The Primordial Rubble Pile Model of the Cometary Nucleus

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The structure of the cometary nucleus remains one of the major unknowns in understanding the source of cometary activity. Whipple's (1950) icy-conglomerate model recognized that the nucleus was a single, coherent body, and was dramatically confirmed in 1986 by the Giotto and Vega images of the nucleus of Comet Halley. The nucleus was revealed to be an irregularly shaped body with high surface roughness down to the limits of the camera resolution, and with apparently active and inactive areas scattered randomly across its surface. However, the modest resolution of even the best images did not allow characterization of the underlying nucleus structure or of the active source regions.

Nevertheless, clues to the structure of cometary nuclei can be obtained from both observations of cometary phenomena and theoretical arguments with regard to the formation of comets in the primordial solar nebula. These lines of evidence suggest that cometary nuclei are weakly-bound agglomerations of many smaller icy-conglomerate cometesimals. This model was first put forward a decade ago by Donn and Hughes (1986) as the "fluffy aggregate" and by Weissman (1986) as the "primordial rubble pile."

Theoretical studies of the accretion of planetesimals in the solar nebula show that material initially came together at very low relative velocities as it settled to the midplane of the nebula, and later as orbiting planetesimals collided and stuck (Weidenschilling, 1997). The gravitational potential energy released in assembling a 5-km radius cometary nucleus with a bulk density of 1 g cm^{-1} is only 4.2×10^{-3} joules gm^{-1}, not enough to raise the mean temperature of the nucleus by even 0.01 K! Barring the existence of other internal energy sources (e.g., short-lived radionuclides), there is no energy source available subsequently to modify the nucleus structure. Thus, comets should retain the initial accretionary structure they had when they were assembled in the primordial solar nebula. It should be noted that one strong modifying process does exist, collisional evolution, but its role in modifying the initial nucleus structure has not been evaluated.

Observational evidence also supports the existence of an underlying rubble pile structure for comets. Comets are occasionally observed to split during perihelion passage, with one or more small, discrete pieces breaking off the main nucleus. Splitting events occur randomly pre- and post-perihelion and in only a few cases are explained by tidal forces due to a close approach to a planet or the Sun. Splitting events are often associated with outbursts, which are likely due to the exposure of fresh cometary ices as the overlying cometesimals break away.

Strong evidence in support of the rubble pile nature of comets came from Comet D/Shoemaker-Levy 9 in 1993-94. Asphaug and Benz (1994, 1996) explained the tidal disruption of the progenitor nucleus and the subsequent reassembly into $\sim$20 independent nuclei, by assuming a rubble pile structure of independent, self-gravitating cometesimals, with an initial bulk density between 0.5 and 1.1 g cm^{-3} (depending on the original rotation state of the nucleus). Such a model was also able to explain observed crater chains on the surfaces of Ganymede and Callisto (Schenk et al., 1996).

Additional evidence in support of the rubble pile model will be presented and discussed.