Section III

Comets, Origins, and Evolution

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THE ACCUMULATION AND STRUCTURE OF COMETS

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ABSTRACT. The evidence for the accumulation of the terrestrial planets and comets from solid grains is reviewed briefly. The various proposals for formation of cometary nuclei are described and commented upon. With three exceptions, all hypotheses conclude or imply that a single compact object forms. It has been almost universally assumed that grain accretion produced compact aggregates as is the case with liquid drops, and that this process continued. Several hypotheses start with Goldreich-Ward-type gravitational instabilities. The collapse for this case also occurs at low velocities in the $cm \cdot s^{-1}$ to $m \cdot s^{-1}$ range. Experiment and theory show that under these conditions, low-density, filamentary clusters form that are fractal aggregates with a fractal dimension approximately equal to two. Agglomeration of these clusters produces larger, compressible planetesimals or cometesimals, which efficiently combine upon colliding. In order to form cometary nuclei, the initial temperature must be about 50 K and not undergo a significant temperature rise during the accumulation process. The collision process can be analyzed with some simplifying assumptions using the limited experimental data available for the compaction of low-density powders. The calculations show that accumulation will occur at low temperatures. For a more refined analysis, experiments to study impacts on low-density powders are required. Models of cometary nuclei are reviewed, and a simple model of the structure that results from the accumulation of fluffy aggregates is described.

1. Introduction

Although this review has a similar title to an earlier one (Donn and Rahe, 1982), the emphasis and consequently the content are significantly different. We are concerned here with the mechanism of accumulation of cometary nuclei from grains and the resultant structure of the nucleus. The related questions of composition and place of formation are considered in this volume by Yamamoto in some detail and to various degrees by others, notably Geiss (1987) and Vanysek and Rahe (1978).

A number of recent reviews of the origin of comets have appeared (Bailey et al., 1986; Weissman, 1988; Bailey et al., 1990). As there has not been a review of proposed accumulation processes and structure of the nucleus, it seemed most appropriate to devote this paper to that aspect.

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2. Accumulation From Solid Grains

It is now generally accepted that the formation of the terrestrial planets and smaller bodies in the solar system occurred via a grain accumulation process (see Safronov, 1969; Hartmann, 1978; Greenberg et al., 1978; Wetherill, 1980). The basis for this conclusion is the depletion of the noble gases Ne, Ar, Kr, and Xe compared with elements forming condensible molecules of equivalent molecular weight (Russell and Menzel, 1933; H. Brown, 1952; Schmidt, 1955). From this analysis, it has been concluded that gravitational capture from the gas phase, which depends upon molecular weight, did not play a role. Rather, accumulation depended upon the ability of an element to form compounds that could condense into solid grains. These grains were accreted to form the terrestrial planets and smaller bodies.

In the case of comets, temperatures had to be sufficiently low for the normally volatile components of comets (H_2O, C_2H_2, CO, CO_2, NH_3, HCN) to condense into grains or be adsorbed on or into grains. In addition, during accumulation, these species must remain in the condensed phase. The constraint that this places upon the relative velocity of grain collisions was pointed out by Donn (1963) and by Greenberg (1985) in connection with preservation of radicals. It was pointed out by Donn and Sears (1963) that the required velocities, less than a few tenths of kilometers per second, would apply to small grains in the primordial solar nebula because of the efficiency of gas drag in slowing them down. Detailed calculations have been made by Volk et al. (1980) and Weidenschilling (1984). It has recently been shown (Meakin and Donn, 1988) that because of the fractal nature of the aggregates, particles containing on the order of 10^4 grains would also be effectively slowed by the gas and have low impact velocities.

3. Survey of Processes for Comet Accumulation

Among the earliest treatments of comet accumulation were two papers published a quarter of a century ago (Donn and Sears, 1963; Donn, 1963). These authors pointed out that grains condensing in space would tend to be filaments or platelets rather than spheres. Because of gas drag, they would collide with low velocities. Both these factors would enhance sticking and lead to fluffy, dust-ball aggregates. Making use of the behavior of snow deposits, the authors suggested that these aggregates would grow into low-density, kilometer-sized cometary nuclei. This model was later modified (Donn, 1981) to take into account the development of a size distribution of planetesimals in theories of planet accumulation (Safronov, 1969; Wetherill, 1980; R. Greenberg et al., 1978). Instead of a single, uniform spherical body, the nucleus was now portrayed as an agglomeration of loosely bound cometesimals with a somewhat irregular shape.

In their second paper on the formation of the solar system, Alfven and Arrhenius (1970) pointed out that fluffy aggregates are expected to accrete from grains, and these should be effective in absorbing impact energy so that there will be little mass loss. The authors called attention to the need for appropriate experiments on such material. They also pointed out that high porosity and low density may have been common on bodies that remained small. When discussing planetesimal growth, these authors did not take into account the porous, energy-absorbing nature of smaller aggregates in reducing fragmentation.

In 1973, several proposals for comet formation were published. Cameron (1973) treated accumulation during several stages of the transformation from a turbulent interstellar cloud rendered unstable by density enhancement until it reached the primordial solar nebula stage. He assumed that the particle radius S was given by

$$S = N^{1/3} S_o \tag{1}$$

where N is the number of grains in the particle and S_o is the grain radius. Equation 1 is applicable to the accumulation of liquid droplets that form a larger spherical volume that is completely filled. This has been the common assumption in accumulation studies. A consequence of Equation 1 is that the ratio of the cross-section to mass varies as $N^{-1/3}$ and decreases rather rapidly with size. Therefore, the distance over which the gas drag slows the aggregates increases rapidly with N. In this treatment, continual growth leads to close-packed, dense aggregates. Problems with coagulation and fragmentation become more serious as the objects become larger but, because of increasing relative velocity, not massive enough for gravitational attraction to dominate. Solid grains cannot fill the volume of the aggregate, and, as discussed in Section 4.2, very porous fractal aggregates are expected to grow. A more detailed description of the growth mechanism and the fractal structure, as well as the consequences, are given there.

In Cameron's 1973 solar nebula model, the density in the outer part of the nebula is 10^{-10} g·cm^{-3} and the temperature 100 K. As the temperature rises still higher, the ice component of the ice/dust grains vaporizes, yielding fluffy, low-density aggregates. However, such particles without the volatile icy constituent cannot build comets.

The region of comet formation involves subdisks postulated to be in orbit about the solar nebula. The accumulation process is the same as outlined for the planetary region, but the temperature remains low enough for volatiles to be retained.

In O'Dell's (1973) hypothesis, many small objects form in the region of the Oort cloud. Some clusters were sufficiently compact to withstand tidal disruption as they were perturbed into orbits with perihelia near the Sun. These clusters survived as comets. For such objects, the space density of component bodies would be so great that collisions among them as they fell toward perihelion would cause them to coalesce into a single Whipple-type nucleus. In order to account for the cometary abundance of volatiles, O'Dell adopted a comet model consisting of ~ 10^{33} volatile-coated interstellar grains with radii of 10^{-5} cm. Neither the origin of the particles in the Oort cloud nor the expected structure of the final single nucleus was discussed.

A comprehensive analysis of comet and planet formation was proposed by Opik (1973). He considered comets to form in pre-planetary rings in the primordial solar nebula. The effect of shielding of solar radiation by dust was to reduce the temperature in the equatorial plane to 4 K at the distance of Jupiter and beyond. Opik concluded that only near Jupiter's distance was the density great enough for gravitational instability to occur. Because he believed angular momentum would prevent collapse, Opik concluded that gradual accretion of grains was the dominant factor in comet formation.

