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Origin of Saturn's rings and inner moons by mass removal from a lost Titan-sized satellite

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The origin of Saturn's rings has not been adequately explained. The current rings are more than 90 to 95 per cent water ice[1], which implies that initially they were almost pure ice because they are continually polluted by rocky meteoroids[2]. In contrast, a half-rock, half-ice mixture (similar to the composition of many of the satellites in the outer Solar System) would generally be expected. Previous ring origin theories invoke the collisional disruption of a small moon[3,4], or the tidal disruption of a comet during a close passage by Saturn[5]. These models are improbable and/or struggle to account for basic properties of the rings, including their icy composition. Saturn has only one large satellite, Titan, whereas Jupiter has four large satellites; additional large satellites probably existed originally but were lost as they spiralled into Saturn[6]. Here I report numerical simulations of the tidal removal of mass from a differentiated, Titan-sized satellite as it migrates inward towards Saturn. Planetary tidal forces preferentially strip material from the satellite's outer icy layers, while its rocky core remains intact and is lost to collision with the planet. The result is a pure ice ring much more massive than Saturn's current rings. As the ring evolves, its mass decreases and icy moons are spawned from its outer edge[7] with estimated masses consistent with Saturn's ice-rich moons interior to and including Tethys.

The Jovian and Saturnian regular satellites are believed to have formed within circumplanetary disks of gas and solids produced during the end stages of nebular gas inflow to the planets[6,8,9]. Recent work predicts that multiple generations of Titan-sized satellites formed and were lost to collision with Saturn[6]. Each satellite grows no larger than a critical mass, at which point its orbit spirals into the planet owing to density wave interactions with the gas disk[6] (see Supplementary Information). This critical mass is comparable to that of Titan (mass $M_{\rm T} = 1.35 \times 10^{26}$ g and solid-body radius $R_{\rm T} = 2{,}575$ km)[6]. The overall process produces a final satellite system with either several large satellites (like Jupiter's Galilean satellites) or a single large satellite (like Saturn's Titan)[6,9]. A Saturn-like system (Table 1 and Fig. 1) can be produced when large, Titan-sized interior satellites spiral into the planet and are lost as gas inflow ends[6].

A large satellite on an approximately circular orbit becomes unstable interior to a distance known as the classical Roche limit, $a_{\rm R} \equiv 2.456 R_{\rm S}(\rho_{\rm S}/\rho)^{1/3}$, where $R_{\rm S} = 58{,}232$ km and $\rho_{\rm S} = 0.687\ {\rm g\,cm^{-3}}$ are Saturn's current mean radius and density, and ρ is the satellite's mean density. For a Titan-like mean density ($\rho_{\rm T} = 1.88\ {\rm g\,cm^{-3}}$), $a_{\rm R} = 1.76 R_{\rm S}$. What happens once a large satellite drifts within $a_{\rm R}$ depends on its interior structure. An undifferentiated, uniform composition satellite disrupts completely. However, by the time a large ice-rock satellite approached the Roche limit, it would probably have undergone substantial ice melting and thus have a differentiated interior.

The energy associated with forming a Titan-sized satellite heats its interior to near the melting point for ice and may cause partial melting[10]. In addition, for even slightly non-circular orbits, the time-varying distortion of the satellite's shape by the planet heats the satellite's interior at a rate[11] $dE/dt \approx (21/2) M_{\rm P} \Omega^3 r^2 (R/r)^5 (k_2/Q) e^2$, where $M_{\rm P}$ is the planet's mass, Ω and r are the satellite's orbital frequency and orbital radius, R is the satellite's radius, (k_2/Q) is the ratio of the satellite's Love number to its tidal dissipation factor (an uncertain quantity but plausibly within the range[11] $10^{-3} < (k_2/Q) < 10^{-1}$; Supplementary Information), and e is the satellite's eccentricity. For example, with $e = 0.002$ (Fig. 1 legend; Supplementary Information), $r = 1.7 R_{\rm S}$, $(k_2/Q) = 10^{-2}$ and $R = R_{\rm T}$, tidal heating dissipates about $5 \times 10^9\ {\rm erg\,g^{-1}}$ in a Titan-mass satellite ($M = M_{\rm T}$) over an estimated orbital decay timescale of about 10^4 years (Supplementary Information), comparable to the latent heat of fusion of water ice ($3 \times 10^9\ {\rm erg\,g^{-1}}$). As ice melts, higher-density rock initially contained within the ice rapidly descends to the satellite's centre, so that melting in a satellite's outer layers creates an outer pure-ice mantle overlying a more rock-rich core[10,12]. For $M = M_{\rm T}$, the separation of rock from ice becomes energetically self-sustaining[13] once about 50% of the rock has migrated to the satellite's centre[12,13], and in this case the satellite differentiates into an ice mantle and a core that is pure rock or rock and metal.

