

ON THE ORIGIN OF THE SATURNIAN SATELLITE SYSTEM: DID IAPETUS FORM IN-SITU?. I. Mosqueira, NASA Ames Research Center/SETI Institute, Moffett Field CA 94035, USA (*mosqueir@cosmic.arc.nasa.gov*), P. R. Estrada, NASA Ames Research Center, Moffett Field CA 94035, USA, (*estrada@cosmic.arc.nasa.gov*).

Current models of planet and satellite formation are marred by our lack of understanding regarding the turbulent state of accretion disks. According to the Rayleigh criterion, Keplerian disks are hydrodynamically stable. Indeed, it has been argued that a carefully designed Taylor-Couette experiment shows stability in the case of positive radial gradients in specific angular momentum even for high-Reynolds numbers [1], in agreement with numerical simulations which consistently show turbulence decay [2]. Other possible sources of turbulence may fail due to low ionization, may decay as the optical depth decreases due to dust coagulation, may involve unrealistic boundary conditions, or result in limited transport. The difficulty stems not only from the degree of turbulence, but also from the kind of turbulence, and whether it may be characterized by an α parameter.

Fortunately, it is possible to construct regular satellite formation models that are not dependent on arbitrary choices for α . One approach is to allow for turbulence decay (which facilitates circumplanetary satellites formation) and resort to gap-opening for satellite survival [3]. The second is to assume sustained turbulence of unknown origin and rely on planetesimal collisional capture from heliocentric orbit [4]. Given the similarities in the bulk properties of the Jovian and Saturnian satellite systems, a unified formation model may be justified. Yet, the differences between the two are as striking as the similarities.

While both the masses and radii of the icy Saturnian moons have been subject to considerable uncertainty, at present the densities of all major Saturnian satellites (Mimas-sized and larger, except for Enceladus) appear to be known with accuracy better than 5% [5]. Taken as a group their densities provide a marked contrast to the density of captured Phoebe ($\rho = 1.6 \text{ g cm}^{-3}$ [5]), which likely reflects their different origin and composition. In the context of a planetesimal capture formation model [4], it is possible to understand the differences between the Jovian and Saturnian satellite systems in terms of collisional processes deep in the planetary potential well. In particular, we explore the possibility that a collision between Titan and a Triton-sized differentiated interloper, (Triton itself likely became captured as a result of a collision with a moon of Neptune [6]) can ultimately account for the disruption of Saturn's pre-existing satellite system, for the accretion of secondary, icy moons (including distant Iapetus; $\rho = 1.11 \pm 0.04 \text{ g cm}^{-3}$ [5]) out of a volatile-rich disk formed in the aftermath of the collision, and for Titan's anomalously large primordial eccentricity $e > 0.03$ (given subsequent tidal circularization).

A possible collisional pathway resulting in a system matching the observed characteristics of the Saturnian satellite system will be discussed. 1) *Impact Between Titan and a Triton-sized Differentiated Interloper*. We start with a pre-existing, well-behaved system of roughly solar-composition satellites, and strike Titan's precursor with a projectile of $m_p \sim 0.1 M_T$

of its mass with a speed of $v_i \sim 10 \text{ km/s}$. 2) *Formation of a Volatile-rich Disk*. Such a collision would result in an eccentric and inclined orbit where the actual eccentricity depends on the collision geometry:

$$e = \frac{m_p}{M_T} \left[4 + \left(\frac{v_i}{v_K} \right)^2 (1 + 3 \cos^2 \theta) - 8 \left(\frac{v_i}{v_K} \right) \cos \theta \right]^{1/2} \quad (1)$$