A unique feature of Opik's analysis is the accumulation of cometary nuclei around gravitational centers formed by collisional fragmentation of 10^3-km-size objects. In this way, he associated meteorites with comets. It is, however, difficult to follow the various stages of the accumulation process. In particular, the early formation of the 10^3-km sublunar objects without accumulation of large ice/dust aggregates was not explained. No discussion of the structure of the nucleus was given. It was implicitly assumed that a close-packed object developed with the mean density of the ice/dust/meteoritic constituents.

Comet formation by stochastic accretion of grains was proposed by Hills (1973). He suggested that grains condensing from vapor would be likely to have a filamentary or snowflake-like structure that would facilitate their sticking to each other. This possibility had been the basis for the accretion mechanism proposed by Donn and Sears in 1963. Hills suggested that smaller agglomerates, on the order of a meter in diameter, are loosely packed, fragile aggregates that can be as readily sand-blasted apart as built up by impacting grains. By the time their radii reach 15 km, these aggregates are assumed to be compacted to the bulk density of meteorites or asteroidal material (e.g., at least 3.6 $g{\cdot}cm^{-3}$). These conclusions do not follow from an analysis of the accretion process, but from fitting a theoretical accretion size distribution to Anders' (1965) empirical distribution. Implicitly, therefore, objects with radii of 15 to 30 km have the characteristics of compacted dense asteroids.

In a later paper, Hills (1982) considered comets to accrete under the influence of unbalanced radiation pressure on grains due to self-shielding by dust clumps. Neither dynamic nor aerodynamic effects on the motion were treated, and the structure and density of the agglomerate were not considered. The origin of the initial clumps was assumed, but not treated.

Cameron (1975) followed his earlier accumulation paper (Cameron, 1973) with a somewhat improved calculation. In his 1973 paper, all clusters were of the same size at each stage. He also assumed that clusters always stuck at a collision, thereby doubling in mass each time. In his 1975 Monte Carlo simulation analysis, collisions took place between particles of different sizes from a distribution that grew with time. Calculations were performed with sticking probabilities of 1 and 0.1. The former led to a distribution of clumps that rose to a peak at the maximum size of 10^{16} grains, whereas a 0.1 capture probability peaked at 10^{10} grains, with a maximum at 10^{12}.

A second approach used an analytical method by integrating the rate equations for the number of particles of size i. Head-on collisions resulted in amalgamation, whereas tangential impacts led to fragmentation of the aggregates. Calculations were carried out for capture probabilities p from 0.5 to 1. The maximum size attained in these calculations was about 10^{-8} cm for $p = 0.5$ to 10 cm for $p = 1$. For $p = 0.5$ to 0.9, there was an almost flat distribution, with peaks at the initial and maximum sizes. For $p = 1$, a small, sharp peak occurred at the smallest sizes, with a steep increase to a large peak at almost the maximum size.

Biermann and Michel (1978) applied the gravitational instability theory of Safronov (1969) and Goldreich and Ward (1973) to comet formation in the presolar nebula at $\sim 10^4$ AU. The initial nebula mass was about 2.5 $M_\odot$. The temperature in the region of comet formation was 10 to 20 K. The upper limit for cometary masses was 10^{18} g, with radii of 10 km. The mean density of the nucleus was ~ 1 $g{\cdot}cm^{-3}$. As in almost all other theories of formation, no discussion of grain accumulation or resultant structure of the nucleus was given.

R. Greenberg et al. (1978) treated the case of planet formation in the region of Uranus and Neptune, starting with planetesimals produced by the Goldreich and Ward (1973) mechanism. For the accumulation of terrestrial planets, 1-km objects were the starting material. For the region of Neptune, Goldreich and Ward's (1973) theory yields initial objects about 100 km in diameter. Greenberg et al. (1978) suggested that coagulation and nonhomologous settling of grains to the mid-plane could cause smaller regions of instability to develop before all material settled out, thus producing a distribution of kilometer-sized aggregates. The authors proposed these initial objects to be the comets that were ejected into the Oort Cloud. Agglomeration into larger bodies formed Uranus and Neptune.

A random accumulation process was proposed by Horanyi and Kecskeméty (1983). This was a rather artificial procedure in which a mixture of volatile and refractory grains were distributed at random about an initial seed particle in a three-dimensional rectangular lattice. Percolation theory (Stauffer, 1979) was used to determine the cluster distribution and properties. Although this suggestion did introduce recent developments in aggregates built by random processes, it was a purely geometric process and omitted any physics of accretion. It assumed that comets formed by single grains adding to the nucleus one by one and that a grain was either a refractory dust grain or an ice grain. This contradicts the generally accepted hypothesis, for which there is rather good evidence (see, e.g., Tielens and Allamandola, 1987), that many grains consist of ice coatings on refractory cores, particularly in the dense clouds where comets would accumulate. There is also good evidence from accumulation simulations (e.g., Cameron, 1975; Meakin et al., 1985) that cluster-cluster accretion is the primary growth mechanism, and the cluster size distribution grows with time.

An interstellar origin for comets was proposed by J.M. Greenberg (1986a, 1986b). He suggested that accretion of his model of roughly cylindrical interstellar grains with refractory cores, a radiation-processed organic intermediate layer, and volatile mantles would yield loosely packed aggregates. These are the fluffy, "bird nest" structures he has proposed. These aggregates cluster together to form larger clumps, and the process repeats itself until cometary-sized objects form. These loosely packed aggregates yield a low-density nucleus. Based on the density of cometary meteors, Greenberg attributed a density to the nucleus of 0.2 to 0.5 $g \cdot cm^{-3}$. He concluded that only 40% of the volume is filled. It appears that his derivation includes the refractory dust component only; adding an approximately equal mass of volatile material would double the density. This accumulation process and structure is generally similar to Donn's (1981) model. Greenberg, however, did not describe the global structure of the nucleus. He seemed to imply an overall uniform composition and structure for his fluffy nucleus.

Another version of interstellar cloud formation has been given by Napier and Humphries (1986). As in the Hills' (1981) process for the outer part of the solar nebula, this scheme depends on the radiation field to build up dust concentrations. In this case, it is not radiation pressure, but photodesorption of a volatile mantle, that provides the impulse causing grains to move towards the obscuring dust concentration. This requires that the adsorption efficiency be large, whereas recent measurements (Bourdon et al., 1982) yielded very low values. The calculated velocity of grains using a high desorption efficiency was about 10 $m \cdot s^{-1}$ and would be less for gravitational collapse.

Weissman (1986) proposed the concept of cometary nuclei as primordial rubble piles (i.e., loosely bound agglomerations of smaller icy-conglomerate fragments) weakly bonded by local melting at contact surfaces and subject to occasional disruptive events. It represents in many ways a variation of the model proposed by Donn (1981) in which the nucleus is a heterogeneous agglomerate of ice and dust aggregates.

