ASPECTS OF ACCRETION IN A CIRCUMPLANETARY NEBULA, S.J. Weidenschilling, Planetary Science Institute, Tucson, Az. 85719

The regular satellite systems of Jupiter and Saturn presumably formed in circumplanetary nebulae (CN's), small-scale analogs of the solar nebula. These may have formed during collapse of giant gaseous protoplanets or accretion of gas by massive protoplanetary cores (1,2). For the solar nebula, at least a minimum mass can be estimated by adding the cosmic complement of H and He to the planets (3). The properties of a CN are more speculative, since its heavy element content may have been depleted by prior formation of a protoplanetary core, or augmented by capture of planetesimals from heliocentric orbits. Still, this approach provides a zero-order model which is useful in suggesting possibly significant differences between heliocentric and circumplanetary environment.

A model jovian nebula is constricted by augmenting the Galilean satellites with H and He, in orbital zones defined as in (3). Its properties are listed in Table I. The most striking difference from a minimal-mass solar nebula is the surface density, which is greater by several orders of magnitude. This produces pressures in the central plane which exceed one bar within Europa's distance. Plausible temperatures would allow existence of a stable liquid $H_2O - NH_3$ phase in a substantial region of the jovian nebula.

The high gas density causes solid bodies to be strongly affected by aerodynamic drag. The mean free path of gas molecules is ~ $10^{-3} - 10^{-5}$ cm, so even small particles are in the continuum (Stokes) flow regime. The timescale for settling to the central plane is ~ $(1/s^2)$ yr, where s is the particle radius in cm. This is in contrast to the solar nebula, where mean free path is ~ $1 - 10^2$ cm; the free-molecular (Epstein) flow regime yields settling on a timescale ~ $(10^3/s)$ yr. If fine dust is present in the CN, its slow settling may allow high opacity and a steep (~ $1/r$) temperature gradient to persist for a significant time. However, the $1/s^2$ dependence means that larger bodies will sink to the central plane much more rapidly than in the solar nebula. If colliding particles can coagulate, the dominant growth mechanism is sweepup of small bodies by larger ones, due to differential setting velocities. Simultaneous coagulation and setting in a jovian nebula has been simulated numerically, using a variant of the method described in (4). If solids are initially present solely as micron-sized dust, meter-sized bodies accrete, and reach the central plane, on a timescale of a few days.

The strong radial pressure gradient causes the gaseous component of the nebula to rotate at less than Keplerian velocity (5). Solid bodies, unsupported by the pressure gradient, move relative to the gas. For small bodies, this motion is radially inward. Large bodies maintain Keplerian motion, with orbits which decay due to drag from the constant "headwind." The maximum radial velocity occurs near the transition between these regimes, at sizes ~ 1 m in the solar nebula, but ~ 1 km in the CN. The characteristic timescale for loss into the planet

($r/\dot{r}$) is less than one year for km-sized bodies in Io's zone. To avoid loss into Jupiter, they must grow to $\gtrsim$ 100 km on a comparable timescale. If bodies form by a Safronov-Goldreich-Ward gravitational instability, their characteristic size is ~ 10 km, so further accretional growth would still be required. A direct calculation of settling and accretion leading to formation of such large bodies has not been completed, due to the range of timescales involved. Analogous calculations for the solar nebula (4) suggest that drag-induced relative motions could produce sufficiently rapid accretion if mutual collisions are the only disruptive process.

The motion of solid bodies relative to the gas may inhibit accretion in the CN. The maximum particle/gas relative velocity is $\sim 10^4$ cm s^{-1}, which is of the same order as in the solar nebula. However, the much higher gas density results in higher dynamic pressure ($P_d = \rho V^2/2$). This may be sufficient to disrupt a body, or the "wind" $\sim 10^4$ cm s^{-1} (at densities comparable to Earth's atmosphere) could ablate its surface faster than it can accrete. Bodies prevented from growing would quickly be lost into Jupiter. Figure 1 shows dynamic pressure and characteristic lifetime as functions of size for a body in Io's zone. P_d (max) $\sim 10^5$ dyne cm^{-2} at $r = 6R_J$, and varies as r^{-4}. It has been suggested that the inner limit for jovian satellite formation was due to high temperatures which prevented condensation (1,2). However, dynamic pressure or ablation may have set an additional limit on satellite formation near Jupiter.

Saturn's satellite/ring system extends much closer to the planet. The lower mass of the system suggests much lower densities in the saturnian CN, and the absence of an aerodynamic limit on accretion.