When a differentiated satellite drifts within its Roche limit, tides first strip material from its outer, lower-density layers. The removal of low-density material causes the satellite's mean density to increase until the remnant satellite is marginally stable. As the satellite spirals inward, this process regulates ρ to approximately the local critical value for stability at the satellite's semi-major axis a, $\rho_{\rm crit} \equiv \rho_{\rm S}(2.456)^3(R_{\rm S}/a)^3$, until the remnant satellite either collides with the planet or fully disrupts.

As a simple example, consider a two-layer satellite with an ice mantle overlying a core of uniform density $\rho_{\rm core}$. The satellite's initial mean density $\bar{\rho}_{\rm o}$ determines the distance at which the tidal loss of ice begins [$a_{\rm max} \equiv a_{\rm R}(\rho = \bar{\rho}_{\rm o})$], while $\rho_{\rm core}$ sets the distance at which the core disrupts [$a_{\rm rock} \equiv a_{\rm R}(\rho = \rho_{\rm core})$]. The satellite sheds only ice across the region:

Table 1 | Saturn's rings and inner moons

Object	$a/R_{\rm eq}$	Mass (10^{22} g)	Mean radius (km)	Density (g cm^{-3})
B ring	1.5–1.9	2–10	–	–
A ring	2.0–2.3	0.6	–	–
Epimetheus	2.51	0.06	58.3	0.63
Janus	2.51	0.20	90.4	0.61
Mimas	3.09	3.75	198	1.15
Enceladus	3.95	10.8	252	1.61
Tethys	4.89	61.7	533	0.97
Dione	6.26	105	562	1.48
Rhea	8.74	230	764	1.23

Shown are key properties[24,27] of Saturn's most massive rings and inner moons with mean radii >50 km. Here orbital radii a are scaled by Saturn's equatorial radius according to convention ($R_{\rm eq} = 60{,}268$ km $= 1.035 R_{\rm S}$). The total mass in the main rings, contained primarily in the B ring, is estimated to be[24] a few times 10^{22} g to 10^{23} g. Saturn's inner satellites interior to and including Tethys are, as a group, unusually ice-rich, with a mass-weighted average density $\bar{\rho}_{sat} \approx 1.07\ {\rm g\,cm^{-3}}$. Disruptive collisions[4] and/or endogenic activity in the case of Enceladus[27] could have removed ice relative to rock owing to ice's higher volatility, so that the current inner satellite compositions probably provide lower limits on their initial ice fraction. Moons orbiting exterior to Saturn's synchronous radius evolve outward owing to tidal interaction with the planet. This implies that the moons interior to and including Tethys could have all been interior to[28] about $4R_{\rm S}$ when they formed, consistent with their having been spawned from the outer edge of the rings. The model here proposes that Tethys, Enceladus and Mimas (or their progenitors) were spawned from a primordial massive ring as it spread diffusively and delivered material to the region outside the Roche limit. A similar process appears to be ongoing today, with the smaller inner moons (interior to and including Janus) probably forming in the last 10^6 to 10^7 years as a result of recent spreading of the A ring[7]. More distant Dione and Rhea have been exterior to about $6R_{\rm S}$ throughout their history[28], and thus probably formed independently of the rings.