Shortly after Weissman's publication, Gombosi and Houpis (1986) suggested a modified icy-glue model of the nucleus. The authors argued that the nucleus was composed of large (tens of centimeters to hundreds of meters), porous refractory boulders that were bonded together with a mixture of ice-dust grains; the composition of the boulders was assumed to be similar to that of the outer asteroid belt objects and the outer satellites of the giant planets (i.e., hydrous silicates containing complex carbon compounds). The large, porous boulders first agglomerated in the region where Jupiter was forming; a large fraction of this material diffused into the regions where Uranus and Neptune were forming. Agglomeration was quite slow in this region, and the boulders came together with the ice and dust that was still in the small-grain phase to form the icy-glue nuclei. As the nucleus evolved, the regions above the largest boulders lost their volatile ices and became inactive. The regions between the boulders, on the other hand, may be quite deep (50 to 100 m) and become inactive only after many passages close to the Sun; jets are supposed to originate from these areas.

O'Dell (1986) hypothesized the continual formation of comets by accumulation of material ejected from the asteroid belt. This hypothesis was based on the Infrared Astronomical Satellite (IRAS) detection of such an asteroidal dust cloud and a possible additional cloud in the outer solar system. Some of the asteroidal grains are ejected by radiation pressure into the outer solar system, where they become coated with volatile mantles of interstellar gas. However, at the low densities, this would consist of atomic and ionized gas only, and mantle formation is questionable. Interstellar grains are observed to have volatile mantles only in dense clouds. O'Dell's calculation makes extremely favorable assumptions. The concept of asteroidal cores collecting the grains also is ad hoc, as O'Dell recognized. A final point concerns the structure of the nucleus. This would consist of the dense core and fluffy outer layer. It is difficult to see how a multiple-core object would form by this mechanism, and the process was not described.

Yamamoto and Kozasa (1988) have also treated the cometary nucleus as an aggregation of planetesimals. In their analysis, as in that of Goldreich and Ward (1973), the basic building blocks were the assumed compact bodies formed in the collapse of the gravitational instabilities in the dust disk. Yamamoto and Kozasa adopt the reasoning of R. Greenberg et al. (1978) that in the Uranus-Neptune region, these bodies will have radii of about 3 km. Therefore, they find that the nucleus is composed of only a few cometesimals.

Bailey (1987) suggested that comets form in cold shells of material that are swept up by a powerful protostellar wind. Grain-grain collisions occur frequently in the dense environments of such shells and lead rapidly to the formation of large grains with radii of $> 1\ \mu m$. These large grains form a thin, but dense, dust shell in front of the gas shell. If the velocity dispersion of the large grains decreases sufficiently, local gravitational instabilities in the dust shells can occur and lead to the amalgamation of dust clumps into masses comparable to those of cometary nuclei. According to this hypothesis, comets would occur frequently around normal stars, as well as in molecular clouds and in the interstellar medium. The structure and composition of the nucleus were not considered.

The analysis of the complex processes involved in this mechanism of comet formation contains many assumptions concerning the processes as well as estimates of physical conditions. It is assumed, for example, that the grain size distribution in the shells is the same as in the interstellar medium. The latter grains, however, are produced in a variety of sources and have undergone a variety of physical and chemical processes. Also, the usual assumption is made that coagulation produces compact grains. This assumption is discussed in detail in the next section.

Bailey does not discuss the ice/dust character of grains or the structure and composition of the nucleus formed by this process.

It is a common feature of essentially all the accumulation proposals that the grains yield a solidly packed object. Only Donn (1963, 1981), Alfven and Arrhenius (1970), and Mayo Greenberg (1985) proposed that aggregates would be more loosely packed. In the next section, we review recent work on grain accretion and its application to the structure of comets.

4. Mechanism of Grain Accumulation

4.1. Impact Velocities of Grains

It was pointed out in Section 2 that the accretion of volatile cometary grains requires collision velocities of less than a few tenths of kilometers per second. Detailed calculations for the primordial solar nebula, carried out by Volk et al. (1980), Weidenschilling (1984), Safronov and Vityazev (1985), and Markiewicz and Volk (1988), confirm the earlier estimate that small grains have relative velocities in the range of 1 $cm \cdot s^{-1}$ to 1 $m \cdot s^{-1}$. Similar velocities are expected in dense interstellar clouds (Volk et al., 1980).

The Brownian velocities of small aerosols at standard conditions in equilibrium with the gas have been tabulated by Fuchs (1964). For particles from 10 to 100 nm, the velocities decrease from 160 to 5 $cm \cdot s^{-1}$. Thus, aerosol velocities coincide with the range of cloud velocities for nanometer-sized particles. In the preparation of soot from hydrocarbons in flames at temperatures of ~2000 K, the velocities are over 2.5 times larger. The small carbon grains readily stick together to form fluffy clusters (Samson et al., 1987).

4.2. Accretion of Grains

It has been pointed out in the past (e.g., Weidenschilling, 1980) that at the relative velocities in the solar nebula, van der Waals forces are sufficient to cause grains to have a high sticking probability. Experimentally, there is a pronounced tendency for grains condensed from the vapor to coagulate into clusters. Figure 1 (Whitlaw-Gray and Patterson, 1932; Fuchs, 1964; Stephens and Russell, 1979; Samson et al., 1987) demonstrates this sticking efficiency. This has an important consequence for the structure of these clusters and more massive aggregates.

It has been demonstrated that such clusters formed under a variety of conditions are fractals (Weitz and Oliveria, 1984; Forrest and Witten, 1979; Samson et al., 1987). Two pertinent characteristics of fractals are that they are self-similar under a large range of scale lengths and that the porosity increases with size. This is illustrated in Figure 2 for a geometrical fractal constructed by starting with an equilateral triangle and at each succeeding step removing the central part of each filled triangle. Figure 3(a) shows a colloidal gold aggregate, and Figure 3(b) is a plot of ln N versus ln L for the aggregate, where N is the number of primary particles within a volume of length L. The straight line indicates that $N \propto L^D$, where D is the slope of the line and is the fractal dimension; in this

