A GAS-POOR PLANETESIMAL FEEDING MODEL FOR THE FORMATION OF GIANT PLANET SATELLITE SYSTEMS: CONSEQUENCES FOR THE ATMOSPHERE OF TITAN.

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Given our presently inadequate understanding of the turbulent state of the solar and planetary nebulae, we believe the way to make progress in satellite formation is to consider two-end member models that avoid over-reliance on specific choices of the turbulence (α), which is essentially a free parameter. The first end member model [1,2] postulates turbulence decay once giant planet accretion ends. If so, Keplerian disks must eventually pass through quiescent phases, so that the survival of satellites (and planets) ultimately hinges on gap-opening. In this scenario, the criterion for gap-opening itself sets the value for the gas surface density of the satellite disk [2].

In the second end member model [3,4], which will be the focus of this abstract, we assume that steady hydrodynamic turbulence is sufficiently strong to cause the evolution of the circumplanetary gas disk on a shorter timescale than that for satellite accretion. This approach uses steady turbulence to remove the gas from the circumplanetary disk but not to fine-tune conditions of the subnebular environment. Giant planet satellite formation is then understood in terms of planetesimal dynamics that are largely uncoupled from the gas with the gas surface density left unspecified. However, we do allow for the presence of some gas to help explain the observations. This second of the two-end member models thus constitutes a *gas-poor* model, where satellites form in a manner somewhat analogous to the terrestrial planets.

Some of the plausible features of this model (see Figure 1) are: (1) late-arriving planetesimals colliding within the vicinity of the giant planet may create a disk of prograde and retrograde objects extending out to as far as $\sim R_H/2$ [5,6], where R_H is the Hill radius of the giant planet. We initially assume a power-law mass distribution of planetesimals $n(m) \propto m^{-q}$ with an exponent $q = 11/6$ (see footnote 2) characteristic for a fragmented population [6]; (2) the net specific angular momentum $\langle \ell_z \rangle$ of the circumplanetary swarm is initially very small; (3) close to the planet, hypervelocity impacts can ultimately lead to a variety of outcomes (*i.e.*, Jovian-like versus Saturnian-like satellite systems); (4) once the density of solids in the swarm becomes sufficiently large, the removal of material from the outer disk is balanced by planetesimal capture by larger swarm particles. We rely on fragmentation to decrease the sizes of incoming planetesimals, but not to capture them into the swarm. Excluding satellite embryos, at any given time the disk mass is less than a galilean satellite ($\sim 10^{26}$ g); (5) the satellite formation timescale of $10^5 - 10^6$ years (presumably consistent with Callisto's partially differentiated state [7]) is controlled by the feeding of planetesimals onto the circumplanetary disk [8]. We first construct a model for Jovian system in which the distribution of satellite density with distance from the primary is quite uniform, and then adapt and draw conclusions for the Saturnian case.

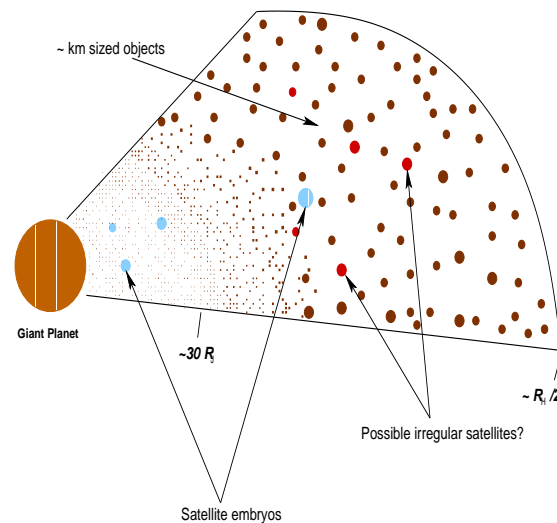There are several outstanding issues that this model must

Figure 1: Graphic representation of some of the characteristics of the circumplanetary swarm from which the satellites of the giant planets will eventually form.

address in order to provide a viable alternative to the model of [1,2]. In particular, one must demonstrate that it is possible to deliver enough mass and angular momentum to the circumplanetary disk to form the regular satellites. From point (2) above, the net angular momentum of the circumplanetary swarm, which will determine the size of the disk from which the satellites will accrete, can be estimated from $\langle \ell_z \rangle = \int \ell_z \Phi(\ell_z) d\ell_z / \int \Phi(\ell_z) d\ell_z$ where $\Phi(\ell_z)$ is a distribution function that describes the accretion of mass and angular momentum [9]. We will show that the size of the disk can be large enough provided that most of the mass that goes into *making* the satellites originated from the outermost regions of the planet's feeding zone. Using a distribution of semi-major axes depleted inside an annulus of width $\sim 2R_H$ centered on the planet, we find

$$\langle \ell_z \rangle \sim 0.36 \Omega R_H^2 \rightarrow R_D = \frac{\langle \ell_z \rangle^2}{GM_J} \sim 30 R_J. \quad (1)$$

