Formation of Regular Satellites from Ancient Massive Rings in the Solar System.

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When a planetary tidal disk—like Saturn's rings—spreads beyond the Roche radius (inside which planetary tides prevent aggregation), satellites form and migrate away. Here, we show that most regular satellites in the solar system probably formed in this way. According to our analytical model, when the spreading is slow, a retinue of satellites appear with masses increasing with distance to the Roche radius, in excellent agreement with Saturn's, Uranus', and Neptune's satellite systems. This suggests that Uranus and Neptune used to have massive rings that disappeared to give birth to most of their regular satellites. When the spreading is fast, only one large satellite forms, as was the case for Pluto and Earth. This conceptually bridges the gap between terrestrial and giant planet systems.

Satellites are generally thought to form concurrently with a giant planet, in a large circumplanetary gaseous disk where there is inflow of solids. Two competing models exist in the literature (*1*–*4*), in which solids aggregate to form satellites that can migrate in the gas (and possibly be lost) before the gas dissipates. These models have their pros and cons, but none can explain the surprising orbital architecture of Saturn's, Uranus', and Neptune's satellite systems, where the smallest bodies accumulate at a distance from the planet that is twice its radius (the Roche radius), and their masses increase with distance starting from this point (Fig. 1A). Moreover, in the frame of a circumplanetary gas disk, Uranus' satellites should orbit in the ecliptic plane, and not the equatorial plane of the tilted planet (*5*). Also, Uranus and Neptune might be too light to have retained a massive enough gaseous disk (*6*). These considerations suggest that an alternative model is needed, to explain at least the origin of the giant planets' innermost satellites.

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Here, we consider a disk of solid material around a planet, similar to Saturn's rings, wherein planetary tides prevent aggregation within the Roche radius r_R (*7*) [supplementary text 1 (SM 1)]. It is known that such a tidal disk will spread (*8*). Thus, the normalized disk lifetime can be defined by $\tau_{disk} = M_{disk}/FT_R$, where F is the mass flow through r_R, T_R is the orbital period at r_R, and $M_{disk} = \pi\Sigma r_R^2$ is the disk's mass (Σ being the surface density). Using a prescription for the viscosity based on self-gravity and mutual collisions (*9*), one finds

$$\tau_{disk} = 0.0425/D^2 \qquad (1)$$

where $D = M_{disk}/M_p$ and M_p is the planet's mass (SM 2.2.1).

As material migrates beyond r_R, new moons form (*10*, *11*). They are then repelled by the tidal disk through resonant angular momentum exchange and migrate outward as they grow. A satellite of mass M orbiting outside a tidal disk experiences a positive gravitational torque (*12*)

$$\Gamma = (32\pi^2/27)q^2\Sigma r_R^4 T_R^{-2}\Delta^{-3} \qquad (2)$$

where $q = M/M_p$, $\Delta = (r - r_R)/r_R$, and r is the orbital radius. Thus, it migrates outward at a rate (SM 2.1)

$$d\Delta/dt = (2^5/3^3)qDT_R^{-1}\Delta^{-3} \qquad (3)$$

The migration rate increases with mass-ratio q and decreases with distance Δ. Based on the