REFERENCES

1) Pollack, J.B. and Reynolds, R.T. (1974). Icarus 21, 248-253.
2) Cameron, A.G.W. and Pollack, J.B. (1976). In Jupiter (T. Gehrels, Ed.), University of Arizona Press, 61-84.
3) Weidenschilling, S.J. (1977). Astrophys. Space Sci 51, 153-158.
4) Weidenschilling, S.J. (1980). Icarus, in press.
5) Weidenschilling, S.J. (1977). MNRAS 180, 57-70.

TABLE I

Jovian circumplanetary nebula model

surface density	$\sigma \propto r^{-2}$
temperature	$T \propto r^{-1}$
pressure	$P \propto r^{-4}$

Conditions at $r = 6R_J$ (Io's zone)

σ (gas)	$= 3 \times 10^6$ g cm^{-2}
σ (solids)	$= 1 \times 10^4$ g cm^{-2}
T	$= 530^{\circ}$K
P	= 6 bars
ρ	$= 3 \times 10^{-4}$ g cm^{-3}
ΔV	$= V(\text{Kepler}) - V(\text{gas}) = 2.3 \times 10^4$ cm s^{-1}

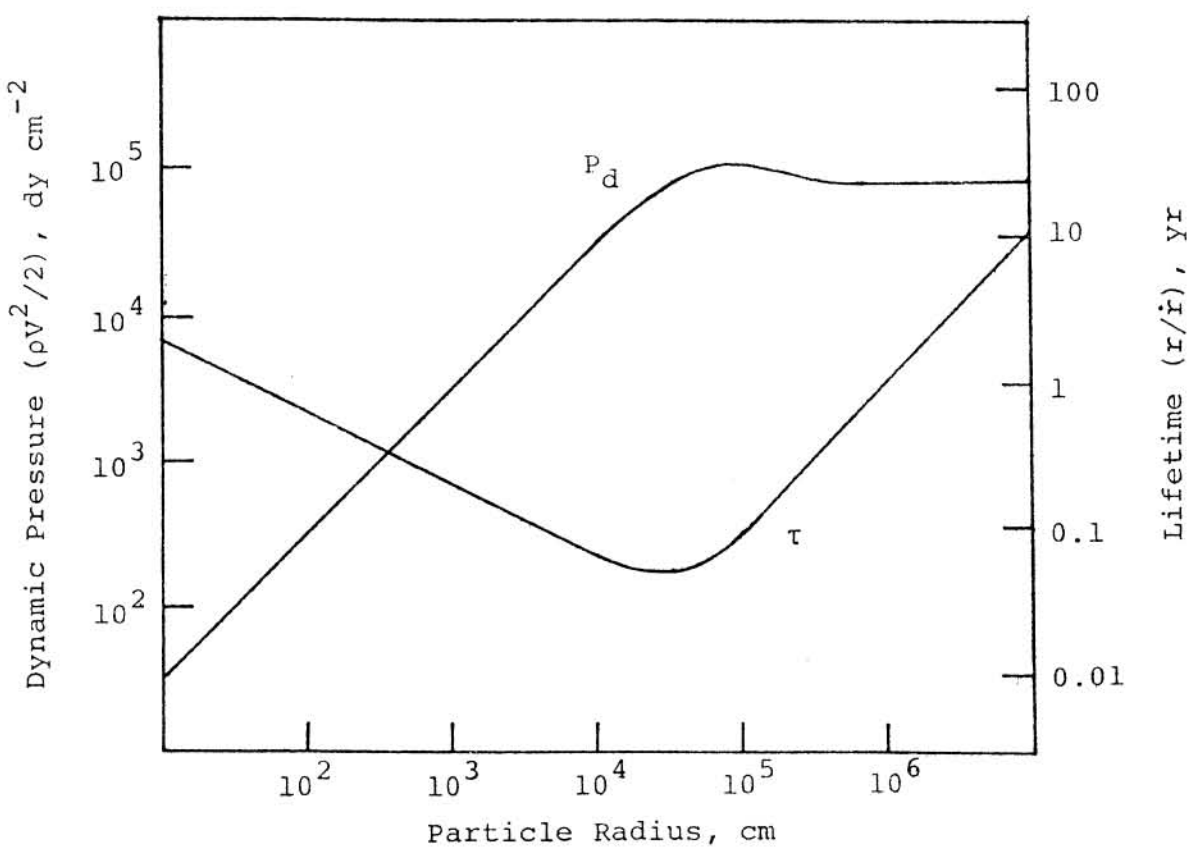

Figure 1. Dynamic pressure ($P_d = \rho V^2/2$) and characteristic lifetime ($\tau = r/\dot{r}$) functions of size for solid bodies at $r = 6R_J$ in the model jovian circumplanetary nebula.