Point (5) above provides another constraint given that an accretion time $\tau_{acc} \sim \rho_C r_C / \Omega \sigma_D \sim 10^5 - 10^6$ years implies an inner disk mass (excluding embryos) of

$$M_D \sim \frac{P_C}{\tau_{acc}} \left(\frac{\pi \rho_C}{3} \right)^{2/3} \left(\frac{M_C}{4} \right)^{1/3} R_D^2 << M_C, \quad (2)$$

where M_C, ρ_C, and P_C are the mass, density, and orbital period of Callisto. This yields a surface density of solids $\sigma_D \sim 10 - 100$ g cm^{-2}. In the outer disk where the bulk of

material is captured, a mass M_D must be delivered to the inner disk and also replenished to the swarm in a "collisional cycle" $\tau_{coll} \sim P_2/\tau_{z2}$. This provides a constraint on the optical depth[1] τ_{z2} in the outer disk

$$\tau_{z2} = \frac{3\sigma_2}{4\rho_s r_2} \sim \frac{P_2}{\tau_{acc}}\frac{M_T}{M_D} \sim 5 \times 10^{-4}, \qquad (3)$$

where quantities with subscript "2" refer to the outer disk, ρ_s is the satellitesimal density, r_2 is the cutoff size of the distribution of swarm pariticles, and M_T is the final mass of the system. The surface density needed in the outer disk is $\sigma_2 \sim 100$ g cm^{-2}. Hence, for Jupiter, a constant surface density (solids) disk may satisfy the system constraints.

Given these assumptions, we can analytically estimate the amount of mass deposition per unit time into the circumplanetary swarm $\dot{M}$ using a mass inflow rate I and probability of capture p [5]

$$\dot{M} = 2\pi \int I(R)p(R)R\,dR$$
$$I(R) = \rho_1 v_1 \tau_{z2}(r_2/r_1)^{1/2}(\tau_{z2} - \ln\tau_{z2}), \qquad (4)$$

where ρ_1, v_1, and r_1 are the planetesimal volume density, mean velocity, and cutoff size (quantities with subscript "1" refer to the solar nebula). During each collisional cycle, we require a mass $\sim \dot{M} \times \tau_{coll}$ be provided to the inner disk. The total mass delivered over $\sim 10^5$ years for a reasonable choice of parameters is $\sim 10^{26}$ g [3,10]. However, a caveat here is that the the power-law index q, and the upper size cutoff of the circumplanetary swarm r_2 are not well constrained at this time[2]. Furthermore, this calculation does not take into account the clearing of Jupiter's feeding zone in $\sim 10^5$ years (which may be replenished with sufficiently small particles).

Applying this approach for Saturn, we find that the gas-poor planetesimal model may be consistent with the mass and angular momentum of Titan. However, low density Iapetus is difficult to reconcile. If Iapetus formed at its present location, we would expect it to have a density like that of Phoebe [4], because the angular momentum of material fed from heliocentric orbit strongly implies that Iapetus (like Callisto) should be of roughly solar composition. A plausible scenario is that Iapetus formed closer in [11,12].

Ar/N$_2$ in Titan's atmosphere: The Galileo probe found that the heavy volatile element global abundances, excluding neon and oxygen, are about 3 times solar [13,14]. At this time there are two approaches in trying to account for this observation. The first idea relies on delivery of volatiles that were trapped in amorphous ice and then incorporated in planetesimals. This approach, which is based on laboratory work [15], initially led to the expectation that, since planetesimals forming near the snowline (taken by some models to be located at $3 - 5$ AU) likely dominated the delivery of heavy elements to planets forming at that location, Jupiter might not be enhanced in

volatile elements such as Ar that condense at much lower temperatures < 30 K. It is important to note, however, that to form the clathrate of Ar, the model of [16] requires a very low solar nebula temperature $T \sim 36$ K. Since even passive disk models of T Tauri stars [17,18] may be too warm at the location of Jupiter for the incorporation of Ar into planetesimals, it is difficult to explain why there is any enrichment of Ar in either model.

However, it cannot be assumed that material condenses from a cooling protoplanetary nebula at its solar abundance and remains in place. Significant radial migration of solids will take place. Indeed there is compelling observational evidence that disks around T Tauri stars can be ~ 100 AU or more [19,20]. Furthermore, some gas disks around young stars show flat density distributions [21,22], implying that a significant fraction of the mass of the disk is located at large distances from the star. Since an ice grain may retain its amorphous state for the lifetime of the nebula ($\sim 10^7$ years) provided the temperature is < 85 K [23], it may be possible for planetesimals that trapped argon *either* as clathrate or in amorphous ice in cold regions of the disk to preserve them as they migrate to warmer regions. If so, our planetesimal collisional capture formation model would appear to imply Ar/N$_2 \sim 0.06$ [24] and that the molecular nitrogen in Titan's atmosphere was delivered as trapped N_2. However, before such a conclusion can be reached one must first gain an understanding of the consequences of planetesimal collisional grinding on trapped volatiles.

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[1]Note here that the optical depth is defined by the largest particle size, which captures the bulk of the mass for our chosen q.

[2]For simplicity, we have assumed that the power-law exponent for both the planetesimal mass distribution and satellitesimal distribution are both that of fragmented populations, *i.e.* $q_1 = q_2 = q = 11/6$. Most of the mass remains in the largest particles.