ORIGIN OF "RUBBLE PILE" COMETARY NUCLEI; S.J. Weidenschilling

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The disruption of comet P/Shoemaker-Levy 9 during an encounter with Jupiter implies that the parent nucleus had extremely low tensile strength, $\sim 10^{-3}$ bar (1). The number of observed crater chains on the Galilean satellites, if due to impacts of disrupted comets (2), is consistent with comparably low strengths for most, perhaps all, cometary nuclei. Such weak bodies must be "rubble piles" consisting of smaller components held together by mutual gravity and/or weak surface forces. This common structure must be the result of the process(es) that formed them in the solar nebula. I show that a two-stage process of collisional coagulation, followed by gravitational instability of a particle layer, yields weakly bound bodies of cometary size, and is a plausible, perhaps inevitable, result of accretion in the outer part of a low-mass ($\lesssim 0.1\ M_{\odot}$) nebula.

Icy particles in the nebula will tend to settle toward its central plane, forming a dense layer. A necessary condition for this layer to become gravitationally unstable is that it attain a critical density, $\delta_c \sim 3M_{\odot}/2\pi a^3$, comparable to the local Roche density at distance a from the Sun. However, it is not possible for a layer of small particles to reach this density, which greatly exceeds the local gas density. The nebular gas, supported by a radial pressure gradient, rotates at less than the local Kepler velocity. If the particles are small enough to be coupled to the gas by drag, the resulting shear between the layer and the surrounding gas generates turbulence and prevents further settling (3,4). Numerical simulations suggest that the mean particle size must grow to $\gtrsim 1$ m before the critical density is attained (5).

Reaching the critical density is not a sufficient condition for gravitational instability. The dispersion relation for a differentially rotating, self-gravitating disk implies that density perturbations can grow if the particle velocities are less than a critical value, $c* \sim \pi G\sigma_p/\Omega$, where G is the gravitational constant, σ_p the surface density of the particle layer, and Ω the Kepler frequency (6). For random, isotropic particle velocities, the thickness of the particle layer is $h \sim c/\Omega \sim \sigma_p \delta_c$, so the two conditions are essentially equivalent. However, in the presence of nebular gas, particle velocities are neither random nor isotropic. For bodies $\gtrsim 1$ m in size, the largest velocity component is a systematic radial motion resulting from orbital decay due to gas drag: $V_r = 2a(\Delta V/V_K)/t_e$, where $\Delta V/V_K$ is the fractional deviation of the gas from Keplerian motion, and t_e is a response time of the particle, which depends on its size. For Epstein drag, $t_e = d\rho_P/2\rho\bar{v}$, where d, ρ_P are the particle's diameter and density; $\rho, \bar{v}$ are the density and mean thermal velocity of the gas. For Stokes drag, $t_e = d^2\rho_P/18\eta$, where η is the gas viscosity.

The condition for gravitational instability with an anisotropic velocity dispersion is not clear. I assume that the dispersion of V_r must be less than c^*, regardless of the density of the particle layer. A sufficient condition is that the median-mass bodies have $V_r < c^*$; this implies $d > 4\Delta V\rho\bar{v}/\pi G\rho_p\sigma_p$ for Epstein drag, or $d > 6(\eta\Delta V/\pi G\rho_p\sigma_p)^{1/2}$ for Stokes drag. Using $\rho_p = 0.7g\ cm^{-3}$, and values of ρ, σ_p and ΔV appropriate for a low-mass solar nebula, the critical diameter falls in the range ~10-100 m for a between 5 and 50 AU. Thus, collisional coagulation must produce bodies of this size before

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gravitational instability can occur. It may be significant that this size corresponds to the mass of material involved in a typical cometary outburst (7).

Once gravitational instability occurs, the largest density perturbations have a size scale $\lambda \sim 4\pi^2 G\sigma_p / \Omega^2$. These would yield bodies of mass $\sim\sigma_p \lambda^2$, corresponding to diameters of several hundred km. However, collapse on these scales is inhibited by angular momentum; direct collapse is possible only on scales that yield solid bodies with $d \lesssim 10$ km. Thus, a typical comet should comprise $\sim 10^6$ components. These collisionally accreted "building blocks" would be fairly compact and more or less uniform in structure. The nucleus itself, bound by gravity and weak contact forces between the blocks, will contain a large fraction of macroscopic void space (8).

Numerical simulations now in progress suggest that the collisional growth stage lasts $\sim 10^5$y at 30 AU. Instability occurs when the median particle size is $\approx$20-30 m and the particle layer has a density $\approx 5\delta_c$; about half of the total solids take part in the instability, with the rest dispersed as smaller particles at larger distances from the central plane of the nebula. Shear-generated turbulence is not strong enough to prevent gravitational instability after particle sizes reach tens of meters; collisional accretion of larger components is unlikely unless there is an additional source of stirring, e.g., global convective turbulence, to delay the onset of instability. The predicted components are smaller than the observed fragments of S-L9, implying that its breakup during its Jupiter encounter was incomplete; further disruption is likely during its final approach in July.

References

1) Scotti, J. and Melosh, H.J. (1993) *Nature*, **365**, 733.
2) Melosh, H.J. and Schenk, P. (1993) *Nature*, **365**, 731.
3) Weidenschilling, S.J. 1980) *Icarus*, **49**, 172.
4) Weidenschilling, S.J. and Cuzzi, J. (1993) in *Protostars and Planets III*, (Eds. E. Levy, J. Lunine, U. of Az. Press), p. 1031.
5) Cuzzi, J. *et al.* (1993) *Icarus*, **106**, 102.
6) Goldreich, P. and Ward, W.R. (1973) *Ap.J.*, **183**, 1051.
7) Larson, H.P. *et al.* (1990) *Icarus*, **86**, 129.
8) Weidenschilling, S.J. (1994), *Nature*, submitted.