**PLANETESIMAL BREAK-UP AND THE FEEDING OF SOLIDS TO THE SATELLITE DISK: CONSEQUENCES FOR THE FORMATION TIMESCALE AND COMPOSITION OF THE SATELLITES OF JUPITER AND SATURN.**

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)*.

In order to create a coherent scenario of satellite formation, the source of the solids (rock-metal and ice) that will eventually make up the satellites must be considered. While it is customary to use a solar composition mixture with a gas/solids mass ratio of $\sim 100$ [1], at the tail end of the formation of the giant planet (when satellite formation is thought to have taken place) the fraction of solids entrained in the gas (particles with sizes lower than the decoupling size $\sim 1$ m for typical nebula parameters) is likely to be significantly lower than cosmic. In particular, in the core accretion model of giant planet formation one expects low dust and rubble content at late times [2] due to particle coagulation leading to a collisional distribution of particle sizes with most of the mass residing in objects 1 km or larger [3], which are not coupled to the gas and whose dynamics must be followed independently. As a result, flow of gas into circumplanetary orbits is not sufficient to constrain the mass available to form satellites.

It is possible to consider a gas-free model of satellite formation such that the satellite mass derives from the feeding of Sun-orbiting planetesimals into circumplanetary orbits. However, it is not clear that a model in which satellites are formed by material sporadically fed into the system would lead to the observed prograde angular momentum of the giant planet satellite systems (other than Neptune's; note that Triton is very likely a captured object [4]). Moreover, there are a number of observations that strongly suggest that gas was present during the formation of the satellites of the giant planets.

The concentration of rock-ice to gas in the subnebula may in fact depend on the ability of the protoplanet to disturb the orbits of planetesimals situated within a few AU of its orbit into ones that crossed it. One expects that in a timescale of a few million years virtually all the planetesimals located in the outer solar system would have their orbits perturbed into giant planet crossing orbits [5]. What happens to such a planetesimal depends on the size of the planet at the time of crossing. If the giant planet's envelope filled a fraction of its Hill radius, then the distended atmosphere would have greatly increased the planet's cross-section [6, 7]. Hence, early arriving planetesimals (before envelope collapse) may dissolve and become well-mixed (due to convection during envelope collapse) in the envelope of the giant planets [8]. Following envelope collapse, a circumplanetary disk may have formed with condensable content perhaps enhanced by a factor of 3-4 from cosmic proportion as indicated by the high-Z enhancement of the giant planet atmospheres.

On the other hand, late arriving planetesimals may have been scattered to further out regions of the solar system. However, it is possible that late arriving planetesimals provided a source of solids to the dense circumplanetary disk. To check this possibility, we must first constrain the gas surface density of the satellite disk. At present, it is still useful to be guided by "minimum mass" models. Given that satellite migration is likely, the question remains how to distribute the mass of solids within the disk. We argue that the subnebula accretion disk for Jupiter and Saturn should be divided into two components: the first extending outside (but perhaps close to) the centrifugal radius located at $\sim R_H/48$, and the second from there out to the location of the innermost irregular satellites at $\sim R_H/5$, where $R_H$ is the Hill radius of the primary. If we use a minimum mass model with a $3-4$ enhanced concentration of solids with respect to solar composition to estimate the gas surface density of the Jovian and Saturnian subnebulae, we obtain $10^4 - 10^5$ g/cm$^2$ (which is also consistent with the gas surface density for Ganymede and Titan to open a gap [9, 10]). Then a planetesimal of density $\sim 1$ g/cm$^3$ passing through the disk will encounter a gas column equal to its mass if its radius is in the range of $0.1 - 1$ km. Thus, such a planetesimal may deposit a significant fraction of its mass in the gas disk. Lower surface densities (corresponding to farther locations in the disk) or larger planetesimals might lead to ablation and partial deposition of condensable materials in the satellite disk.

