S27-90 ABS O. N94-35422
2967
p. 2

WHAT INITIATED PLANETESIMAL FORMATION? J. N. Cuzzi, A. R. Dobrovolskis, and R. C. Hogan; Space Science Division, 245-3, Ames Research Center, Moffett Field, California 94035-1000

The physical structure of primitive (chondritic) meteorites, even after some geological processing and modification, is thought by most to contain clues as to the first stage of accretion of solid matter into objects that might be called "planetesimals". However, theoretical understanding of the processes responsible for this important stage is shaky. We note what we believe are fundamental obstacles for the Goldreich-Ward version of rapid and direct planetesimal formation via gravitational instability in a settled particle layer [1], and describe an alternative scenario which might lead from grainy nebula gas to primitive planetesimals in a way that has intriguing connections to the meteorite evidence.

Primitive meteorite morphology appears to call for some specific, and geologically unusual, process of accumulation. Chondritic meteorite samples are fairly uniform (within a class) from the standpoint of constituent size distribution, arguing against "hierarchical" accumulation and in favor of a spontaneous coming together of constituents [2] which are very well size-sorted [3]. Recent work indicates that aerodynamic drag is the sorting mechanism [4], and raises the distinct possibility that the very earliest aggregates may be composed entirely of size sorted objects consisting of a solid object (chondrule or fragment, silicate or metal) covered with a fine-grained dust rim [5].

In its original form, the Goldreich-Ward (GW) scenario postulated that volumes of centimeter-sized objects could collapse directly (in a two-stage process) into solid, asteroid-sized objects; the similarity of the centimeter size scale to that of chondrules was encouraging. However, Weidenschilling [6] and subsequently we [7] have shown that the conditions for gravitational instability are difficult to achieve in the presence of nebula gas, at least while the typical particles are less than a meter or so in radius. This is due to the stirring effects of the turbulence that is generated around the differentially rotating dense midplane particle layer. Nevertheless, it is still commonly assumed that the particle layer instability will still occur, but at yet larger particle sizes for which turbulent diffusion is less effective.

We believe this is not the case. The GW instability requires not merely "marginal" gravitational instability, the criterion normally cited, but *extreme* instability in order for a volume fragment of particulates to collapse directly to solid density. The extremely large compression factor requires gravitational instability of initial fragment scales λ which are orders of magnitude smaller than the *critical* wavelength λ_c. As a fragment collapses, potential energy is converted to kinetic energy until a certain equilibrium fragment size λ' is reached. Equation 36 in [1], along with the standard definition of λ_c, shows that $\lambda/\lambda_c \sim \lambda'/\lambda$. GW require the equilibrium fragment to have achieved solid density; thus $\lambda'/\lambda \sim \lambda/\lambda_c \sim 10^{-2}$. Equation 37 of [1] then requires the particle random velocities to begin and remain far smaller than the "critical" random velocity $c_c = 2\pi G\sigma/\Omega$ which merely allows λ_c to be unstable. For the centimeter-sized particle layer originally described in [1], a combination of collisional damping and gas drag damping makes this a reasonable assumption. However, turbulent stirring prohibits the instability until the particles grow to meter-and-larger sizes for which both of these dissipation mechanisms become inefficient on a dynamical collapse time Ω^{-1}. Thus, while incipient fragments may become unstable at or near the critical wavelength, they are unable to shrink and collapse very far. These fragments are likely to be dispersed by differential rotation, or exist only as a standing wave or pattern with no capability of concentrating a specific ensemble of particles, much like the "wakes" in Saturn's ring system. Alternatively, Safronov [8] has proposed that *axisymmetric* or annular instabilities may initiate at close to the scale λ_c with random velocities c_c, and slowly compress radially until fragmentation densities (nearly 10 times higher) result. This process is much slower than a dynamical collapse time and not obviously relevant to meteorite structure or mineralogy, some of which indicates "short" accumulation timescales (perhaps comparable to or less than an orbit period) [e.g., 2].

A completely different mechanism that operates in very much the desired way, at least in terrestrial laboratories and numerical simulations, is turbulent *concentration* of appropriately sized particles [9]. The process appears to be capable of producing a substantial concentration of aerodynamically size-sorted objects into massive clumps, *and* of simultaneously providing the constituents with rims of fine dust. Order of magnitude concentration factors are already seen relative to the average particle density (and the gas density); considerably larger concentration factors are feasible in the nebula context. These are of mineralogical interest whether or not the process leads directly to planetesimals [e.g., 2, 10]. The primary uncertainties at present are in relating the time, length, and mass scales of the process to nebula and meteoritic scales, and in understanding the role of turbulence damping in stabilizing particle clumps. Turbulence now accessible to computational study has a Reynolds number which is orders of magnitude smaller than expected for the nebula, and we must understand the basic physics before being able to confidently extrapolate current results. It is in this area that we are devoting our current studies [11]. We present the scaling relations which we believe support this hypothesis as a candidate for the initial stage in the planetesimal formation process, and show how it could lead to concentrations with the mass equivalent of a 10 - 100 meter size object. Objects of this size would settle rapidly to the nebula midplane, and their subsequent growth and radial evolution may be modeled as "drift-augmented accretion" in which subsequent growth to asteroid radius r, at heliocentric distance R, can be geologically rapid (roughly $10^4(r/10\text{km})(R/1\text{AU})^2$ yr) [7].

There are many unexplored and uncertain aspects of the turbulent clumping scenario. Solid chondrule-sized elements are merely presupposed, and the elusive intense thermal processing stage leading to chondrule formation is not addressed. Nor does this scenario explain evidence for high relative velocities between chondrule-sized objects, leading to considerable fragmentation *prior to* accumulation. Compression of loose agglomerations of chondrule-sized constituents to "rocks" is another "detail left to the reader". On the positive side, however, new physics has been introduced that appears to provide a fruitful direction for future study.

References: [1] Goldreich P. and Ward W.; Astrophys J., 183, 1051-1061; [2]: Kerridge J. (1993) Icarus 106, 135-190; [3] Dodd R. T. (1976) EPSL 30, 281-291; Hughes D. W. (1978) EPSL 38, 391-400; [4] Skinner W. R. and Leenhouts W. (1993) LPSC XXIV, 1315-1316; Scott E. R. D. and Haack H. (1993) Meteoritica 28, 434; [5] Metzler et al. (1992); GCA 56, 2873-2898; [6] Weidenschilling S. (1980) Icarus 44, 172-189; (1984), Icarus 60, 555-567; [7] Cuzzi J. N. et al. (1993) Icarus 106, 102-134; [8] Safronov V. S. (1991) Icarus, 94, 260-272; [9] Squires K. D. and Eaton J. K.; Phys. Fluids A2, 1191-1203; Phys. Fluids A3, 1169-1178; [10] Wood J. and Hashimoto A. (1993) GCA 57, 2377 - 2388; [11] Cuzzi J. N. et al. (1993) Meteoritica, 28, 339; Dobrovolskis A. R. et al. (1993) B.A.A.S. 25, 1122, and B.A.A.S. 25, 1248