# On the Origins of the Saturnian Moon-Ring System

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**Abstract: We examine a recent proposal [1] concerning the origin of Saturn's rings and inner moons by tidal mass-stripping from the mantle of a differentiated Titan-sized satellite that is lost to the planet. We point out the major issues present in this work itself; the inconsistencies between this work and prior papers by this group [2,3]; and the weaknesses of the underlying satellite formation model (see, e.g., [4-6]). We argue that the origins of the rings advocated in this work should be divorced from the "starved-disk" satellite formation models [2,3]. Indeed, a formation model in which Titan starts out either fully or partially differentiated [7-9] provides a natural framework for the tidal-stripping origin for the rings. Whether such a ring origin is more likely than the alternatives remains to be clarified. In particular, other condensation sequence mechanisms have been offered in the literature that can lead to the formation of ice-rich moons – for Saturn, but not Jupiter – which could then be either collisionally or tidally disrupted to produce the rings [10, 8]. In this regard, it should be noted that Rhea's composition, a satellite which likely formed independently of the rings given its distance from the planet (e.g., [11, 1]), may be similar to that of Mimas, if allowance is made for a somewhat larger porosity in the case of the much smaller Mimas. Thus, Rhea's size and ice-rich composition lessens the need to account for the silicate fraction of the "disrupted moon" that led to the formation of the rings, thereby undercutting the argument in favor of the tidal-stripping scenario. We conclude by investigating the idea that planetary tidal interactions can be simultaneously responsible for differentiating a Titan-sized object and stripping it of its mantle [1].**

We start with the problems with the ring formation scenario as presented in [1]. This study posits that a Titan-sized object is lost due to a combination of slow Type I migration [3] and planetary tides[1]. Yet, the ring itself survives the gas disk and up to the present day, albeit in a depleted state. This claim is vulnerable on at least five grounds: first, because it involves fine-tuning of the gas surface density of the disk, which is an unknown parameter; second, because it assumes that a Titan-like satellite was the last object to migrate inwards; third, because the argument advanced regarding the survival of the ring in the presence of gas is questionable; fourth, because the satellites out to Tethys that are spawned from the massive, primordial ring, as well as Dione and Rhea that are formed independently, exhibit a stochastic compositional component which clouds a straightforward interpretation of the observations; and fifth, because, given the implied ratio of solids to gas and the collisional processes involved, it is difficult to see how MRI can drive disk turbulence in such a scenario, yet the presence of "dead-zones" (e.g., [12,13]) has not been considered[2].

Concerning the first objection, this scenario depends sensitively on the choice for the gas surface density of the disk, which is taken to be $\sigma_g \sim 10$ g/cm$^2$ [1]. Earlier work suggests that the "starved disk" model should be constrained by setting the inflow rate to a value such that the *steady-state* subnebula disk would result in a "snowline" located roughly at the radial position of Ganymede, which is then invoked to explain the compositional gradient of the Galilean satellite system [2]. These authors further assume that the temperature structure of the subnebula disk is dominated by viscous heating due to the presence of global turbulence. However, [1] explicitly reverses this assumption by arguing that the planet's luminosity controls the temperature of the disk and ignoring the contribution due to viscous heating[3]. This switch begs the question of the methodology employed to obtain $\sigma_g$. The difficulty stems from the fact that the compositional gradient argument [2] use for the Galilean satellite system cannot be applied to the Saturnian system. The literature does not clarify this issue beyond stating that $\sigma_g \sim 10$ g/cm$^2$ can produce "Saturnian-like" systems [3]. However, given that in addition to the inflow rate $F_*$, the value for the subnebula turbulence parameter $\alpha$, the value for the size of the circumplanetary disk upon inflow $r_c$, and the ratio of gas to solids of the inflow $f$ are all taken to be free parameters, and that solar nebula planetesimals are neglected[4], it is fair to say that the claim that simulations indicate that $\sigma_g \sim 10$ g/cm$^2$ is ill-founded. Furthermore, hydro simulations have established that the value of $r_c$ used in [1-3] is far too small [4-6][5], which means that there is a mismatch between the angular momentum budget of gas coming through the gap (which [1-3] rely on to form satellites) and that of the satellites themselves (see [4] for further discussion of the implications).

Concerning the second objection, it is useful to consider what happens to other satellites that are located between the Titan-sized object that is lost and the actual Titan that survives. That is to say, what would be the consequence of letting the last object lost be Callisto-sized instead of Titan-sized, for instance? Tidal heating depends on the satellite size. Thus, a presumably undifferentiated Callisto-like satellite might plow through any pre-existing material located inside the Roche-limit of Saturn, depriving the planet of its icy rings. It could

[1]Note that in the low gas surface density regime if planetary tides dominate migration could be outwards.

[2]"Dead-zones" can cause the gas to pile up close to planet. In addition, satellite migration can be affected since large satellites can open gaps in a quiescent disk [8]. At any rate, [2,3] fail to specify the source of the turbulence in their models.

[3][14] provide yet another variant in which the inflow rate is used to calculate the temperature of the Kronian disk. Despite claims to the contrary, [15-17] each provide their own methods at odds with all the others.

[4][1-3] find themselves in the predicament of assuming that the inflow onto the subnebula disk incorporates its full complement of solids $f \sim 10^2$, yet the gas accreting onto the planet is largely free of solids (see [4] for a discussion).