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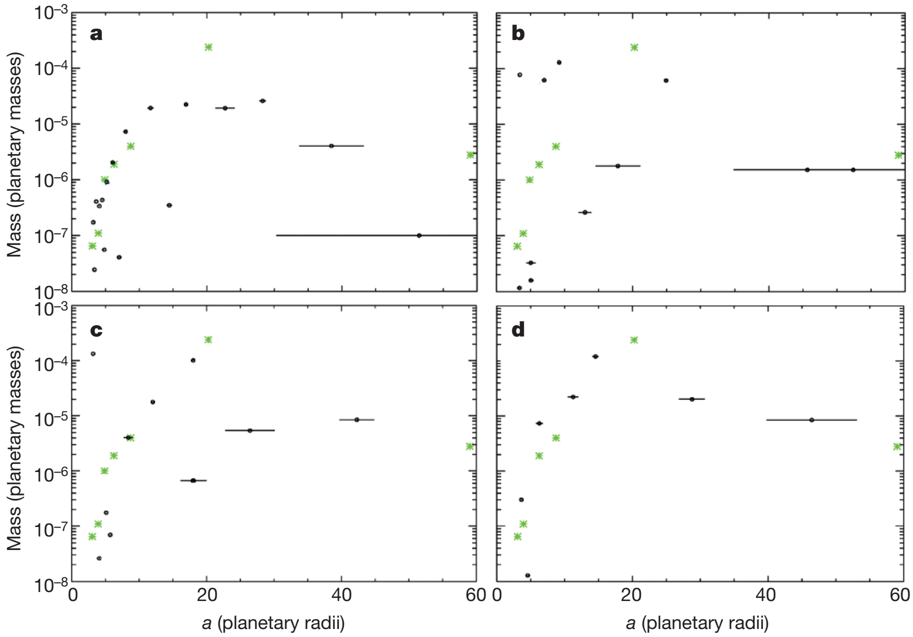

Figure 1 | Results of a satellite accretion simulation[6] that produced a Saturn-like system of satellites. The satellite disk is supplied by an inflow of gas and solid particles from solar orbit, the rate of which decays exponentially with a time constant τ_{in} that is comparable to the solar nebula lifetime. Satellites undergo inward type I migration on a timescale proportional to $(M\sigma_g)^{-1}$, where M is satellite mass, and σ_g is the disk gas surface density, with the latter proportional to the inflow rate[6,8]. Black circles show the simulated satellites (with horizontal lines proportional to orbital eccentricities); Saturn's satellites are shown as green stars. **a**, Multiple satellites form as solid material flows into the disk ($t = 0.2\ \tau_{in}$). Once satellites grow to a mass M of a few times 10^{-5} planetary masses, they begin to migrate inward. **b**, At $t = 1.4\ \tau_{in}$, the system resembles Jupiter's Galilean system, with four similarly sized large satellites. **c**, The inner three large satellites are lost to collision with Saturn, with the last large satellite lost at time $t \approx 3\ \tau_{in}$, when the inflow rate has slowed substantially and the disk gas density has decreased to $\sigma_g \approx 10\ \mathrm{g\ cm^{-2}}$. The last lost satellite acquires most of its mass at distances of 25 to 30 planetary radii, where disk temperatures were low enough for water ice, implying that the satellite would have a Titan-like composition with approximately 50% rock and 50% ice. **d**, The final system at $t = 10\ \tau_{in}$ has a single large Titan-like satellite at $a \approx 15$ planetary radii. The satellite eccentricities in these simulations reflect a balance between mutual gravitational interactions and eccentricity damping by density waves, yielding an average final eccentricity for the large satellites of $\langle e\rangle \approx 0.02$ (ref. 6). Inclusion of eccentricity damping by tides raised on the satellites by the planet is estimated to reduce this to $\langle e\rangle$ of a few times 10^{-3} (Supplementary Information).

$$a_{\mathrm{rock}} < a < a_{\max}$$
$$1.5R_S\left(\frac{3.0\ \mathrm{g\ cm^{-3}}}{\rho_{\mathrm{core}}}\right)^{1/3} < a < 1.8R_S\left(\frac{1.9\ \mathrm{g\ cm^{-3}}}{\bar{\rho}_{\mathrm{o}}}\right)^{1/3} \quad (1)$$

For a rock or a rock–metal core, ρ_{core} would be about 3.0 to 3.5 g cm^{-3} (the latter is the density of Jupiter's rocky satellite, Io), while $\bar{\rho}_{\mathrm{o}} \approx \rho_T$ is expected.

Planet contraction models[14,15] predict that 2 to 5 Myr after the peak rate of its gas accretion, the young Saturn's radius R_P would have had a value between about $1.6R_S$ and $1.5R_S$. Mean observed nebular lifetimes[16] are about 3 Myr, so that the end of gas inflow to Saturn and the loss of the final large satellites interior to Titan would probably occur in this timeframe. For $a_{\mathrm{rock}} < R_P < a_{\max}$, a satellite will collide with the planet before its rocky core disrupts, so that it tidally sheds only ice. Although each lost satellite may have produced tidal debris (depending on the state of the planet at that time), such material would generally be removed through collision with the planet as it was shepherded by subsequent satellites migrating inward[17] or perhaps driven to high eccentricities by not-too-distant large satellites[18]. However, tidal debris from the last large satellite to be lost from the Saturnian system could survive.

