THE ORIGIN OF STRUCTURE IN COMETARY NUCLEI BY ACCRETION IN THE SOLAR NEBULA; S.J. Weidenschilling (Planetary Science Institute/SJI)

The record of the formation of planetesimals from microscopic grains has been obscured in the asteroid belt by aqueous alteration, thermal metamorphism, and collisional processing. Comets, the most primitive members of the solar system, are more likely to preserve evidence of their accretion. The detection of comets in situ in the Kuiper belt [1] shows that they originated as icy planetesimals in the outer Solar Nebula. Comets are physically and compositionally heterogenous; outbursts and jetting suggest a preferred scale for these inhomogeneities ~100 m [2,3]. Models of the tidal disruption of S-L 9 suggest that the parent comet separated into a swarm of components ~100 m or smaller in size before reaccreting into the observed subnuclei [4]. These properties may be due to their accretion in the presence of gas in the Solar Nebula, which tended to produce structure on this scale due to the size-dependence of drag-induced velocities.

The gas inhibited gravitational instability of a particle layer and limited it to scales that did not allow collapse to solid bodies [5]; planetesimals therefore formed by collisional coagulation. The collisions were caused by differential motions of solid bodies relative to the pressure-supported gas, which deviated from Keplerian rotation [6]. Fig. 1 shows particle velocities as function of size in a typical low-mass nebula. For particles ~10 μm to km size, radial motion dominates, and causes collisions between particles of different sizes. Transverse velocity relative to the gas is smaller than radial velocity for <m-sized bodies, and for larger bodies it reaches a constant value, independent of size, and so does not cause collisions. The radial velocity reaches a peak (typically tens of m/s) at ~m-size, and decreases for larger bodies. Only at size >km does the escape velocity V_e exceed the radial velocity V_r, allowing gravity to influence accretion.

I have carried out numerical simulations of particle settling and coagulation similar to those described in [7]. Because gas inhibits gravitational instability, these simulations allowed collisional coagulation to continue at later stages, even after the density of the particle layer exceeded the usually assumed threshold for instability. These simulations show a strong tendency to produce a size distribution with a peak at d ~100 m (Fig. 2). This peak is a direct result of the size dependence of radial velocity. In the range ~m-km, V_r decreases, but the velocity dispersion still exceeds the escape velocity, so there is no gravitational enhancement of collision cross-section. Thus, the growth rate decreases with increasing size. This effect causes pileup of mass at the largest size, opposite to the "runaway" growth seen in gravity-dominated accretion. Meter-sized bodies have large velocities and are rapidly accreted by the larger bodies, causing a gap to open in the size distribution at d ~1-10 m. Eventually the largest bodies begin gravitational accretion and the size distribution broadens (Fig. 3), while gravitational stirring increases their relative velocities.

The size dependence of radial velocity ensures that collisions of comparably-sized bodies are infrequent and gentle. A body typically accretes most of its mass as bodies ~0.001-0.1 times its own mass. This process may produce fractal-like structures over some size range, but this will depend on impact velocities and mechanical properties of the growing cometesimals; i.e., whether collisions preserve the identity of impactors or result in compaction. Impact velocities decrease with size, suggesting structures are more likely to survive at larger scales. In these simulations, mean impact velocities decrease from ~10 m/s to ~10 cm/s as the largest bodies grow from m to km size. Actual values depend on nebular parameters (for a more massive nebula, drag-driven accretion continues to larger sizes), but is insensitive to heliocentric distance.

The size at which transition occurs from gas dominated accretion to "classical" gravitational accretion depends on the gravitational stirring model as well as on nebular structure. However, the general result is robust that relative velocities have a minimum at this transition, and that mass piles up at this size during accretion. Comets produced by collisional coagulation in the Solar Nebula should have structural components with a range of sizes, but preferentially of size ~100 m, with macroscopic voids. Radial migration caused by orbital decay due to gas drag can be significant (10-50% of original heliocentric distance), and may be responsible for mixing of material from different sources, producing compositional inhomogeneities.