This mechanism has several potentially important consequences for the process of satellite formation. First, it means that the delivery of solids to the disk may have taken place over a timescale as long as the timescale to scatter planetesimals in the outer solar system $\sim 10^6$ years [5], provided that the subnebula remained dense for that long (which would imply a weakly turbulent subnebula). By contrast, planetesimals that dissolve in the collapsing envelope of the giant planet would have been delivered on a much shorter timescale given by the envelope collapse time. Second, planetesimal ablation and/or preferential break-up of icy objects may enhance the volatile content of regions of the disk far from the planet. A similar mechanism may also apply to planetesimals captured by the planet's envelope provided convective mixing does not encompass the entire envelope during collapse. Third, continued planetesimal feeding may have further enhanced the concentration of solids in the satellite disk.

Measurements of Callisto's gravity by the Galileo spacecraft indicate that the distribution of mass is less centrally condensed in Callisto than in Ganymede. This is likely to mean that Callisto formed in long timescale of $\sim 10^6$ years. We argue that there are two possible reasons for this long formation timescale. First, satellite embryos situated between Callisto and the irregular satellites would have taken as long as $10^6$ years to migrate inwards by gas drag into Callisto's feeding zone [11]. Second, it is also possible that the late delivery of solids to the disk lengthened Callisto's formation timescale. To check this possibility, we will attempt to estimate the total mass that could have been deposited by planetesimals passing through the disk.

In light of the similarities in sizes and densities between Ganymede, Callisto and Titan it is fair to ask whether Titan can be expected to be more like Ganymede or more like Callisto in its degree of differentiation. Though measured in planetary radii Titan is located between Callisto and Ganymede, in terms of Hill radii of the primary the association is much closer to Ganymede. This leads us to expect that (unlike Callisto) Titan formed in the inner disk (inside the centrifugal radius) in $< 10^5$ years, unless the delivery of solids to the satellite disk lasted longer than $10^5$ years. This timescale is too short for the heat generated by accretion to be radiated away, so Titan may be fully differentiated if it derived most of its mass from solids delivered to the disk by the collapse of the giant planet's envelope.

On the other hand, both Callisto and Titan are likely to have received significant amounts of volatile-rich materials from the extended portion of the disk in the late stages of their accretion brought to their feeding zones by gas drag. Furthermore, we argue that Iapetus itself is too volatile-rich to have been formed by solids accreted directly from heliocentric orbit.

**References** [1] Pollack, J. B., D. Hollenbach, S. Beckwith, D. P. Simonelli, T. Roush, and W. Fong 1994. Composition and radiative properties of grains in molecular clouds and accretion disks. *Astrophys. J.* **421**, pp. 615-639. [2] Mizuno, H., K. Nakazawa, and C. Hayashi 1978. Instability of a gaseous envelope surrounding a planetary core and formation of giant planets. *Progress of Theoretical Physics* **60**, pp. 699-710. [3] Weidenschilling, S. 1997. The origin of comets in the solar nebula: A unified model. *Icarus* **127**, pp. 290-306. [4] Goldreich, P., N. Murray, P. Y. Longaretti, and D. Banfield 1989. Neptune's story. *Science* **245**, pp. 500-504. [5] Gladman, B., and M. Duncan 1990. On the fates of minor bodies in the outer solar system. *Astron. J.* **100**, pp. 1680-1693. [6] Bodenheimer, P., and J. B. Pollack 1986. Calculations of the accretion and evolution of the giant planets: The effects of solid cores. *Icarus* **67**, pp. 391-408. [7] Pollack, J. B., O. Hubickyj, P. Bodenheimer, J. J. Lissauer, M. Podolak, and Y. Greenzweig 1996. Formation of the giant planets by concurrent accretion of solids and gas. *Icarus* **124**, pp. 62-85. [8] Pollack, J. B., M. Podolak, P. Bodenheimer, and B. Christofferson. Planetesimal dissolution in the envelopes of the forming, giant planets. *Icarus* **67**, pp. 409-443. [9] Mosqueira I., and P. R. Estrada 2003. Formation of regular satellites of giant planets in an extended gaseous nebula II: Satellite migration and survival. *Icarus*, submitted. [10] Estrada, P. R., and I. Mosqueira 2003. Gap-opening, disk clearing and the survival of the regular satellites of Jupiter and Saturn. *This conference*. [11] Mosqueira I, and P. R. Estrada 2003. Formation of the regular satellites of giant planets in an extended gaseous nebula I: Subnebula model and accretion of satellites. *Icarus*, submitted.