I use smooth particle hydrodynamics (SPH) to simulate tidal stripping from Titan-sized satellites (Fig. 2; Supplementary Information). The simulations predict initial tidal fragment orbital eccentricities of $e_p \approx 0.1$. Fragments would have radii of about 1 to 50 km, depending on the tensile strength of the satellite's outer ice shell[5] (Supplementary Information). Subsequent collisions between fragments occur with a characteristic velocity $v \approx e_p r\Omega$, where $\Omega \equiv [GM_S/r^3]^{1/2}$ is the orbital frequency, $M_S = 5.69 \times 10^{29}$ g is Saturn's mass, G is the gravitational constant, and $r\Omega$ is the orbital velocity at radius r, which is about 20 km s^{-1} at $r = 1.7R_S$. The collision energy per unit mass, $v^2/2 \approx 10^{10}$ erg g^{-1}, exceeds that needed to catastrophically disrupt[19] ice objects with radii of 1 km to 50 km ($\sim 10^6$ erg g^{-1} to a few 10^8 erg g^{-1}), so that collisions shatter the fragments into small particles.

Mutual collisions also rapidly drive the particles into a ring with nearly circular and co-planar orbits (Supplementary Information). To estimate the total mass of ice produced, I compute the equivalent circular orbit, $a_{\mathrm{eq}} \equiv a_p(1 - e_p^2)$, for each SPH particle having the same angular momentum as its initial orbit with semi-major axis a_p and eccentricity e_p. I then compare a_{eq} to an estimate (Supplementary Information) of the ice stability distance a_{ice}, obtained by balancing heating of the disk by the planet's luminosity, occurring with a rate per unit area of the disk $\dot{E}_P \approx (18/7)\sigma_{\text{S-B}} T_P^4 (R_P/r)^2 (c/r\Omega)$, with radiative cooling from the disk surfaces, occurring with a rate per unit area of the disk $\dot{E}_{\mathrm{rad}} = 2\sigma_{\text{S-B}} T_d^4$. Here $\sigma_{\text{S-B}}$ is the Stefan–Boltzmann constant, T_P and R_P are the planet's temperature and radius determined by planet contraction models[14,15], $c \propto T_d^{1/2}$ is the speed of sound in the gas, and T_d is the disk temperature at radius r. Setting $\dot{E}_P = \dot{E}_{\mathrm{rad}}$ and solving for the distance at which $T_d = 200$ K gives $a_{\mathrm{ice}}/R_S \approx 1.6(T_P/400\ \mathrm{K})^{8/3}(R_P/1.5R_S)^{4/3}$. As a Titan-like satellite orbit spirals towards the planet, up to a few times 10^{25} g of thermally stable ice particles is produced (Table 2).

The earliest dynamical evolution of the tidally stripped debris is dominated by gravitational interactions with the remnant satellite (Supplementary Information), but after the satellite collides with Saturn, the debris settles into a pure ice ring containing up to a few times 10^{25} g, with a surface density $\sigma_{\mathrm{ring}} \approx 10^5$ g cm^{-2}, and a ring outer edge at the Roche limit for ice: $a_{\mathrm{R,ice}} \approx 2.2R_S$. The gas disk at this late time is estimated to have a much lower surface density than the ring, with $\sigma_g \leq 10$ g cm^{-2} (Fig. 1; Supplementary Information). Describing

