard-resolution SPH simulations with 10^5–10^6 particles can produce unreliable and unconverged results, adding to the importance of improving numerical resolution beyond simply providing more detail[12]. We used our open-source code SWIFT[13] and the DiRAC COSMA7 and COSMA8 systems to run SPH simulations with $10^{7.5}$ particles, over two orders of magnitude higher resolution than previous studies[14], to model a wide variety of impact scenarios.



Background

Whatever their origin, Saturn's rings appear to be young. Key observations made during the Cassini mission provided new measurements of the ring mass[1], the fraction of non-icy material in the rings[2], and the flux of extrinsic micrometeoroids at Saturn[3], which continuously erode and darken the almost pure-ice rings (>95% by mass) over time. Together, these three factors constrain the ring age to be less than a few 100 Myr[3,4]. Furthermore, the currently ~0.4 Mimas-mass (~1.5 × 10^{19} kg) rings are losing mass so rapidly that they will only survive for another few hundred million years[5,6].

However, the rings' youth and transience are at odds with most current ideas about their origin being primordial or ancient[e.g.,7–9]. One recent scenario suggests that a moon beyond Titan was destabilised and stripped into rings[10], but the evolution of the disrupted material has not yet been modelled.

Ćuk et al. (2016)[11] demonstrated how moons in a precursor system analogue to Rhea and Dione could be destabilised when the outer moon reaches the evection resonance with the Sun, leading to crossing orbits and a high-speed collision. Furthermore, Rhea today is not far outside the resonance. If it had migrated through it, then its inclination would have been excited far above the observed value[11], adding to other indications that at least some of Saturn's mid-sized icy moons also formed recently.

Results

We find that impacts at low-to-mid angles eject large masses of rock and ice in both diffuse debris and a broad distribution of fragments, as illustrated in Fig. 1 – including large objects of 10^{18}–10^{20} kg on eccentric orbits that could disrupt other precursor moons. These highly dissipative collisions distribute the ejecta on a wide range of orbits, as shown by Fig. 2, including large amounts heading directly into the Roche limit. The total mass crossing the Roche limit is shown by Fig. 3, reaching more than twice the present-day ring mass in some cases, and with the required composition of pure ice.

More than an Enceladus mass of ice and rock can also be placed onto crossing orbits to potentially erode or disrupt any moons in the vicinity of Mimas, Enceladus, or Tethys – and outwards to impact Titan.