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References: [1] Cochran, A. et al. (1995), *Ap.J.*, **455**, 342; [2] Larson, H. et al. (1990), *Icarus* **86**, 129; [3] Mumma, M. et al. (1993), *Protostars & Planets III*, 1177; [4] Asphaug, E., and Benz, W. (1995), *Nature* **370**, 120; [5] Weidenschilling, S. (1995), *Icarus* **116**, 433; [6] Weidenschilling, S. (1977), *MNRAS* **180**, 57; [7] Weidenschilling, S., and Cuzzi, J. (1993), *Protostars & Planets III*, 1031.

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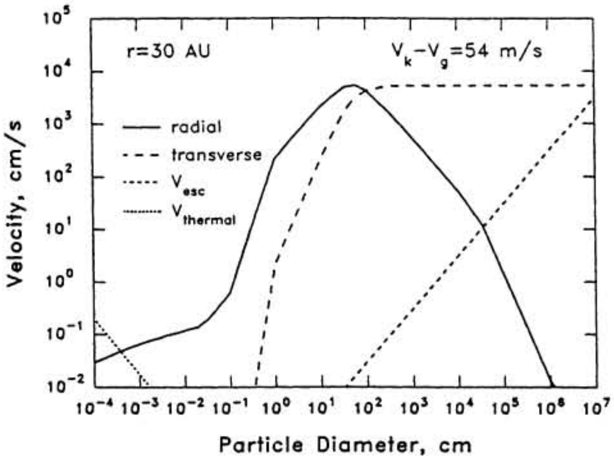

Fig. 1. Radial and transverse velocities relative to the (non-Keplerian) pressure-supported gas at 30 AU heliocentric distance. Also shown are thermal velocity (T = 50 K) and gravitational escape velocity (for density 0.7 g/cm^3). Nebular density corresponds to mass 0.05 $M_\odot$ inside 50 AU, with deviation from Keplerian rotation 54 m/s.

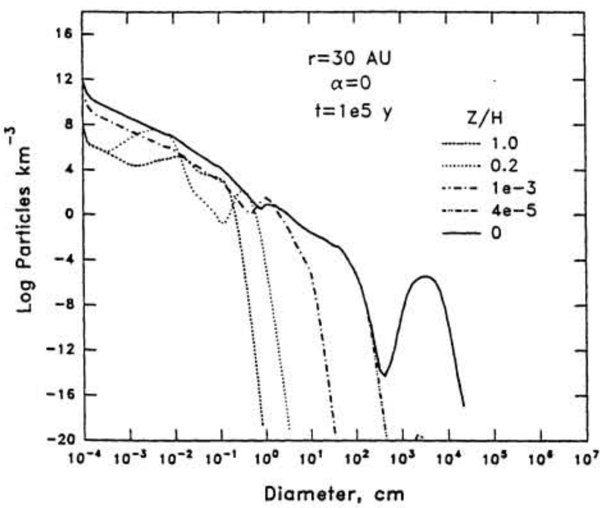

Fig. 2. Size distribution (particles per volume per logarithmic diameter interval) at different distances from the central plane (z in units of gas scale height H). Most of the mass is at z=0, where the size distribution has developed a peak at d~50 m. Elapsed time is 1e5y from an assumed initial state of μm-sized grains uniformly mixed with the gas.

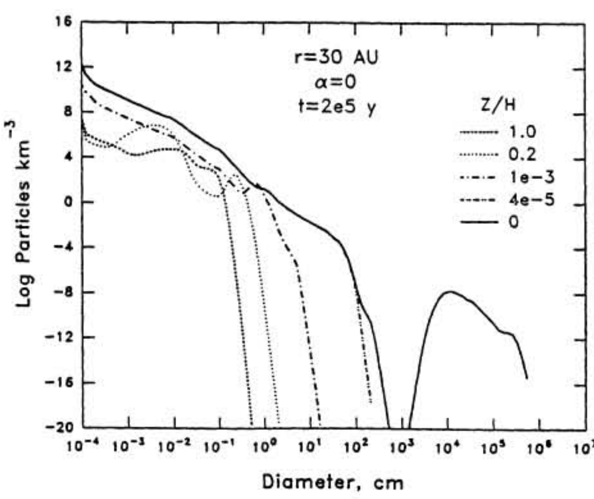

Figure 3. Same as Fig. 2, at t = 2e5y. Mass peak at d~100 m. Bodies larger than km size have begun gravitational accretion.