COAGULATION AND SETTLING OF DUST IN GIANT GASEOUS PROTOPLANETS,

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The cosmogonical theory of Cameron (1) involves formation of giant gaseous protoplanets (GGP's) by gravitational instability of the solar nebula. These undergo a stage of gradual, quasi-static contraction at low density. In the outer part of the nebula, a GGP can survive until adiabatic heating leads to dissociation of H_2 at its center. The resulting hydrodynamic collapse forms a giant planet. In the inner solar system, GGP's may be disrupted by tidal forces or thermal evaporation. Terrestrial planets are assumed to be residual cores formed by raining out of heavy elements before loss of the gaseous envelopes.

As particles with sizes typical of interstellar grains settle too slowly, some type of coagulation process is necessary for core formation. DeCampli and Cameron (2) assumed that presence of a liquid phase was required for coagulation. In their models for evolution of isolated GGP's, they found that they passed through a pre-collapse stage in which the P-T regime of the central region allowed liquid Fe to exist. The coagulation of Fe droplets under these conditions was modeled by Slattery (3) and Slattery et al. (4), using numerical techniques based on studies of raindrop formation in terrestrial clouds. They showed that coagulation and rainout of Fe droplets would be rapid. DeCampli and Cameron's models were largely convective, allowing most of grains originally present in a GGP to be processed through the region of liquid stability.

More recent models by Cameron et al. (5) subject GGP's to boundary conditions appropriate to the solar nebula environment. These alter their evolution in important ways. Thermal flux from the surrounding nebula decreases the temperature gradient, preventing convection in much of the interior. Also, GGP's in the region of the terrestrial planets do not reach central temperatures high enough for Fe melting. The nebular thermal flux eventually causes the GGP to evaporate. Formation of a core under these conditions requires some other mechanism.

Presence of a liquid phase is probably not necessary for grain coagulation. Weidenschilling (6) presented arguments for the effectiveness of van der Waals forces in promoting coagulation in a solar nebula environment. The same arguments should apply to GGP's, where temperatures, gas density, and particle relative velocities are generally similar. I have computed numerically the simultaneous coagulation and radial settling of grains in a GGP, using a variant of the algorithm described in (6). This calculation differs from those in (3) and (4) in that the latter computed the evolution of a droplet size distribution only at a single location. In the present work, a GGP is divided into 20 radial zones. The evolution of the grain size distribution is computed for each zone. In each timestep, some of the grain appregates are transferred to the next lower zone, at a rate proportional to the terminal fall velocity at each size. Grain collisions are due to thermal Brownian motion and differential settling velocities; the latter dominates for particles larger than a few μm in size. Larger aggregates fall faster than smaller grains, sweeping up those they encounter. Collisions were assumed to result in coagulation unless the energy involved exceeded a specified impact strength, in which case the bodies were shattered into smaller aggregates or individual grains.

The calculation was performed for conditions listed in Table 1. This represents case 2 of Cameron et al.(5), a GGP in a "thermal bath" with external temperature rising at 10^{-3} deg/yr, at a time when its radius is at a minimum. The evolution of the GGP is slow compared to the coagulation timescale, and can be neglected. Ice is assumed present at levels where $T < 160^{\circ}K$; only Fe and silicate grains are present at higher temperatures. The ice portion evaporates when it settles into the warmer region.

Results: Coagulation begins slowly, and accelerates as larger bodies with higher terminal velocities form. The calculation to date has been carried to an elapsed time of 900 yr. At that point, the solids/gas ratio in the outermost zone has been depleted by a factor of 5. The mean depletion in the outermost 25% (by radius) is about a factor of 2, with a moderate enhancement in the rest of the GGP. The maximum aggregate size ranges from ≃0.05 cm in the outer zone to several meters in the inner 25%.

The opacity, κ, due to grains is affected by changes in both the solids/gas ratio and the size distribution. For particles smaller than the wavelength, κ is proportional to the mass concentration, independent of size. However, much of the mass is in aggregates larger than $\lambda_{eff} = (0.29/T)$ cm. The aggregate growth has reduced the grains' geometric cross-section by about two orders of magnitude. A detailed calculation of opacity, taking into account the size distribution and λ-dependence of absorption, has not been performed, but it is estimated that κ has decreased by about one order of magnitude. Even the "low opacity" cases of DeCampli and Cameron may overestimate κ. Lower values lead to more rapid evolution of the GGP. A detailed evolutionary calculation would require time-dependent opacity, but it may suffice to simply neglect the contribution of grains.

I conclude that a zone of stability of a liquid phase is not necessary for core formation. The process need not go to completion before evaporation of a GGP, as large grain aggregates would not be carried off during escape of the gas. The reduction in opacity due to coagulation and settling of grains suggests that the structure of a GGP will be radiative rather than convective.

REFERENCES: (1) Cameron, A.G.W. (1978). Moon and Planets 18, 5. (2) DeCampli, W.M. and Cameron, A.G.W. (1979). Icarus 38, 367. (3) Slattery, W. (1977). Moon and Planets 19, 443. (4) Slattery, W., DeCampli, W.M., and Cameron, A.G.W. (1980). Moon and Planets 23, 381. (5) Cameron, A.W.G., DeCampli, W.M., and Bodenheimer, P. (1981). preprint. (6) Weidenschilling, S.J. (1980). Icarus 44, 172.

TABLE 1: Protoplanet Properties

Radius	3.25×10^{13} cm
Mass	1.9×10^{30} g
Central temperature	378°K
Central density	3.3×10^{-8} g cm^{-3}
Background nebular temperature	34°K
Initial dust/gas ratio	0.01 ($T<160^{\circ}$K) 0.0034 ($T>160^{\circ}$K)
Initial particle radius	4×10^{-4} cm
Aggregate bulk density	1g cm^{-3}
Effective impact strength	10^{5} erg cm^{-3}