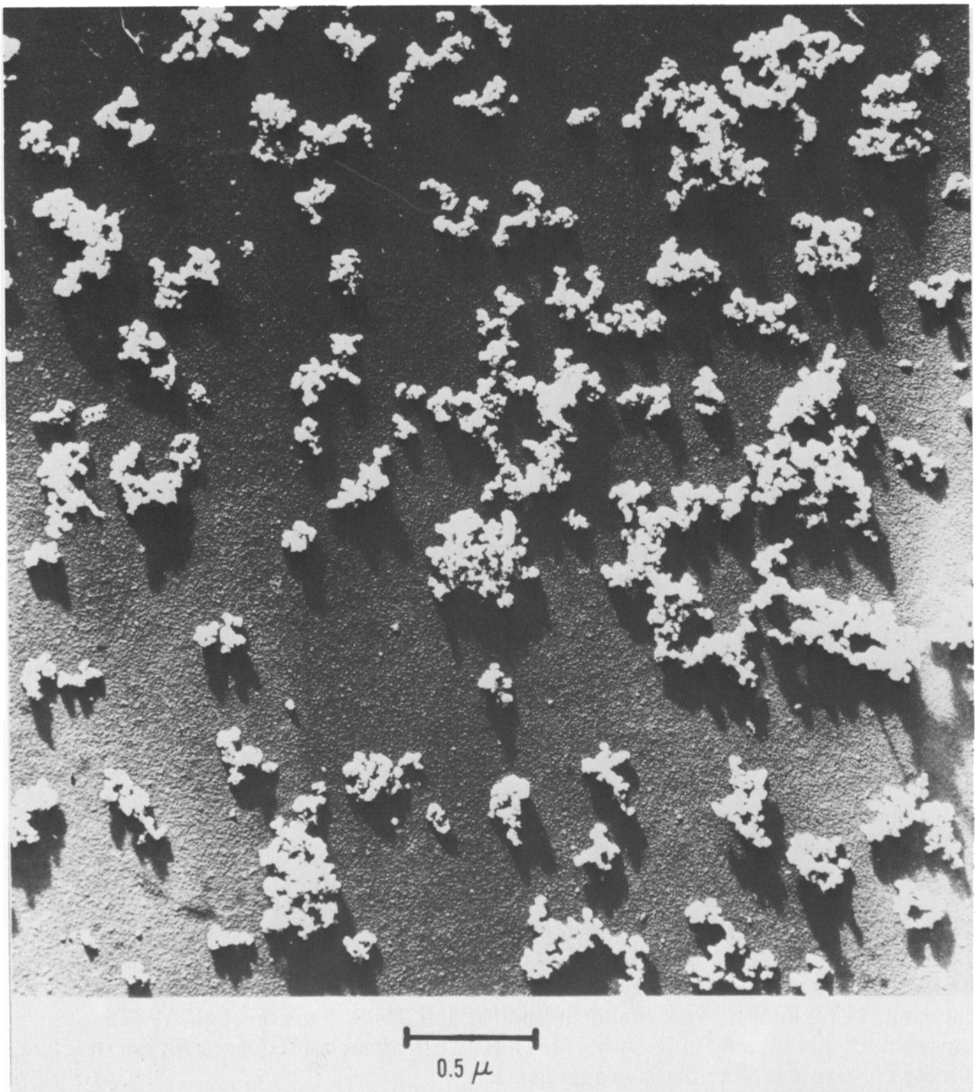

Figure 1. Electron micrograph of SiO_2 clusters formed by oxidation of SiO_4 in a flame of oxygen and hydrogen. The clusters are gold-shadowed to show three-dimensional structure, and 1 cm in figure corresponds to 0.2 μm. (Courtesy of Cab-O-Sil Division, Cabot Corporation.)

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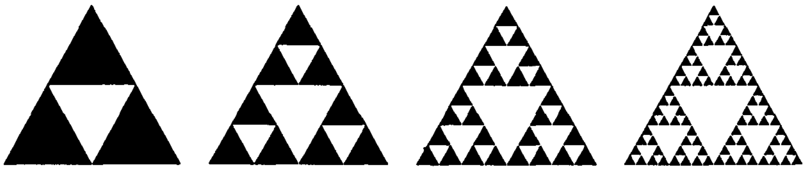
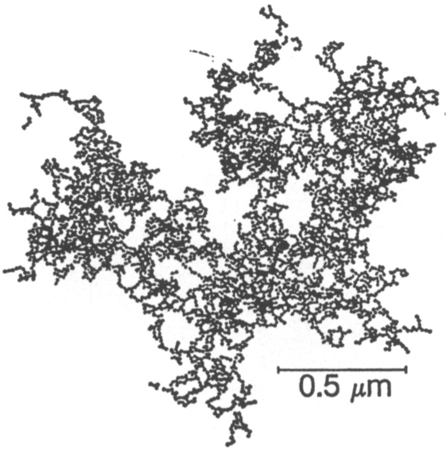


Figure 2. A geometric fractal, the Sierpinski gasket generated by removing a central triangle from each filled triangle. The fractal dimension obtained in the limit of an infinite number of generations is 1.58.... Note how the area of the voids increases in successive generations.



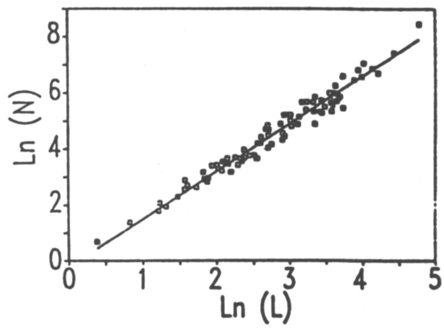


Figure 3. (a) TEM image of a typical gold colloid aggregate. This cluster contains 4739 gold particles. (b) Ln N versus ln L for the gold cluster where N = the number of grains in a volume of side L. The solid line is a least-square fit to the data, with the slope giving D ~ 1.75. N can be converted to mass by multiplying by the mass of a single gold particle, ~ 10^{-17} g, while L can be converted to nanometers by multiplying by 14.5.

case, D = 1.75. The density ρ of the aggregate equals N/L^3. Hence, $\rho \propto L^{D-3}$, which for the colloidal particle equals $L^{-1.25}$. This illustrates the increasing porosity or decreasing density with size for a fractal.

Figures 4(a) and 4(b) show two views of a soot aggregate and a computer simulation of accretion by a cluster-cluster mechanism. The similarity of the structures of the soot particle and the simulation are apparent. Because of the general agreement in primary particle size and velocity, the laboratory and simulation fractal structures are expected to apply to grain accretion in cosmic clouds (Meakin and Donn, 1988).

