The compositions of the regular satellites of Jupiter and Saturn compared to Kuiper Belt Objects. I. Mosqueira, San Jose State University, San Jose CA 95192 (Ignacio.Mosqueira@sjsu.edu)

Given the similarities in the bulk properties of the Jovian and Saturnian satellite systems, a unified formation model is justified. Yet their differences are also striking. There exist only two self-consistent regular satellite formation models [1,2]. These two approaches treat planetesimal dynamics explicitly (which is a model requirement), and also account for the angular momentum budget of the regular satellites. The properties of the regular satellites can be used to discriminated between these two models, and also to link the subnebulae of the giant planets to the solar nebula.

The inner satellites of Jupiter, Io and Europa, are depleted of volatiles either due to the temperature gradient in the subnebula [3,4], collisional processes involving differentiated objects [5], and/or the Laplace resonance. The observed densities of the Saturnian regular satellites are not compatible with solar compositions [6]. The inner satellites of Saturn (inside of Titan) include a stochastic compositional component (e.g., Tethys vs. Enceladus) due to collisional or other processes deep in the kronian gravitational-potential well; however, such an argument can not be applied to faraway and isolated Iapetus (but see below for a possible collisional scattering origin for Iapetus [7]). The bulk compositional and size similarities between Ganymede, Callisto and Titan argue strongly in favor of non-stochastic processes for these satellites. Thus, the non-stochastic masses and densities of the large, outer regular satellites of Jupiter and Saturn (Ganymede, Callisto, Titan and Iapetus) provide the most directly useful constraints for satellite formation models.

Observations indicate that Kuiper Belt Objects (KBOs) are of different composition than the regular satellites of Jupiter and Saturn. Indeed the largest KBOs, Triton, Eris and Pluto-Charon have densities that imply a rock/water-ice ratio of ~ 70/30, which has long been interpreted as a direct consequence of the sequestration of oxygen in uncondensed CO. In contrast, self-compression leads to rock/water-ice ratios of ~50/50 in the case of Ganymede, Titan and Callisto. Furthermore, Iapetus' density indicates an even lower rock/water-ice ratio of ~ 20/80. Therefore, the key issues here are both the relative depletion of rock in Iapetus compared to other non-stochastic regular satellites and outer solar nebula objects, and the overall enrichment in water-ice of the large regular satellites compared to the large KBOs.

It could be argued that Triton, Eris, and Pluto-Charon may have experienced impact histories which could have increased their bulk densities. If we attempt to build the large KBOs from smaller ones, then we might arrive at lower bulk densities, as indicated by the densities of KBOs with diameters < 1000 km [8]. **However, the collisions needed to significantly alter the compositions of the large KBOs are unfeasible [9]**. In addition, smaller KBOs cannot be used to infer the composition of the solar nebula because: the error bars for these objects are generally large; objects of these sizes are known to be porous; the amount of mass represented is very small compared to the large KBOs; and objects of these sizes are compositionally stochastic. Indeed some of the small KBOs are likely to come from the mantle of differentiated larger objects, so they can hardly be used to constrain the composition of the nebula disk. **In fact our knowledge of the masses of KBOs largely depends on the presence of satellites, which implies that for small objects collisional fragments are likely overrepresented. As a result, small KBOs do not provide a fair sample of solar nebula composition**s.

Alternatively, it could be argued that the accretion process itself (as opposed to individual impacts) may account for the observations of the rock-rich large KBOs. However, such accretional processes would also apply to the ice rich regular satellites. **Thus, the simplest explanation of the observations remains that the subnebulae of Jupiter and Saturn are enriched in water-ice compared to the outer solar nebula.** The contrast between icy Iapetus and rocky Phoebe reinforces the interpretation of Phoebe as a captured moon [10]. Allowing for moderate porosity in the case of Phoebe its rock/water-ice fraction is larger than those of Ganymede, Callisto and Titan.

We explain the observed enrichment of water-ice by the delivery of fractionated planetesimal fragments to the circumplanetary disks of Jupiter and Saturn [11]. The disk and the giant planet envelope are both enriched in high-Z material for the same reason, i.e., due to planetesimal ablation in a gaseous medium. Therefore the overall mass delivery mechanism advanced here should be seen as a natural extension of the process that is widely believed to account for the Galileo probe observation of a 3-4 enhancement in the high-Z content of Jupiter's envelope [12]. **This model naturally accounts both for the overall water-ice enrichment of the subnebulae, and also the compositional gradient between Titan and Iapetus [11].**

In the context of a planetesimal capture formation model [2], we attempt to understand the differences between the Jovian and Saturnian satellite systems in terms of collisional processes deep in the planetary potential well. In particular, [7] consider the possibility that a collision between Titan and a Triton-sized differentiated interloper can ultimately account for the disruption of Saturn's pre-existing satellite system, for the accretion of secondary, icy moons (including distant Iapetus) out of a volatile-rich disk formed in the aftermath of the collision, and for Titan's anomalously large primordial eccentricity (given subsequent tidal circularization).