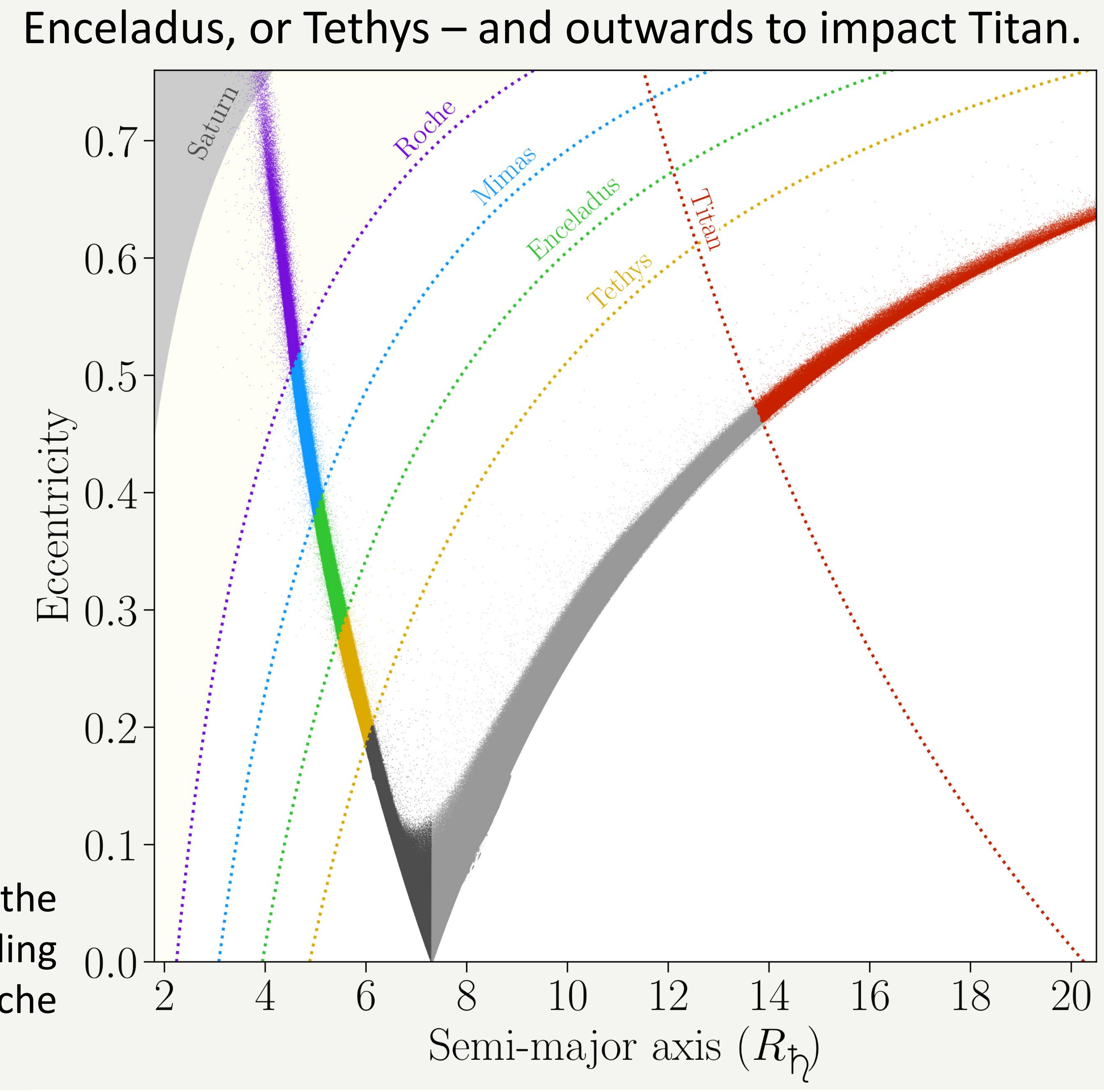


Fig. 2: The eccentricities and semi-major axes of the post-impact debris. The dotted lines and corresponding particle colours show where an orbit crosses the Roche limit or the locations of other present-day moons.

More info

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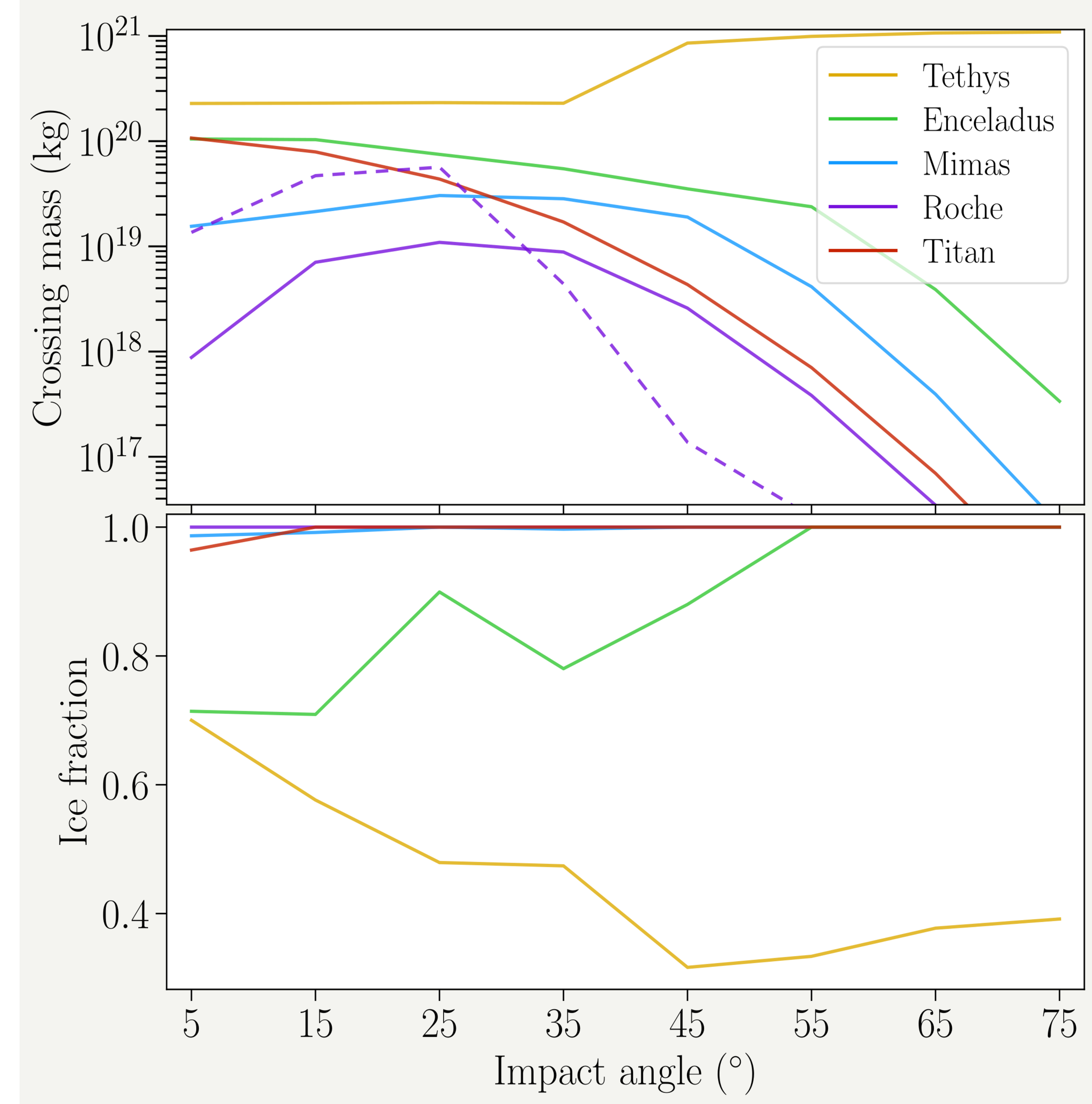