[5][16] claim that the inflow can form a compact disk as assumed by [1-3], but these simulations have artificial boundary conditions; see [4-6] for further discussion.

be argued that adding radiogenic heating would result in a differentiated Callisto-like object, but the reader should recall that the motivation for the protracted, slow-inflow "gas-starved" model is to accrete an undifferentiated Callisto and Titan [2,3,14,18,19]. Since the actual (Jovian) Callisto is likely to receive a greater amount of radiogenic heating than any Saturnian counterpart, it is difficult to see why one might expect Saturnian satellites to be differentiated. In contrast, the SEMM model [7,8] does not face this objection, as satellites in this model accrete faster in the inner disk than they do in the outer disk (see [20] for a concise discussion).

Concerning the third objection, the claim is that the massive primordial ring ($\sigma_{ring} \sim 10^5$ g/cm$^2$) – formed once the icy, secondary moon migrates inside the Roche-limit – can survive against aerodynamic drag for $\sim 10^7$ yrs (see [1] S22). This equation is obtained by treating the ring as a monolithic plate that suffers gas drag at the surface boundary only. This approximation may apply when ring particles orbit in the wake of other particles, analogous to bicyclists riding in a peloton, and when particles are sufficiently large that the gas turbulence does not significantly stir them [21,22]. Assuming that most of the mass (but not necessarily most of the optical depth, though we ignore the distinction here) in this primordial ring is in particles of mass $m_p$ and size $r_p$ large enough to ensure that the velocity dispersion $c \sim \sqrt{2Gm_p/r_p} \sim 1$ m/s keeps the ring gravitationally marginally stable with Toomre parameter $Q_T = \Omega c/(\pi G \sigma_{ring}) \sim 1$, we obtain $r_p \sim 1$ km. Such particles would not be stirred by the gas so that the plate drag formula would apply in the case of a radially extended ring. However, using $\nu \sim 0.46\tau c^2/[2\Omega(1+\tau^2)]$, where $\tau = \pi r_p^2 \sigma_{ring}/m_p \sim 1$, the viscous time is $t_\nu = w^2/\nu \sim 10^5$ yrs, where $w$ is the width of the ring. The spreading rate due to the collisional evolution of the ring including the effects of particle-to-particle self-gravity [23] is given as $t_\nu \sim 10^5$ yrs (see [1] equation 2). Therefore, the ring would spread in a timescale shorter than the gas dissipation timescale of $10^6$ yrs. Ring particles would diffuse outwards out of the Roche-limit and inwards inside the ice boundary line and would be permanently removed from the ring. Thus, the ring mass would deplete while gas is still present. This means that it is inaccurate to use the initial ring surface density in the expression of the timescale for ring survival against aerodynamic gas drag. To the extent that the viscous evolution results in a ring in which particles drag in individually the ring would then decay in a timescale $t_d \sim 10^5$ yrs for $r_p \sim 1$ km (smaller particles would decay faster). Thus, a careful treatment is needed to decide whether the ring would survive gas drag at all. In fairness, the conclusion that the secondary, icy moon migrates inside the Roche-limit while gas is still present is parameter dependent, but this points out the vulnerability of the scenario to a long chain of parameter choices.

Concerning the fourth objection, the argument is that the moons that are spawned by the ring would consist essentially of water ice but that mixing from material originating from outside the rings would increase their rock content relative to that of the rings to some extent [1]. However, the observations do not support such an interpretation. For one thing, this viewpoint might lead one to expect a greater degree of mixing for the outermost moon linked to the rings, but the opposite is observed as Tethys ($\rho = 0.97$ g/cm$^3$; $r = 533$ km) is icier than either Enceladus ($\rho = 1.61$ g/cm$^3$; $r = 252$ km) or Mimas ($\rho = 1.15$ g/cm$^3$; $r = 198$ km). In addition, this interpretation would also lead one to expect a marked compositional contrast with Dione ($\rho = 1.48$ g/cm$^3$; $r = 562$ km) and Rhea ($\rho = 1.23$ g/cm$^3$; $r = 764$ km), which formed farther out and independently of the ring. Of these moons, Rhea is almost certainly too far from Saturn to be linked to the rings (see Fig. 4.18 of [11]), yet only Tethys appears to be icier than Rhea. Lastly, close-in Epimetheus ($\rho = 0.63$ g/cm$^3$; $r = 58.3$ km) and Janus ($\rho = 0.61$ g/cm$^3$; $r = 90.4$ km) have a similar bulk density to far-out Hyperion ($\rho = 0.57$ g/cm$^3$; $r = 135$ km), which once again discourages the interpretation of the observations advocated in [1]. Indeed, the inner satellites of Saturn (inside of Titan) may include a stochastic compositional component due to collisional and tidal (at least for Enceladus) processes deep in the Kronian gravitational potential-well [6,24].

In closing, we test the presumption [1] that tidal heating is likely to differentiate a Titan-like object as it migrates inwards. We use the ACCTHERM code [9] and add energy dissipation due to tides using Maxwell rheology and Newtonian viscosity. We find that the results are sensitive to the initial state following accretion and other model parameters. This is because to melt the satellite tidal dissipation must not only provide the latent heat of fusion but also raise the temperature of the interior of the satellite to the melting point.

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