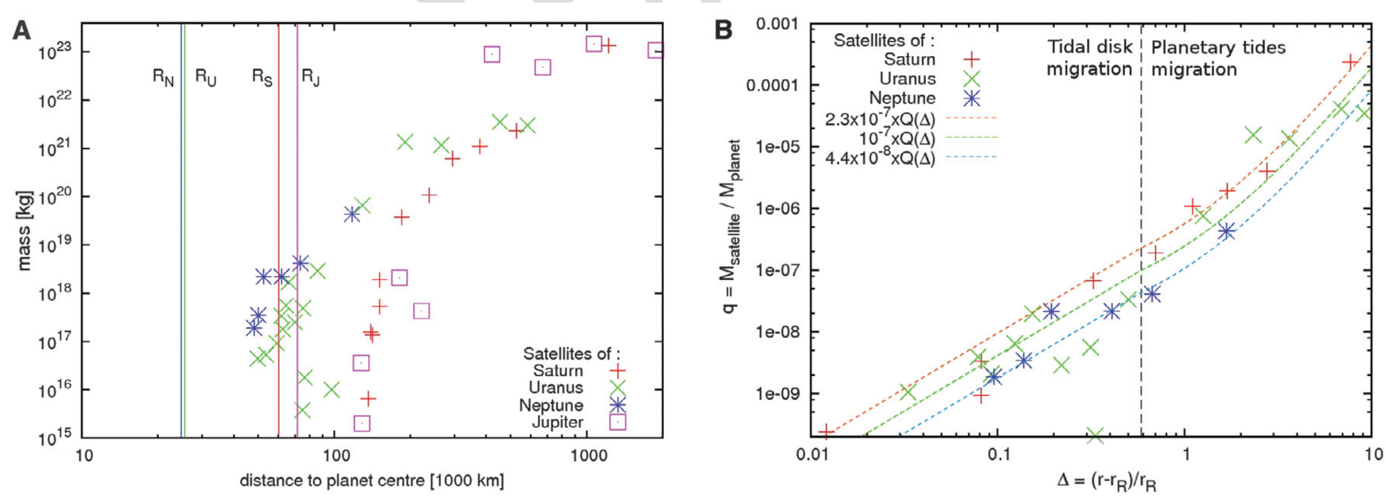

Fig. 1. Distribution of the regular satellites of the giant planets. Saturn: 9 satellites from Pandora to Titan. Uranus: (A) 18 from Cordelia to Oberon; (B) 14 satellites, from Bianca to Oberon (except Cupid and Mab, out of scale). Neptune: Naiad, Thalassa, Despina, Galatea, Larissa, and Proteus. Jupiter: Metis, Adrastea, Amalthea, These, Io, Europa, Ganymede, and Callisto. (**A**) Mass as a function of the orbital radius. The four systems do not extend all the way down to the planetary radius (vertical line), but a pile-up of small satellites is observed at a specific distance (the Roche limit, r_R). The mass increases from zero with the distance to r_R, not to the center of the planets. (**B**) Satellite-to-planet mass ratio q as a function of $\Delta = (r - r_R)/r_R$. The Roche radius for each planet is taken consistently with the mean density of satellites, or with the orbit of the closest one (SM 1). For Saturn, Uranus, and Neptune, r_R = 140,000, 57,300, and 44,000 km, respectively. Short dashed curves: our model for the pyramidal regime $Q(\Delta)$ (Eq. S25, SM 6.3): for $\Delta < \Delta_{2:1}$, $q \propto \Delta^{9/5}$; for $\Delta > \Delta_{2:1}$, $q \propto (\Delta + 1)^{3.9}$, where $\Delta_{2:1} = 0.59$ is marked by the vertical dashed line. Jupiter's system does not fit well and is not shown (SM 7.3).

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restricted three-body problem, we assume that a satellite accretes everything within 2 Hill radii, r_H, from its orbit (*13*, *14*) [$r_H = r(q/3)^{1/3}$]. Thus, as a tidal disk spreads, a competition takes place between accretion and migration. We assume that the satellites do not perturb each other's orbit or the disk (SM 10), that $\Delta \ll 1$, and that D and τ_{disk} (thus F and Σ) are constant. We find from our analytical model (SM) that moon accretion proceeds in three steps, corresponding to three different regimes of accretion.

When the disk starts spreading, a single moon forms at the disk's edge (moon 1). As long as $\Delta < 2r_H/r$, it will directly accrete the material flowing through r_R and grow linearly with time, while migrating outward. This is the "continuous regime" (Fig. 2A, SM 3). Integrating Eq. 3 with
F2 $M = Ft$, one finds that the condition $\Delta < 2r_H/r$ holds until

$$\Delta = \Delta_c = (3/\tau_{disk})^{1/2}$$
$$q = q_c = {\sim}2\tau_{disk}^{-3/2} \qquad (4)$$

Using Eq. 1, one finds $\Delta_c = 8.4D$, occurring after ~10 orbits (SM 3.1).

