GAP-OPENING, DISK CLEARING AND THE SURVIVAL OF THE REGULAR SATELLITES OF JUPITER AND SATURN.

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We can estimate the timescale for giant planet gap opening by calculating the angular momentum L_Δ in an annulus of half-width Δ. Given the planetary torque on this annulus $\dot{L}_T$, the timescale for gap opening is given by $\tau_{gap} \approx L_\Delta/\dot{L}_T$. An analytical estimate for the gap opening timescale can be obtained using the tidal torque formula [1]

$$\dot{L}_T = 0.23 \left(\frac{M_P}{M_\odot}\right)^2 \Sigma a^4 \Omega^2 \left(\frac{a}{\Delta}\right)^3, \tag{1}$$

where the planetary feeding zone Δ must be larger than the scale-height of the nebula H, and the semi-major axis of the secondary is a. Assuming a constant gas surface density Σ, the angular momentum the planet must add/remove from the annulus of half-width $\pm\Delta$ in order to open up a gap is given by

$$L_\Delta = 2\pi\Sigma a^3 (GM_\odot/a^3)^{1/2} \times$$
$$\int_0^{\pm\Delta} \left[\left(1 \pm \frac{\Delta}{a}\right)^{1/2} - \left(1 + \frac{x}{a}\right)^{1/2}\right]\left(1 + \frac{x}{a}\right) dx, \tag{2}$$

which can be written as

$$L_\Delta = \pi\Sigma\Omega a^4 \left[\frac{1}{5}\left(1 \pm \frac{\Delta}{a}\right)^{5/2} - \left(1 \pm \frac{\Delta}{a}\right)^{1/2} + \frac{4}{5}\right]. \tag{3}$$

Then expanding to second order in Δ/a, we find

$$L_\Delta \approx \frac{1}{2}\pi\Sigma\Omega a^2 \Delta^2. \tag{4}$$

The gap opening time is then given by $\tau_{gap} \approx (\Delta/a)^5 P/q^2$, where $q = M_P/M_\odot$ is the mass ratio of the secondary to the primary [2]. Unless Δ is several times the planet's Hill radius, accretion onto the planet will continue. For some nebula models [3] gap-opening will fail to stop the accretion of a Jupiter mass ($1M_J$) giant planet. However, the above conclusion depends on the strength of the assumed turbulent viscosity of the nebula. In any case, it is clear that the relevant size of the annulus Δ has to be large compared to the Roche-lobe of the planet in order to lower the mass rate accreted onto the planet. Using $\Delta \sim 0.2a_J$ (which is about three times larger than the Hill radius for Jupiter), one obtains $\tau_{gap} \sim 380P$, where P is the period of Jupiter's orbit. This estimate is similar to the numerical value $\tau_{gap} \sim 320\,P \sim 4 \times 10^3$ years [2].

In the context of the satellites we are more interested in stalling inward migration than we are in ending accretion. We expect that at least the largest satellites truncated the gas disk in which they were formed. In particular Io, Ganymede and Titan may have been able to open a gap at their present locations for a gas surface density of $10^4 - 10^5$ g/cm^2, depending on the details of the damping of acoustic waves [4], which may be consistent with a minimum mass model whose solids concentration is enhanced by a factor of $3 - 4$ with respect to solar composition. Given weak Type II migration [5], gap-opening may explain satellite survival.

Several workers [6, 7] discuss a process by which the gas in between two giant planets may be cleared by the action of planetary torques, which may lead to subsequent evolution of the planets into resonant orbits as the gas disk evolves. By analogy, we can obtain an estimate of the time τ_{dis} it would take for gas dissipation between Io and Ganymede by finding the location a_{dis} inside of Ganymede and outside of Io such that both Io and Ganymede will open a gap extending to this same position in the same amount of time. Using Eqs. (1) and (3) we obtain $a_{dis} \approx 9R_J$ and $\tau_{dis} \approx 1 \times 10^5$ yrs (for the sake of comparison, we note that an equivalent calculation for Jupiter and Saturn yields a timescale of $\sim 5 \times 10^5$ years). This timescale is considerably shorter than the planetary cooling time $\sim 10^6$ years [8]. Hence, the gas disk between Io and Ganymede may dissipate before the water content in the disk has a chance to condense. It is also tempting to ascribe the resonances of Io, Europa and Ganymede to the aforementioned process of gap opening followed by disk evolution; however, for the Galilean satellites it is more likely that the resonant configuration is due to gas drag capture and/or tidal evolution (significant disk evolution might lead to Type II migration and result in the loss of the satellites, though there may be ways around this).

However, the above is a very simplified, somewhat erroneous, view of gap-opening and a number of important corrections must be taken into account. In particular, it is only recently that the theory of disk-companion interactions [9] yields migration rates due to the gas tidal torque that are in agreement with numerical simulations [10, 11] and up to an order of magnitude slower than previous estimates [12]. Also, for a weakly turbulent disk, the gap size is controlled primarily by the damping length of acoustic waves launched by the secondary at Lindblad resonances, which in turn depends on whether the waves are 2-D [13] or 3-D [14]. At least for small azimuthal wavenumbers this damping length is of the order of the radial location of the Lindblad resonance [15]. This may have important consequences for disk dispersal in satellite systems. In the case of Jupiter, it means that the inner Galilean satellites may have jointly opened a gap. On the other hand, in Saturn's system the satellites inside of Titan are probably too small to have opened gaps in the gas disk at the time of their formation; but the possibility exists that, by effectively clearing the gas disk inside its own orbit, Titan may have allowed smaller satellites to survive, depending on whether Titan can clear the disk in a timescale comparable to the migration rates due to gas drag and gas tidal torque for these objects.

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