We consider a possible collisional pathway resulting in a system matching the observed characteristics of the Saturnian satellite system (Fig. by P. Estrada based on the scenario of [7]). *1) Impact Between Titan and a Triton-sized Differentiated Interloper. We start with a pre-existing regular satellite system, including primordial satellite Mylinus (as coined by P. Estrada). 2) Formation of a Volatile-rich Disk. For such a collision to result in a volatile-rich disk the core of the impactor must wind up in the target. 3) Eccentricity and Inclination Damping and Accretion of Satellites. The collisions would result in a eccentric and inclined Titan. Interactions with the gas and debris disks then damp Titan's eccentricity and inclination. Secondary satellites, including Hyperion and Iapetus, accrete in such a volatile-rich disk. 4) Collisional Removal, Ejection, and the Final Eccentricities of Titan and Iapetus. Titan then re-accretes most of the collisional debris and scatters Iapetus into a distant orbit. Gas drag circularizes Iapetus to its current low eccentricity (but not Titan's eccentricity). Tidal damping circularizes Titan on a longer timescale, resulting in its present-day inclination and eccentricity.*

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 secondary satellites, 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 requires either fine-tuning unknown disk properties, or resorting to a later, separate event to explain Titan's eccentricity. **In addition, such a scenario does not address the issue of the bulk properties of the regular satellites. Hence the former ablation-based scenario is to be favored.**

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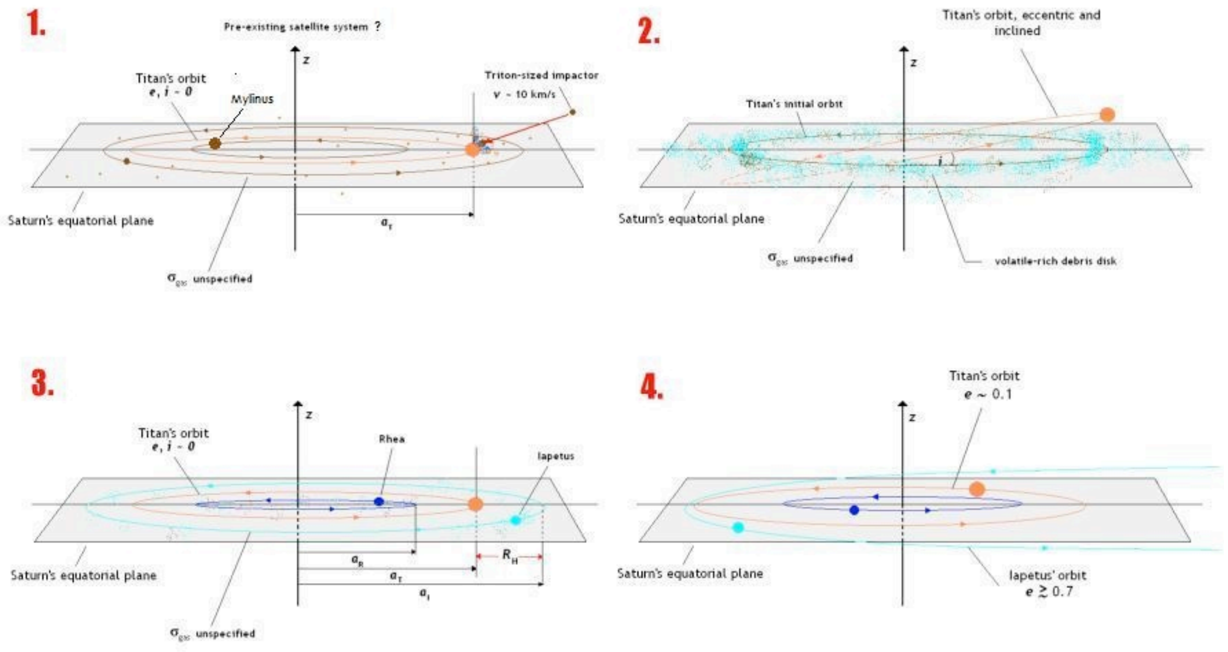
References: [1] Mosqueira and Estrada, 2003a,b. Icarus 163, 198-231 and 232-255 [2] Estrada and Mosqueira, 2006. Icarus 181, 486-509 [3] Pollack et al., 1976. Icarus 29, 35-48 [4] Lunine and Stevenson, 1982. Icarus 52, 14-39 [5] Shoemaker, 1984. Kuiper Prize Lecture [6] Wong et al., 2008. Mineralogy and Geochemistry 68, 219-246 [7] Mosqueira and Estrada, 2005. 36th LPSC, 1951 [8] Brown, 2012. AREPS 40, 467-494 [9] Brown, 2013. ApJ 778, L-34-39 [10] Johnson and Lunine, 2005. Nature 435, 69-71 [11] Mosqueira et al., 2010. Icarus 207, 448-460 [12] Atreya et al., 1999. PSS, 47, 1243-1262.



Mosqueira and Estrada (2005)