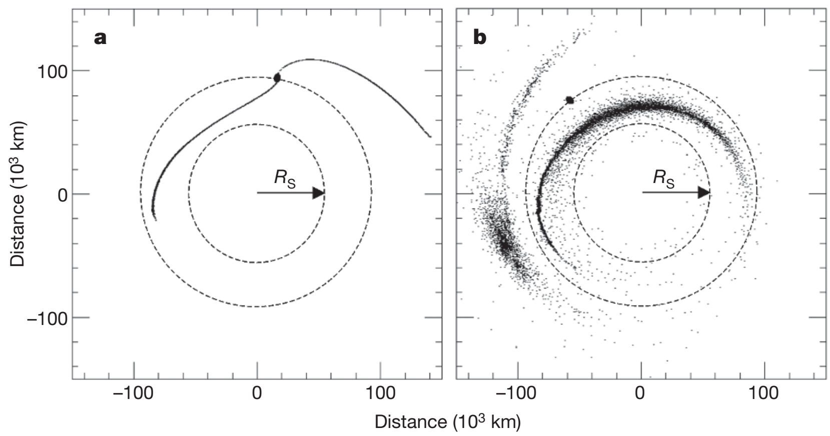

Figure 2 | SPH simulation showing the tidal removal of ice from a differentiated, Titan-mass satellite. SPH represents matter as particles, which are here evolved in response to gravity, shock dissipation, and pressure using the equation of state M-ANEOS[29,30] (Supplementary Information). Type I migration and tidal interaction with the planet cause the satellite's orbit to spiral inward from its initial Roche limit (a_{max}) to the planet's surface (R_P) in about 10^4 years (Supplementary Information). The satellite's evolution across this region is tracked with a series of SPH simulations. The satellite starts with $a = a_{max}$ and is evolved for several orbits with SPH to simulate tidal mass removal and the establishment of a stable satellite remnant. The remnant satellite is then shifted inward by $\Delta a \approx 10^{-2}a$ (Supplementary Information) and re-simulated, with the process repeated until a is small enough that the satellite's rocky core disrupts, which determines a_{rock}. Frames here show tidal stripping from a satellite with a composition of 55% ice and 45% silicate + metal (see Table 2) orbiting a Saturn-mass planet at $a = 0.97a_{max}$ after 8 simulated hours (**a**) and 25 h (**b**). Distances are shown in units of 10^3 km; for comparison, Saturn's B and A rings lie between ~92,000 and 137,000 km from the centre of Saturn. Dashed circles indicate the satellite's orbit and Saturn's current mean radius, R_S; Saturn's radius at the time of the satellite's decay was probably $R_P \approx 1.5R_S$ (refs 14 and 15; Supplementary Information). Material originating from the satellite's ice mantle is lost through its inner and outer Lagrange points (L1 and L2), leading to particles on highly eccentric orbits (with $e \approx 10^{-1}$) with semi-major axes interior and exterior to that of the satellite, respectively (Supplementary Information). Subsequent collisions between particles will tend to circularize their orbits, and the clumps seen in **b** are transient features. Interior particles will probably collide directly with the planet or be driven into the planet by the satellite, while exterior particles can supply the ring.

drag by the gas disk on the ring as a shear stress on the disk surfaces gives a ring decay timescale[3,20] of $\tau_{gd} \approx 14\mathrm{Re}(\sigma_{ring}/\sigma_g)(GM_S/c^3)$, which is about 10^7 years for these surface densities, $T_d \approx 200$ K and a Reynolds number $\mathrm{Re} \approx 10^2$ (Supplementary Information). This exceeds the expected persistence time of the gas disk (nominally ~10^6 years), so the ring survives.

Interparticle collisions cause the ring to spread and decrease in mass as inward-flowing material is lost and outward-diffusing material accumulates into moons[7,21]. The spreading timescale for a massive ring is[22,23]:

$$\tau_\nu \approx \left(\frac{r\Omega^2}{G\sigma_{ring}}\right)^2 \frac{\Omega^{-1}}{C} \approx 10^5\ \text{years}\left(\frac{10}{C}\right)\left(\frac{10^5\,\text{g cm}^{-2}}{\sigma_{ring}}\right)^2\left(\frac{1.8R_S}{r}\right)^{5/2} \quad (2)$$

where $C(r)$ is a scaling factor[23] of ~10 in the B ring and ~40 at $a_{R,\,ice}$. The initially massive ring envisioned here would, over the age of the Solar System, have decreased in mass[21] such that $\tau_\nu \approx 4.5$ Gyr, implying that σ_{ring} would now be a few times 10^2 g cm^{-2}, consistent with current estimates for the B ring[24].

Ring material spreading beyond the Roche limit accretes to form icy moons[7]. Each moon spawned from the ring's outer edge grows until it reaches a mass such that the timescale for its recoil from the ring due to resonant interactions, τ_{recoil}, is comparable to the timescale for the ring's outward diffusion[7]. With[17] $\tau_{recoil} \approx M_S^2[(a_m - r)/a_m]^3/[1.68a_m^2\sigma_{ring}\Omega m_m]$, setting $\tau_{recoil} \approx \tau_\nu$ gives a characteristic moon mass:

$$m_m^* \sim r^2\sigma_{ring}\left(\frac{C}{1.68}\right)\left(\frac{r}{a_m}\right)^{1/2}\left(\frac{a_m - r}{a_m}\right)^3 \quad (3)$$

that depends on σ_{ring} and the position a_m at which the moon accretes relative to the ring edge r. Accretion models[25] find $a_m/a_R \approx 1.1$ to 1.2. With $1.1 < (a_m/a_{R,\,ice}) < 1.2$, $r = a_{R,\,ice}$, a uniform surface density ring, and $C = 40$, the estimated moon mass in grams is $3 \times 10^{23}(\sigma_{ring}/10^5\,\text{g cm}^{-2}) < m_m{}^* < 2 \times 10^{24}(\sigma_{ring}/10^5\,\text{g cm}^{-2})$ (in approximate agreement with Supplementary Fig. 4 of ref. 7). This is comparable to Tethys' mass (6×10^{23} g) for the initial σ_{ring} values predicted here.