We find $e \sim 0.3$ for $\theta \sim \pi/2$, where θ is the angle of impact ($\theta = \pi$ for a head-on collision), and v_K is the satellite's orbital velocity, which may be large enough to disrupt the system. We can estimate the amount of mass with sufficient energy to exceed the escape speed v_{esc} of Titan as $f_{esc} = m_{ej}/m_p \approx 0.09 [(v_i/v_{esc})^{1.65} - 1] \sim 0.4$ [7], where m_{ej} is the ejecta mass. This is enough disk mass to account for the inner Saturnian satellites plus Iapetus, but this estimate needs to be validated with numerical simulations. Moreover, one expects that a significant fraction of this mass would be re-accreted by Titan, while some of this mass may drift in due gas drag inward migration. At any rate, for such a collision to result in a volatile-rich disk at least the core of the impactor must wind up in the target (in analogy to Earth's moon-forming impact event [8]). 3) *Eccentricity and Inclination Damping and Accretion of Satellites*. Gas drag would result in the circularization of Titan. The timescale for this is unknown because the gas surface density is unspecified [4]. In any case, dynamical friction with the debris disk with surface density of $\sigma_{solids} \sim 200 \text{ g cm}^{-2}$ may damp Titan's eccentricity and inclination on a timescale of $\tau_{df} \sim 100$ years, but it should be noted that heating of the debris disk and formation of a gap by Titan may decrease the efficiency of this process. The Safronov accretion timescale for a $r \sim 1000 \text{ km}$ satellite is given by $\tau_{acc} \sim \rho_s r / \Omega \sigma_{solids} \sim 10^3$ years, where ρ_s is the satellite density, and Ω is its orbital frequency. 4) *Collisional Removal, Ejection, and the Final Eccentricities of Titan and Iapetus*. The timescale for Titan crossing objects to collide with it is $\tau_{coll} \sim P_s a (v_{esc}/\Omega)^2 / R_H R_s^2 \sim 10^3 - 10^4$ years where a , R_s , and P_s are Titan's semi-major axis, radius and orbital period, and R_H is its Hill radius. The timescale for scattering is

$$\tau_{ej} \sim \frac{0.1}{\Omega} \left(\frac{M_P}{M_T} \right)^2 \sim 10^4 \text{ yrs}, \quad (2)$$

where M_P is Saturn's mass. Given that $\tau_{ej} \sim \tau_{coll} > \tau_{acc}$, it may be possible first to grow, and then scatter Iapetus to its present orbit. Assuming Titan scattered Iapetus, we can obtain an estimate for Titan's final eccentricity using conservation of energy and angular momentum and obtain $e \sim 0.1$. For Iapetus the resulting eccentricity would be $e \gtrsim 0.7$. Given some subsequent tidal circularization, this scenario may be consistent with Titan's present day eccentricity and inclination.

But gas drag would still be needed to circularize Iapetus. To accomplish this task in a timescale of $10^5 - 10^6$ years would require a gas surface density of $10 - 100 \text{ g cm}^{-2}$.

However, this scenario has a number of hurdles to overcome. First, Titan may heat particles in the disk thus lengthening the timescale of accretion of satellites τ_{acc} , or even preventing accretion from taking place. Second, even if an Iapetus' sized satellite does form the chances of scattering are small. Finally, circularizing Iapetus but not Titan might require either fine-tuning unknown disk properties, or resorting to a later, separate event to explain Titan's eccentricity.

In-situ Formation of Iapetus. On the other hand, on the basis of the composition of regular satellites (compared to that of objects such as Pluto-Charon, and captured Triton and Phoebe) a number of workers have argued that the regular satellites of giant planets did not derive the bulk of their material directly from heliocentric orbit [9,10,11,12]. Here we focus on the case of Iapetus because – provided it formed in-situ – this satellite may furnish a more direct test of this hypothesis [12]. Indeed, Iapetus' size and isolation make it difficult to argue in favor of a stochastic compositional component for this satellite.

In the context of our decaying turbulence satellite formation model [3,13], it is possible to process planetesimals either in the distended envelope of the growing giant planet or in the circumplanetary gas disk. A number of processes might result in compositional gradients in such a complex setting, but the connection to actual regular satellite properties is not always straightforward. For this reason, we first attempt to tackle the simpler problem of the melting and vaporization of disk crossers. Our aim is to investigate whether it is possible to increase the ice/rock ratio of satellites by preferential ablation of icy planetesimal fragments that cross the circumplanetary gas disk.