Then, a second moon forms at r_R (moon 2). Moon 2 migrates away rapidly, approaches moon 1, and is caught by it. Another moon forms, which is also eventually accreted by moon 1, and so on. The growth of moon 1 thus proceeds at the same average rate as before, but step by step through the accretion of moonlets: This is the "discrete regime" (Fig. 2B, SM 4). When $\Delta > \Delta_c + 2r_H/r$, moon 1 is too far away to accrete a newly formed moon before this new moon leaves the continuous regime (SM 4.1). This corresponds to

$$\Delta = \Delta_d = {\sim}3.1\Delta_c \qquad (5)$$

and $q = q_d \sim 20\tau_{disk}^{-3/2} \sim 2200D^3$ as shown in SM 4. Equation 1 implies that this occurs after ~100 orbits. Also, $q_d < 0.1D$ provided $D < 6.7 \times 10^{-3}$. This is always the case around giant planets (see below and SM 7), and it justifies the assumption that D and τ_{disk} are constant. After Δ_d is reached, a third moon appears in the system, and the discrete regime ends.

As moons of fixed mass (produced by the discrete regime) appear successively at a given radius, they migrate outward with decreasing rate, and hence their mutual distance decreases; eventually, they merge. Therefore, moons of double mass are periodically formed, migrate outward, merge again, and so on. Assuming that the satellites do not perturb each other's orbit, mergers occur hierarchically—this is the "pyramidal regime" (SM 6). The moons' masses increase with distance, and an ordered orbital architecture settles. In the region $r < r_{2:1} = 2^{2/3}r_R$, the migration is controlled by the disk's torque (Eq. 3); then the mass-distance relation follows $M \propto \Delta^{1.8}$, and the number density of moons is proportional to $1/\Delta$ (SM 6.1). Consequently, just outside r_R, an accumulation of small moons is expected, consistent with observations (Fig. 1A). Beyond $r_{2:1}$, the migration is controlled by the planet's tides and $M \propto r^{3.9}$ (SM 6.2).

This specific architecture is a testable observational signature of this process. A comparison with today's giant planet systems of regular moons reveals a very good match for Saturn, Uranus, and Neptune (Fig. 1B). Neptune's inner moons (blue stars) match our model (blue dotted line) very well, except for Despina, whose mass is underpredicted by a factor of 3. Uranus' satellites are somewhat more scattered, but the system globally follows our model on the two sides of $r_{2:1}$ (SM 7.4), and the large number of satellites outside r_R appears to be a natural byproduct of the pyramidal regime; however, the four main bodies are not ranked by mass. Saturn's case is especially notable because the eight regular satellites from Pandora to Titan (considering Janus plus Epimetheus as one object) have masses that closely follow our model (red dashed line), through four orders of magnitude in distance and six in mass. Although unlikely, given our present understanding of Saturn's tides (*15*), this result suggests that even Titan might have formed from the spreading of Saturn's initially massive rings. Titan being about 50 times more massive than Rhea could be understood in the frame of our model if the rings were initially very massive ($D \sim 10^{-3}$, see below), favoring the formation of one dominant moon, which migrated fast outward, taking most of the mass. Then, as the mass of the rings decreased, a standard pyramidal regime took place, giving birth to the other moons. However, Titan's tidal age (the time needed to reach its orbit through Saturn's tides) is estimated at about 10 billion years (*11*); thus, Titan's fit with our model may be a coincidence.

Jupiter's system isn't compatible with the pyramidal regime (SM 7.3), suggesting a different formation mechanism, even if the Laplace resonance may have erased the initial configuration. The system of the Galilean moons is satisfactorily explained by the circumplanetary disk models (*1*–*4*). These models may also explain the formation of Saturn's moons Titan and Iapetus but not those of the other satellites. Indeed, the conditions inside Saturn's circumplanetary disc were very different. Jupiter opened up a gap in the protoplanetary nebula early in the history of the solar system, whereas Saturn, which formed later and is less massive, hardly did (*16*).