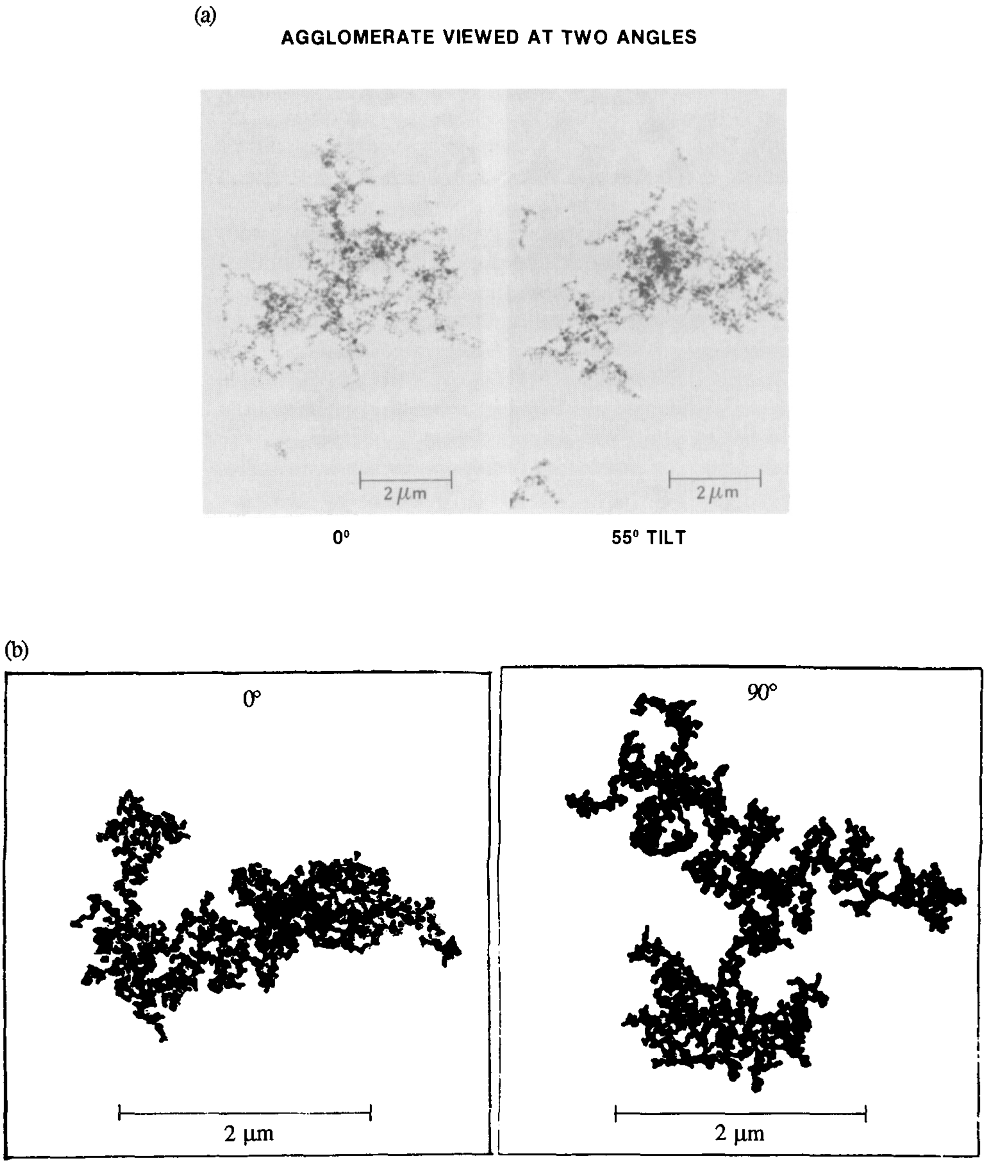


Figure 4. (a) Soot agglomerates formed by acetylene combustion. The primary particle size is about 30 nm. For more details and analysis, see Samson et al. (1987). (b) Two perpendicular projections of a numerical simulation of ballistic cluster-cluster accretion. The aggregate shown has 10,000 particles.

An example of a fluffy particle collected high in the atmosphere is illustrated in Figure 5. Terrestrial collections of interplanetary particles are biased towards more sturdy, compact samples. In order to be collected, cometary particles must first survive incorporation into comets and an assortment of evolutionary processes associated with comets. After release from a comet, they must survive several thousand years of exposure to the solar wind and possible impacts with other interplanetary particles. Then there is atmospheric entry, and impact with the collector. Finally, Brownlee pointed out (Brownlee et al., 1980) that small, very low density particles would probably flow around the collector and not be captured.

As a consequence of the high sticking probability and low impact velocities, accreting grains tend to stick where they first make contact. This prevents the formation of the usually assumed close-packed particles and instead produces the porous, filamentary fractal structure. Fractals have a large surface-to-mass ratio (Meakin and Donn, 1988), causing the gas drag to decrease slowly with size, as illustrated in Figure 6. Aggregates consisting of many primary particles, therefore, also have low relative velocities. Another consequence of their open, irregular shape and low velocity is that fractal aggregates will readily cluster into larger, fluffy agglomerates.

Cluster-cluster accretion also produces fractal aggregates (Meakin and Julien, 1988) with a fractal dimension about 1.95. If an impinging cluster contacts the growing cluster at

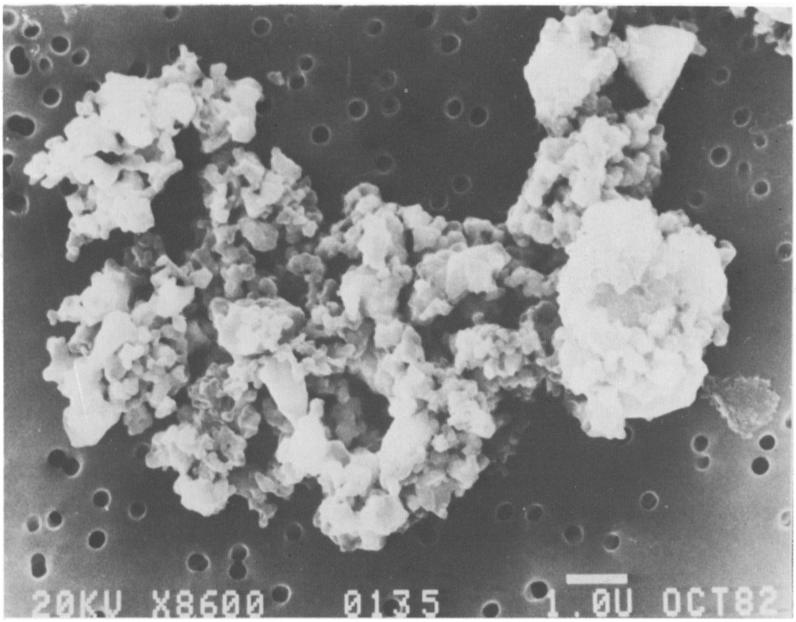


Figure 5. An interplanetary dust particle collected in the stratosphere by a U2 aeroplane. Note the similarity to the more compact fractal clusters in Figure 1. (Courtesy of Don Brownlee.)

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several points, a more compact aggregate results and the fractal dimension increases (Julien and Meakin, 1989). For three contact points, D = 2.12.

Fractal aggregates with their filamentary structure and decreasing density cannot grow too large without undergoing some distortion and becoming more compact. This behavior is roughly equivalent to cluster-cluster growth with multiple contact points. It appears that the resultant distorted aggregate can approximately be represented by a fractal with $2.2 < D \leq 2.5$ (Mulholland, 1989).

4.3. ACCUMULATION OF FLUFFY AGGREGATES

To study comet formation, it is necessary to treat much larger objects produced by the continual agglomeration of the initial fractal clusters (Donn and Meakin, 1989). There does not appear to be any data regarding the properties and behavior of fractal-like particles more than a few micrometers in size. However, there is evidence that very fine particles form macroscopic objects of very low density, even in the Earth's gravitational field.

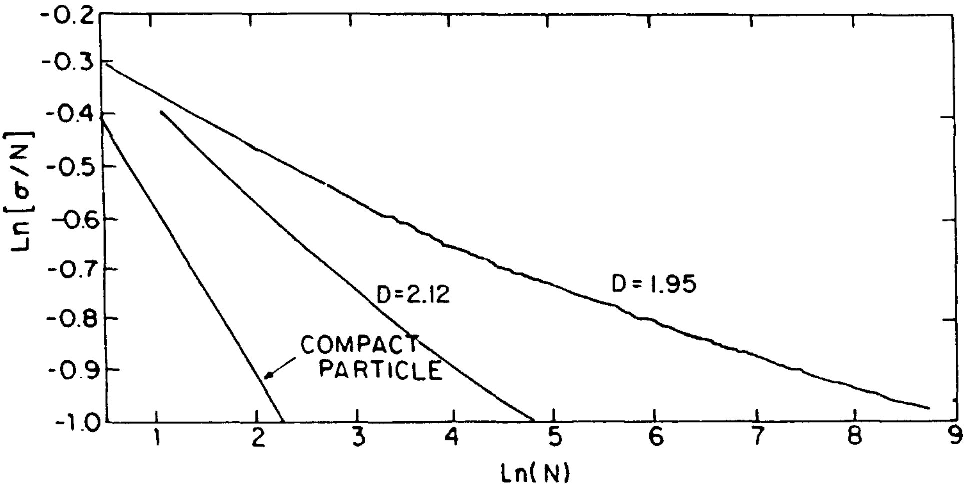

Figure 6. Ratio of the projected cross-section, σ, to the number of grains, N, in aggregate versus N. The cross-section is measured in terms of particles of unit diameter, $\sigma_0 = \pi/4$. Results are shown for fractals with fractal dimensions of 1.95 and 2.12 and for compact spherical particles. $\sigma = \sigma_0 N^{2/3}$, $\sigma/N \propto N^{-1/3}$. For D = 1.95, σ/N approaches an finite value as N becomes very large.