The rate at which energy is transferred to the planetesimal is given by $E \sim C_D \rho v^3 / 4$, where $C_D = 0.44$ is the gas drag coefficient, ρ is the gas density, v is the speed of the planetesimal through the gas, and moderate planetesimal flattening (which increases its cross-section) has been assumed. Ignoring conduction into the interior and ablation, we can obtain an estimate of the surface temperature T_S by balancing this heating and radiative cooling $\varepsilon \sigma_{SB} T_S^4$, where ε is the emissivity, and σ_{SB} is the Stefan-Boltzmann constant. Using parameters from [3,13] appropriate at the location of Iapetus $v \sim 5 \text{ km/s}$ and $\rho = \Sigma / 2H \sim 7 \times 10^{-10} \text{ g cm}^{-3}$, where Σ is the gas surface density and H is the scale-height, we obtain a surface temperature of $T_S \sim [(C_D / 4 \sigma_{SB}) \rho v^3]^{1/4} \sim 600 \text{ K}$, which is sufficient to melt and vaporize icy objects but not rocky objects. In contrast, at Titan ($v \sim 8 \text{ km/s}$, $\rho \sim 3 \times 10^{-7} \text{ g cm}^{-3}$) and Callisto ($v \sim 11 \text{ km/s}$, $\rho \sim 2 \times 10^{-7} \text{ g cm}^{-3}$) the surface temperature can exceed 4000 K, which is enough to melt and vaporize rocky objects as well.

We can estimate the change in radius due to either melting or vaporization due to the net rate of energy input $E - \varepsilon \sigma_{SB} T_S^4$ [14] as the planetesimal crosses the gas disk in a time $t \sim 2H/v$ (ignoring gas drag), and find that the amount of ice melted or vaporized at Iapetus is in the order of meters, whereas

at Titan and Callisto it is up to a kilometer. It should be noted that at Iapetus ($\Sigma \sim 100 \text{ g cm}^{-2}$) meter-sized objects (with density of order unity) traverse a column of gas equal to their mass, whereas at Titan and Callisto ($\Sigma \sim 10^4 \text{ g cm}^{-2}$) the same is true for up to kilometer-sized objects. Hence, ablation of planetesimal fragments may contribute significantly to the bulk of regular satellites provided a significant fraction of the mass resides in fragments with sizes in the kilometer to meter size range.

This calculation pre-supposes the existence of a population of icy and rocky planetesimal fragments $< 1 \text{ km}$. Thus, it must be asked whether planetesimal fragmentation following giant planet formation can result in such a population of objects. Although this issue is beyond the scope of this abstract, we make the following observations. Assuming that most of the mass in the first generation of planetesimals resided in objects $10 - 100 \text{ km}$ in the first $10^5 - 10^6$ years [15], these objects may have incorporated significant amounts of ^{26}Al . If so, depending on their porosity, $\sim 100 \text{ km}$ planetesimals may have differentiated [16] (Phoebe itself may be such an object). While at Jupiter 100 km planetesimals may survive collisional grinding, the longer ejection timescale at Saturn means that objects as large as 100 km may fragment and lead to a population of icy/rocky objects available to ablate through the extended Saturnian gas disk and lead to the formation of Iapetus. Alternatively, it is possible that the fragmentation of 10 km objects at typical collisional speeds of 5 km/s results in partial melting and localized ice/rock separation on sufficiently small scales ($< 1 \text{ km}$), which may ultimately serve to provide a population of small, icy objects to ablate at the location of Iapetus.

A detailed comparison between Rhea and Iapetus may address the question of whether Iapetus formed in-situ or was scattered by Titan. At present, radar data for these two satellites [17] and other compositional issues appear to favor an in-situ formation for Iapetus. Data from the Cassini mission may discriminate between the two scenarios.

This work is supported by the National Research Council, and a NASA PGG grant.

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