Fig. 3: The mass and composition of debris on orbits crossing the Roche limit or other moons, as a function of the impact angle, where zero is head-on. The dashed line shows a different orientation of the impact in Saturn's frame.

Implications and future work

The initial trajectories of the debris are only the starting place for this formation scenario, including the encouraging potential for a collisional cascade to further distribute material throughout the system that could form the rings and re-form the inner system of icy moons. While not all the mass of ice crossing the Roche limit is expected to form rings, we find that even with a simplified and conservative assumption that the debris will only settle onto an equivalent-momentum circular orbit, significant ice (and no rock) would end up within the Roche limit. We find similarly promising results across different impact angles, speeds, and precursor-moon masses.

The outputs of simulations like these provide the inputs for the next key stage of modelling the full evolution of the system. With this paper in review, we are developing a novel combination of *N*-body integrations with full SPH models of the subsequent impacts and tidal disruption events, to constrain the consequences of this scenario for Saturn's rings, moons, and their eventual cratering populations.

[1]Iess et al. 2019, Science 364. [2]Zhang et al. 2017, Icarus 294. [3]Kempf et al. 2023, Sci. Adv. 9. [4]Durisen & Estrada 2023, Icarus 400. [5]O'Donoghue et al. 2019, Icarus 163. [6]Estrada & Durisen 2023, Icarus 400. [7]Canup 2010, Nature 468. [8]Dubinski 2019, Icarus 321. [9]Dones 1991, Icarus 92. [10]Wisdom et al. 2022, Science 377. [11]Cuk et al. 2016, ApJ 820. [12]Kegerreis et al. 2019, MNRAS 487. [13]Schaller et al. 2023, www.swiftsim.com. [14]Hyodo & Charnoz 2017, AJ 154.

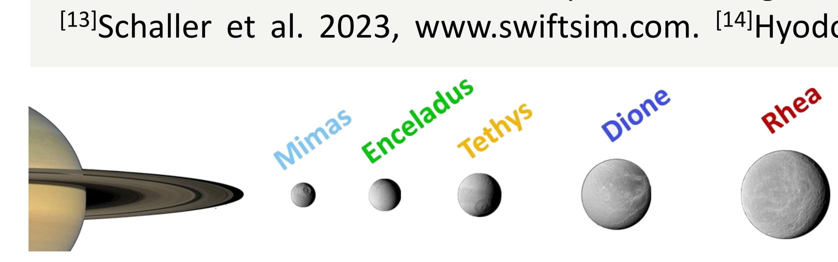

Fig. 4: The inner Saturn system.