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Table 1 compares the apparent density of powders of several materials with the density of the bulk material. The low ratio of apparent to bulk density shows that the packing fraction is low for these samples. The effect of size on packing of grains is shown in the measurements of Oudemans (1965) presented in Table 2. Each sample was moderately vibrated under controlled conditions as the vessel containing the powder was filled to a height of 6.6 cm. It is seen that the density is very low for the smallest size and increased with particle size or mass. It is therefore assumed that aggregates with very low self-gravity, accumulating in space, would have low density and be compressible because of their porosity. The analysis of accumulation that follows shows that this is a self-consistent assumption.

For aggregates too large to be fractals, the assumption is made that the soft impacts will cause some compaction of the tenuous filamentary structure, producing particles of a more uniform density. As these bodies grow, there is less interaction with the gas, and the impact velocity increases up to meters per second. At some size, which is rather arbitrarily taken to be a meter, collisions will cause significant compaction and smaller aggregates will interpenetrate larger ones.

Because these aggregates are essentially inelastically compressible, they are effective absorbers of energy. Unless there is considerable fragmentation or complete penetration, the coagulation efficiency is high. The problem of large rocky objects bouncing apart raised in previous accumulation studies does not occur with the porous,

Table 1. Density of Particles in Smokes (Fuchs, 1964)

Material	Density True	Density Apparent	Method of Producing Smoke
Au	19.3	0.2 - 8.90	Vaporization in electric arc
Ag	10.5	0.64 - 4.22	Vaporization in electric arc
Hg	13.6	0.07 - 10.8	Heating in boat
MgO	3.6	0.24 - 3.48	Burning metallic magnesium
$HgCl_2$	5.4	0.62 - 4.3	Heating in boat
CdO	6.5	0.17 - 2.7	Vaporization in electric arc

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Table 2. Dependence of Powder Density on Grain Size (αFE_2O_3 Chemically Pure Powder; Density = 5.24 g)

Grain Size (μm)	Density ($g \cdot cm^{-3}$)
0.05	0.580
0.1	0.613
0.3	0.667
1.0	1.428

compressible objects expected to form when self-gravity is small.

The analytical treatment of the coagulation of such bodies is rather straightforward. One equates the relative kinetic energy of the two bodies prior to the collision to the work done in penetration and compaction. This yields Equation 2:

$$1/2\mu V_R^2 = 2 \int_0^{<S_o>} P(S)\, \Sigma\, (S)\, dS \tag{2}$$

where μ = the reduced mass and is approximately the mass of the smaller cluster, V_R = the relative velocity, P(S) = the pressure exerted in penetrating or compacting to a depth S, $\Sigma(S)$ = the cross-section of the penetrating body at S and can be approximated by $2\pi RS$, and S_o = the maximum penetration. The average penetration $<S_o>$ over the interface is $S_o/2$ for spheres. The factor 2 in Equation 2 occurs because it is assumed that the same amount of work is done on each body. The task is to determine S_o when the circumstances of the collision, characterized by μ and V_R, are given. If the response of fluffy aggregates to an impact and the function P(S) were known, the determination of S_o would also be straightforward. At present, neither is reliably known and it is necessary to resort to simplifying assumptions and approximations. These assumptions are: (1) the aggregates are spherical with uniform density; (2) one body is significantly smaller than the other; (3) V_R lies nearly along the line of centers (i.e., there is a small impact parameter); and (4) the effect of the impact is to compact material only in a cylindrical volume with a cross-section identical to that of the smaller body. The length of the cylinder is taken to be proportional to the penetration S_o, and equal to λ S_o. Values of λ have been estimated from the experiments of Oudemans (1965) and Peak et al. (1989), which suggest a number on the order of unity.

As an approximation for P(S), the results of Oudemans (1965) for 0.3-μm Fe_2O_3 powder are used. These are shown as a pressure-density relation in Figure 7. Similar data for snow (Abeles and Gow, 1975) are also presented. In a later paper (Donn, 1990), a simple analysis suggested that compaction occurs under approximately constant pressure corresponding to some appropriate density. The mean density $<\zeta>$ of the compacted zone is adopted here. This is given by

$$\frac{\lambda + 1}{\lambda} \rho \tag{3}$$

as the mass in a cylinder of length S is combined with the material initially in the compacted zone of length λS. The mean density depends only upon λ, not S, and remains constant as penetration occurs. It seems a reasonable approximation to view the penetration process as one in which material is continuously compressed to a density $<\zeta>$. These assumptions yield Equation 4:

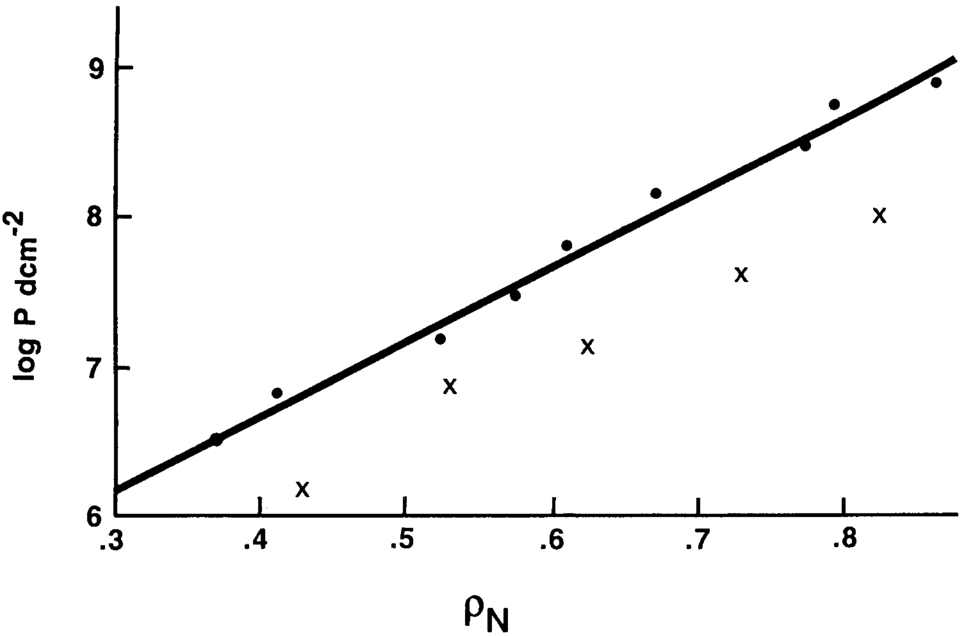

Figure 7. Compaction of 0.3-μm Fe_2O_3 powder, showing compaction pressure versus compacted density of the sample. Dots represent Fe_2O_3, and crosses represent snow.