Upon reaching a mass of about $m_m{}^*$, resonant torques drive the moon away from the ring until its most distant strong resonances migrate out of the ring[7,26]. For the 2:1 inner Lindblad resonance, this occurs when $a_m = 1.6r$, or when $a_m \approx 3.6R_S$ for $r = a_{R,\,ice}$. At this point the moon is exterior to Saturn's early synchronous radius (Supplementary Information), so that it continues to evolve outward because of tidal interaction with the planet. As each moon recoils away from the ring, a new moon is spawned from the ring's outer edge, with the moon masses decreasing with time as σ_{ring} decreases[7]. As moons evolve outward, any mixing with material originating from outside the rings would increase their rock content somewhat relative to that of the rings. The densities of the moons interior to and including Tethys imply that as a group they contain about 90% ice and 10% rock (Table 1; Supplementary Information).

A primordial ring must avoid contamination by impacts of silicate-rich micrometeoroids throughout its 4.5-billion-year lifetime in order to produce the >90 to 95% water-ice ring observed today. Previous

Table 2 | Results of SPH simulations of tidal stripping

Satellite composition	a_{max}	$R_{P,\,min}$	a_{ice}	M_{ring} ($a_{eq} \geq a_{ice}$)
50% ice, 15% hydrated silicate and 35% silicate	1.7	1.5	1.8	2×10^{25} g
50% ice and 50% silicate	1.7	1.5	1.8	2×10^{25} g
55% ice and 45% silicate + metal	1.7	1.4	1.5	3×10^{25} g
45% ice and 55% silicate + metal	1.6	1.4	1.5	2×10^{25} g

The first four columns list the compositions of the simulated satellites (which all had $M = M_T$), the semi-major axis at which tidal loss of ice commences (a_{max}), the smallest planet radius consistent with pure ice loss ($R_{P,\,min} \equiv a_{rock}$), and an estimate (see main text and Supplementary Information) of the ice stability radius in the circumplanetary disk (a_{ice}), based on planet contraction models[14,15]. All distances are shown in units of Saturn's mean radius, R_S. For a given satellite composition, the mass of tidally stripped ice is maximized if the planet's surface at the time of the satellite's orbital decay is located at $R_P = R_{P,\,min}$, so that the satellite is consumed by the planet just before the loss of rock from its core. A more extended planet with $R_P > R_{P,\,min}$ causes an earlier collision and a reduced mass of stripped ice, while a smaller planet radius and a later collision would lead to rocky fragments inconsistent with the composition of Saturn's rings. The final column shows the mass of ice particles having an equivalent circular orbit a_{eq}, exterior to a_{ice} assuming $R_P = R_{P,\,min}$. Similar total ring masses can be estimated analytically (Supplementary Information). The a_{eq} distance is representative of the orbital radius to which the mass of an initial fragment will settle after undergoing dissipative collisions but before substantial diffusive spreading of the ring. By comparing a_{eq} to a_{ice}, I assume ring particles are in thermal equilibrium with the circumplanetary gas disk. If they instead radiate into the cooler background nebula, ice particles could be thermally stable interior to a_{ice} (Supplementary Information).

work[2] suggests that Saturn's current rings would be polluted in only a few times 10^8 years. However, the rings could be primordial and still unpolluted if the impact rate was overestimated and/or the rings' mass was underestimated[1]. During its extended mission, the Cassini spacecraft will indirectly sample the impact rate, and will directly measure the rings' current total mass[1]. While prior ring origin theories (Supplementary Information) have envisioned an initial ring comparable in mass to the current rings, the model here implies an initial ring that is several orders of magnitude more massive. A massive early ring would be less vulnerable to pollution by rock-rich impacts, and also has the advantage of providing sufficient mass and angular momentum (Supplementary Information) to account ultimately for both the current rings and the inner ice-rich Saturnian satellites.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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