Our model also predicts the conditions under which one moon is formed rather than numerous ones: Surprisingly, the mass and distance of moon 1 at the end of the discrete regime depend on only one parameter, τ_{disk} (or D). Figure 3 F3
shows the different regimes encountered during the recession of a moon in the (Δ,τ_{disk}) space (SM 8). When τ_{disk} is large, a moon that forms in the discrete regime reaches a low mass and small Δ, as shown by Eq. 5. Thus, the pyramidal regime dominates, where many moons coexist and migrate away. For each of the solar system's planets, the mass of the putative tidal disk is chosen to be about 1.5 times the mass of its current satellite system (SM 7) (Fig. 3). For all the

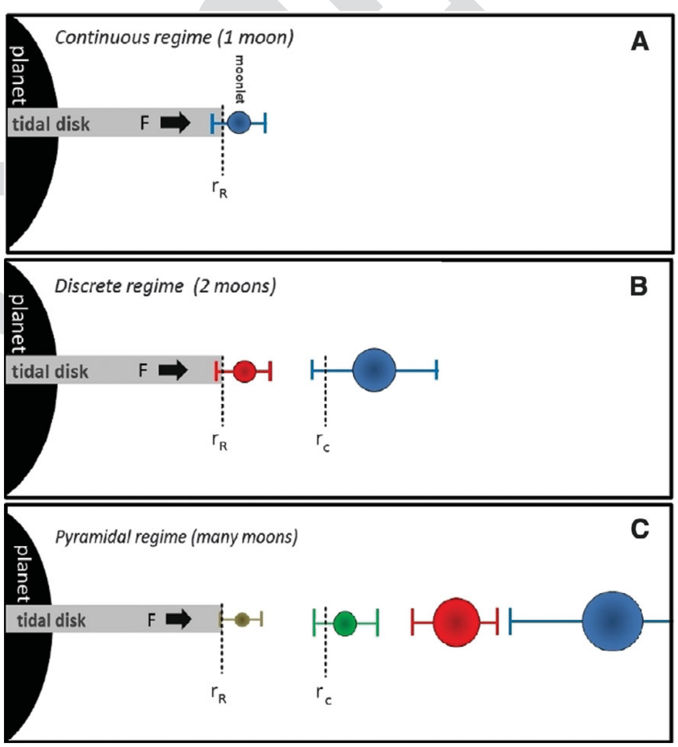

Fig. 2. Sketches of the three accretion regimes, where the accretion regions are defined as $\pm 2r_H$ around a moon's location. The tidal disk is in gray with F denoting the mass flow at the edge. The first moon to form is in blue, the second in red, and the third in green. (**A**) Continuous regime: only one moon is present, directly fed by the disk's mass flow. (**B**) Discrete regime: When the first moon has $r > r_c = r_R(\Delta_c + 1)$, a new moonlet forms (in red). The first moon (blue) continues to grow by accreting these moonlets (red), which are fed by the disk and have masses $\leq M_c$. (**C**) Pyramidal regime: When the first moon has $r - 2r_H > r_c$, several moons can form and grow up to $M \geq M_c$. Moons with $r - 2r_H > r_c$ grow through merging events between moons of similar masses.

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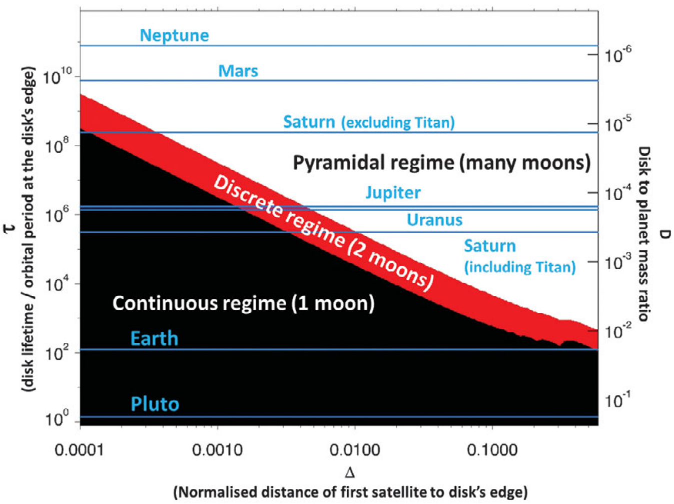