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$$\langle S_o \rangle = \left[\frac{0.65\ \rho_o \rho_s}{3\mathbf{P}(\langle\rho\rangle)}\right]^{1/2} R\, V_R \tag{4}$$

where ρ_o, the aggregates' normalized relative density before collision, $= \dfrac{\rho}{0.65\ \rho_s}$, ρ_s = the solid density, $P(\langle\rho\rangle)$ = the adopted constant pressure corresponding to density $\langle\rho\rangle$, R is the radius of the smaller aggregate, and V_R is the relative velocity. An assortment of grains can be compacted only to a maximum density equal to about 0.65 ρ_s (Yerazunis et al., 1962; Dexter and Tanner, 1971; Rodriguez et al., 1986; Julien and Meakin, 1987). The occurrence of ρ_o and P under the square root means the result is not very sensitive to these quantities. Collisions will approximately uniformly compact the smaller body and compact a portion of the larger. Hence, the average density increases with size. A rather arbitrary run of density with size was adopted and is given in Table 3. In Table 4, the data for representative collisions are displayed. The first two columns are the basic collision parameters—size and relative velocity. The last two show the effect of the impact—maximum penetration and size of the impact zone.

It is seen that for $V_R < 10^3$ cm·s^{-1}, complete agglomeration results from small impact parameters. Relative velocities of 5×10^3 cm·s^{-1} yield impact zones slightly larger than the diameter for the adopted effective density. For unequal-size bodies, agglomeration would occur. Larger velocities require that one aggregate be at least twice the size of the other. Limiting V_R to be under 5×10^3 cm·s^{-1} is not a serious constraint for low-density aggregates, according to current theories of accumulation in the primordial nebula (Volk et al., 1980; Weidenschilling, 1984).

4.4. FORMATION TEMPERATURE AND MAXIMUM COMET SIZE

The temperature rise, ΔT, caused by the impact can be obtained from the relation

$$\mathbf{1/2}\mu V_R^2 = JCM^1\ \Delta T + \Delta E \tag{5}$$

In Equation 5, J is the mechanical equivalent of heat, C the average specific heat of the material, M^1 the mass of impacted material, and ΔE the energy going into breaking bonds in the compaction. As there is essentially no information on ΔE and it is presumably small in the aggregates, the last term has been neglected, yielding a maximum value for ΔT. For V_R values of 10^3, 5×10^3, and 10^4 cm·s^{-1}, the corresponding values of ΔT are 1, 25, and 100 K, respectively. Any compaction outside the cylindrical impact zone or diffusion of heat outside it will reduce ΔT. For $V_R < 5 \times 10^3$ cm·s^{-1}, no significant thermal effects from the impact will occur. Higher velocities will tend to vaporize the volatile component of the aggregate. This effect, combined with fragmentation at velocities appreciably in excess of 5×10^3 cm·s^{-1}, suggests that comets can form only when $V_R \leq 5 \times 10^3$ cm·s^{-1}. Velocities increase for larger aggregates, and the calculations of Volk et al. (1980) and Weidenschilling (1984) indicate V_R will be ~ 10^4 cm·s^{-1} for aggregates larger than about a kilometer. This suggests that nuclei composed of such size aggregates will not grow much larger and will start being depleted in volatiles. Objects rich

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Table 3. Assumed Radius-Density Relation

R	ρ	λ
< 50 cm	0.1	0.5
50 - 200	0.2	1
200 - 1000	0.3	2
> 1000	0.4	3

Table 4. Representative Collisions $\rho' = <\rho>$

r (cm)	V_R (cm·s^{-1})	S_o (cm)	$(1 + \lambda)S_o$ (cm)
100	10^3	32	32
1000	10^3	300	600
10^4	10^3	2060	6180
1000	10^4	1780	5240
10^4	10^4	2.1×10^4	6.3×10^4

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in volatiles would be limited to radii of less than some tens of kilometers, in agreement with observations (Opik, 1966).

5. Structure of the Nucleus

Models of cometary nuclei that formed by the accumulation of cometesimals have been prepared on several occasions. On the basis of the observed behavior of comets, particularly fragmentation, Fesenkov (1963) developed a model composed of a relatively small number of closely packed aggregates.

Donn's (1963) single, low-density aggregate model formed by grain accumulation was modified (Donn, 1981) to take into account accumulation of a hierarchy of cometesimals (see, e.g., Greenberg et al., 1978). This was also a close-packed array of dust and ice-dust objects with an arbitrary size distribution. In 1985, Donn, Daniels, and Hughes (1985) applied the random accretion calculations for meteoroids carried out by Daniels and Hughes (1981) to comets. Those authors used a constant size distribution $n(m)m^{-1.73}$. It was assumed that scaling the dimensions of the aggregates from submillimeters to kilometers would not significantly affect the structure. The meteoroid structure adopted for comets was very porous and contained many large voids. This was the fractal model of the nucleus.

Weissman (1986) described a structure similar to that of Fesenkov (1963) and Donn (1981), which Weissman called the primordial rubble pile. It consisted of an agglomeration of macroscopic icy conglomerate bodies weakly bound by local melting at contact surfaces. Another variation was the icy-glue model of Gombosi and Houpis (1986). This is a close-packed collection of boulders held together by an ice-dust mixture of grains. Four models—the original icy conglomerate, the fractal model, the rubble pile, and the icy-glue models—are portrayed in Figure 8. Jewitt and Meech (1988), from careful photometry, found that a number of nuclei had significant periodic brightness variations. This was attributed to rotation of an elongated nucleus. They sought to explain such a shape by assembling a nucleus of randomly placed cometesimals around a seed particle. This process is somewhat similar to that of Donn et al. (1985), but uses identical-sized aggregates instead of clusters and places them in position at random instead of accumulating them along ballistic trajectories. The Jewitt procedure produces a much more close-packed structure. As is the case with the cluster-cluster ballistic accretion process, it tends to produce elongated nuclei.

It has been shown that for fractal accretion from grains (Meakin, 1984; Hayani and Nakagawa, 1975) and for accumulation of planetesimals (Greenberg et al., 1978), the growth process consists of the formation of a size distribution of aggregates that shifts to larger sizes as time proceeds. Consequently, a simulation of comet accumulation must use cluster-cluster interaction. This was done in the meteoroid simulation by Daniel and Hughes (1981), but they used a fixed-size distribution for the clusters. This deficiency was incorporated into the comet model of Donn et al. (1985). A schematic model of a comet formed by cluster-cluster accumulation with a time-dependent cluster size distribution is shown in Figure 9. A second deficiency in the extension from meteoroids to comets was the neglect of compaction and fragmentation that occurs when the aggregates become sufficiently massive. Compaction was introduced by Donn and Hughes (1986). The analysis of Section 4 (Donn, 1990) extends the treatment of compaction. A more