Fig. 3. Zones of the three regimes in the $\Delta - \tau_{disk}$ space obtained through numerical integration of the exact disk's torque (SM 8). The right vertical axis displays the corresponding D to τ_{disk} through Eq. 1. When a disk spreads and forms satellites, a satellite follows a horizontal line (Δ increases and τ_{disk} is constant), from left to right. First, the satellite appears in the continuous regime (black region) where it is fed directly from the disk, while migrating away. Then it enters the discrete regime (red region) where it grows by regularly accreting new moons appearing at the disk's edge, in the black region. Finally, it leaves the discrete regime, and many satellites may form and accrete all together—this is the pyramidal regime (white region). The boundaries between the regions follow exactly our analytical expressions for small Δ (Eqs. 4 and 5). Refined equations for the boundaries are provided in SM 9. The horizontal lines show the path that may have been followed around the solar system's planets. The corresponding values of D were computed in SM 7 and for Jupiter, Saturn, Uranus, and Neptune are 1.6×10^{-4}, 1.3×10^{-5}, 1.7×10^{-4}, and 7.3×10^{-7}, respectively.

giant planets, $D < 2 \times 10^{-4}$, so that $\tau_{disk} > 10^6$, making the pyramidal regime the final outcome, which explains the presence and the distribution of their numerous innermost regular satellites.

Conversely, when τ_{disk} is short, the continuous and discrete regimes are more efficient, and thus a massive satellite is built and migrates to large distances (*17*). This applies to Pluto and Earth, which have only one moon. Our model agrees well with *N*-body numerical simulations of the formation of Charon and the Moon (*10*, *18–20*), but neglects thermodynamical effects. This limitation is investigated in SM 7.1. In this case, where a single moon forms as the disk spreads, D varies strongly with time, making Eqs. 4 and 5 inaccurate. The system can still be solved provided F is constant, which is likely in a disk at thermodynamical equilibrium. The Earth's Moon probably finished its accretion in the discrete regime, allowing the possibility of a short-lived and low-mass companion moon. As the companion approached the proto-Moon, it may have been trapped in a horseshoe orbit, and later impacted the proto-Moon, as was recently suggested to explain the Moon's highlands (*21*).

These results strongly suggest that, like the Moon and Charon, most regular satellites of Saturn, Uranus, and Neptune formed from the spreading of a tidal disk. It may be that only the giant planets' most massive regular satellites (the Galilean moons, Titan, and Iapetus) formed directly from the planet's subnebula (*1–4*). Many models have been proposed for the formation of the giant planets' massive rings. Rings could be remnants of disrupted satellites [either by an impact (*22*, *23*) or by tides (*24*)], an explanation that is favored for Saturn, or remnants from tidally disrupted comets (*23*, *25*), which is more likely for Uranus and Neptune (*23*). Uranus' and Neptune's large inclinations indicate that giant impacts capable of generating massive rings were common on the ice giants during the formation of the solar system (*26*). However, the many uncertainties in the initial conditions of giant planet formation make it hard to conclude how massive rings formed. The way Uranus' and Neptune's massive rings disappeared is also an open question. Viscous spreading by itself would not be efficient enough to make the rings disappear because it becomes increasingly inefficient when the disk loses mass (*8*). Atmospheric gas drag (*22*, *27*), the Yarkvosky effect (*28*), or slow grinding of the rings through meteoritic bombardment (*22*) could all be invoked, but their role is still not well understood. However, our model is compatible with existing ring-formation scenarios, and thus the most common mechanism of satellite formation is likely to be the spreading of a tidal disk surrounding a planet, terrestrial or giant, besides other processes (*1–4*). The structure of the satellite system then depends only on the disk's lifetime.

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