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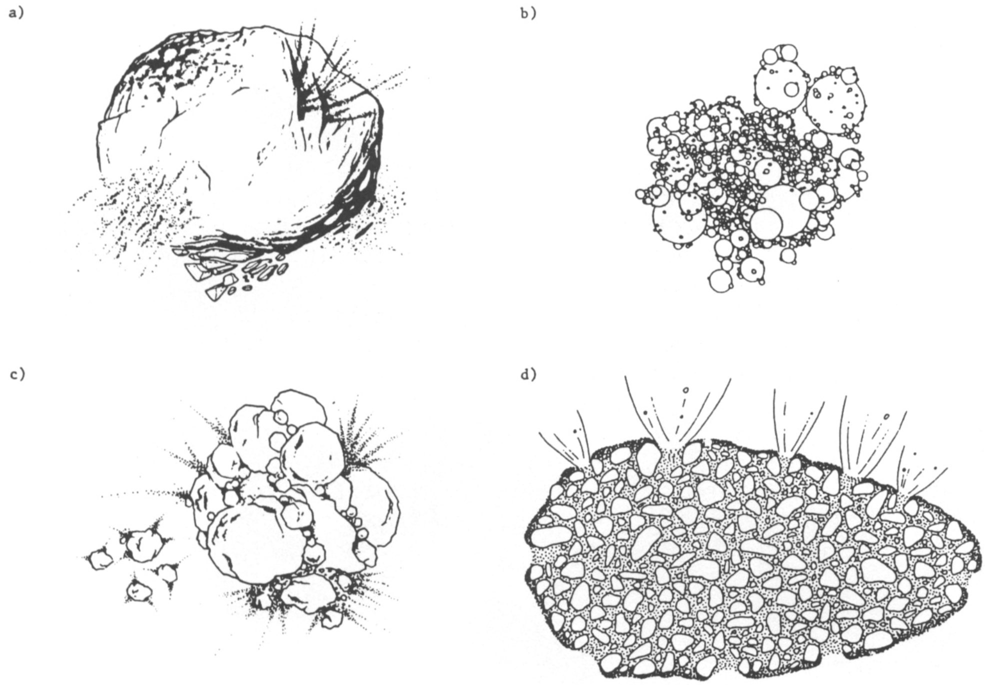

Figure 8. Proposed models of cometary nuclei: (a) Icy conglomerate model (Whipple, 1980). (b) Fluffy aggregate model (Donn, 1989). (c) Primordial rubble pile (Weissman, 1986). (d) Icy-glue model (Gombosi and Houpis, 1986).

complete simulation including cluster-cluster accumulation, compaction, and fragmentation is being developed by Meakin and Donn.

A more reliable simulation of comet accumulation requires more appropriate and more complete information on the behavior of fluffy aggregates undergoing collision. Such experiments are under way (Peak, 1989), and preliminary data on impacts in vacua have been obtained. These support the assumption that such impacts produce essentially cylindrical impact zones. The combination of the realistic accumulation procedure described in the preceding paragraph and the experimental impact data will give a better picture of the formation of comets. It will then provide a basis for a still more refined theory of comet accumulation, to compare with increasingly refined observations and the results of cometary missions now being planned.

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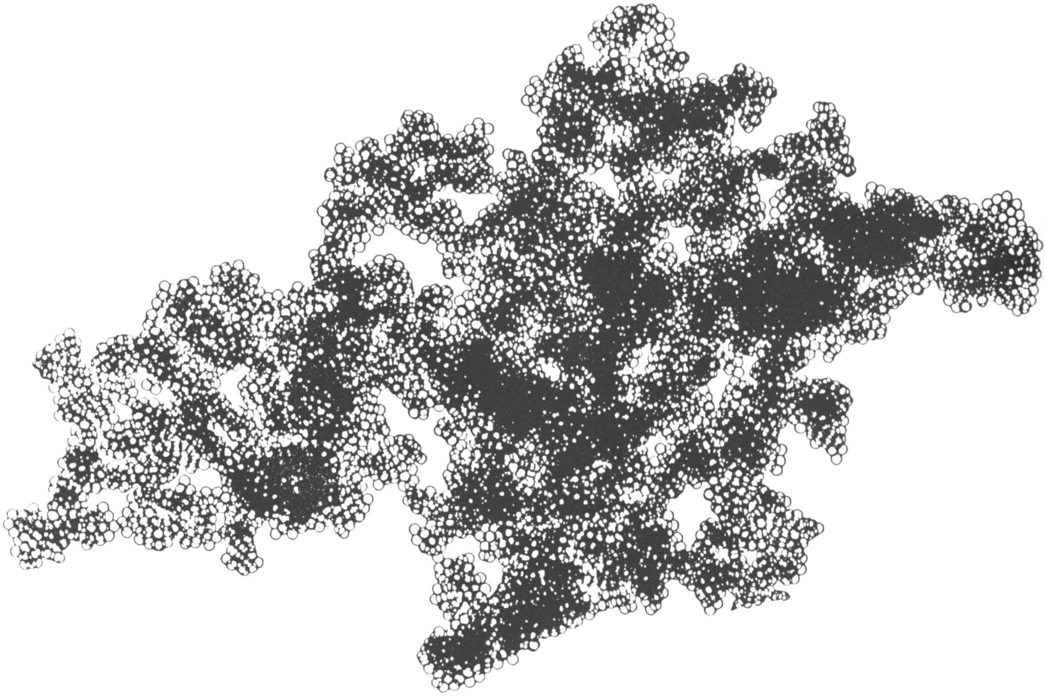

Figure 9. Projection of a three-dimensional model of a comet nucleus produced by cluster-cluster Monte Carlo simulation without interpenetration or fragmentation. The voids are probably exaggerated over what is expected to occur.

6. Observational Data on the Nucleus

Observational data of the structure of the nucleus are discussed in considerable detail in other chapters. In this section, a brief summary of the most relevant results is presented.

About 3% of comets, proportionately divided between short-period ones and longer period ones, including new comets, have been observed to fragment (Sekanina, 1982). Usually, one fragment is comparable to the original comet and all others are much smaller, although showing characteristic cometary behavior. A second phenomenon is the release of material into the coma from a small number of active regions covering from about 5% to 20% of the surface of the nucleus (Sekanina, 1990a). This behavior was shown strikingly in the images obtained by the Giotto and two VEGA spacecraft during the Comet Halley encounter. The analysis by Sekanina (1987, 1990) of the ground-based images obtained over extended time periods provided information on the duration of the active regions. Sekanina (1990) concluded that active regions should have life spans on the order of hundreds of revolutions around the Sun. However, dust jets and associated active regions do not appear to be associated with new comets, which have generally structureless comae. Another conclusion of Sekanina (1990) is that the evolution of an active region at one location is largely independent of the evolution of one located elsewhere. This further confirms the heterogeneity of the nuclear surface.

The most direct evidence for the structure of the nucleus is the encounter images from VEGA 1 and 2 and Giotto (Keller, 1987; Keller et al., 1987). These show the elongated, rather irregular shape of Halley's nucleus that is described in detail in other chapters. The encounter images showed features on the nucleus down to the limit of resolution, which was about 100 m for VEGA (Shergel et al., 1987) and 50 m for Giotto (Keller et al., 1987).

Ground-based observations of light variations from the nucleus yield not only rotation periods, but also shapes. The most systematic study of cometary light curves carried out by Jewitt and associates (Jewitt and Meech, 1988) yields axial ratios about 2:1.

All observations of nuclear properties and determinations of nuclear characteristic appear to have been made on older comets. These objects have been modified by mass loss and heating at numerous perihelion passages. However, surface features certainly differ considerably in detail between old and new comets. To what extent evolutionary processes, especially mantle formation, cause fundamental differences in structure is not clear. New comets show greater activity at large heliocentric distances, but the spectra from ultraviolet through the infrared are strikingly similar. An investigation of the continuum to molecular band emission intensity ratio for eighty-five comets (Donn, 1977), although with large uncertainty, indicated no difference between age classes. More recent measurements (A'Hearn et al., 1979, 1980) of much greater accuracy, but on many fewer comets, confirmed that conclusion.

The rather sparse observational data on cometary nuclei are consistent with the accumulation model, which suggests that they consist of a rather loosely bound aggregation of cometesimals.

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