EVOLUTION OF COMETARY DEBRIS: PHYSICAL ASPECTS

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ABSTRACT. Cometary dust particles, larger grains, and fragments as products of the disintegration processes are subjected to gravitational and nongravitational forces, causing their dynamical and physical evolution. Critical analysis of some fairly large differences in the observational data obtained for the mass productions, dust/gas ratios, cut-off masses, particle size/mass distributions, erosion factors, bulk densities, and other physical properties of particles leads to a more complex view of the cometary matter than is assumed in some of the current models. This view allows reasonable limits for the dynamical and physical interrelations between the debris and its parent bodies to be obtained.

1. Introduction

This paper deals with the physical aspects of the evolution of the end products of comets, while the dynamical evolution of meteor streams is reviewed in a paper, also from this colloquium, by B.A. McIntosh (1989). We would like to combine the dynamical evolution of particles released from comets with their physical evolution. Then we can show how these two approaches contribute to our understanding of the whole evolutionary history of cometary products from the very beginning as a halo around the nucleus and an expanding cloud of particles, through the thin filament of the first stage of the stream formation, to a broad stream of particles with its balance between the sink and supply, up to the decay of the stream and its merging into the background. All these stages of cometary debris can be characterized by physical quantities changing with time and giving information on the physical state of matter within the stream and on the structural features corresponding to the particular evolutionary stage and the dynamical history of the parent body.

2. The Early Evolution of the Physical State of Cometary Debris

Gas, dust, and larger debris released from comets are subject to gravitational and nongravitational forces that influence both their further motion and their physical states in very different ways, depending mainly on the particle mass and physical properties. The evolution of the physical state of cometary products can be followed by measuring the

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change in physical quantities characterizing the process of the disintegration of comets, the stream-forming process, and the further evolution of the stream. We will consider now the gradual change with time (corresponding obviously to the number of revolutions of the parent body) of three physical quantities characterizing the phases of this evolutionary process:

1. Mass production or mass-loss ΔM of a comet, or, on a long-term time scale, the gradual change of the comet's mass into the mass of the stream of particles and background.
2. Mean mass distribution factor S, indicating the particle's mass or size distribution and its changes from the time of particle ejection until the particles become old branches of the stream.
3. Mass range M_{max} of particles, from which the maximum mass contribution is observed at the various evolutionary stages of the stream formation process.

The time-dependent evolution of these quantities is shown in Figure 1. These results are based on numerous observational data as discussed below.

The results from space probes to P/Halley (mainly from Giotto, VEGA 1, and VEGA 2) indicate the dominant contribution of "large" particles in the cometary halo (McDonnell et al., 1987; Mazets et al., 1987). The observed packets of particles in cometary halos (Simpson et al., 1987) suggest not only the presence of large grains as sources of packets, but also a high dust concentration, causing high rates of particle collisions in this stage, and hence a quick erosion process. Curdt and Keller (1989) confirmed the dominant contribution of large particles in the vicinity of the nucleus of P/Halley in quite an independent way, analyzing the changes in the viewing direction of the Halley multicolor camera. Fulle (1988) explains the observed strongly time-dependent size distribution produced by comets Arend-Roland, Seki-Lines, and Bennett by fragmentation processes of the large dust. High large-particle rates follow also from the extrapolated dust/gas ratios over the mass scale. It should be mentioned here that even if $S < 1$, the results of D/G ratios without the reference to the limiting mass have no value, as each extra decade in the upper limit of the mass scale significantly increases the total dust contribution. For example, let the mass production $\Delta M = M_0$ for particles of masses $m \leq 1$ g. If the integrated mass index $S \leq 0.5$ is valid for $1 \text{ g} < m < 10^8$ g, then $\Delta M = 10^2 M_0$ for $m \leq 10^8$ g. This was shown clearly by Crifo (1987) and Hajduk (1987a and 1987b).

The question of a limiting mass released from the comet cannot be answered simply from observations of a single return of one comet. The full answer requires the study of the long-term mass-loss process, for these additional reasons:

1. From the observed outbursts and splitting of comets, it follows that there is no definite limit for the particle mass released. We should therefore reject any theory for a particle upper mass limit of 10^2 kg based upon the aerodynamic drag of gas escaping at normal cometary surface temperatures. Cometary fragments larger than one meter in diameter probably have been observed by IRAS (Kürth et al., 1986), and certainly particles larger than centimeter to decimeter size have been observed. Weissman (1986) reports on co-moving debris of cometary nuclei with dimensions of centimeters up

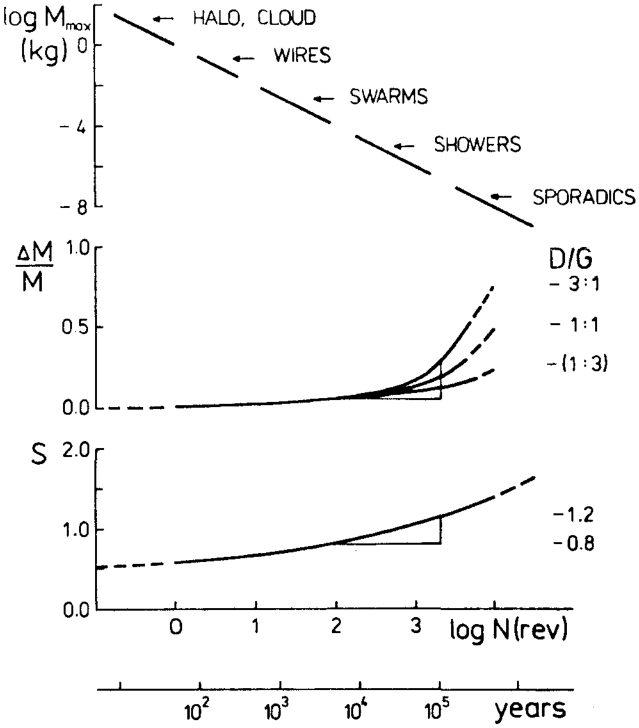

Figure 1. Evolutionary diagram of cometary debris represented by three time-dependent physical quantities: M_{max}, the maximum mass distribution point; $\Delta M/M$, the relative mass-loss of the comet for different dust/gas ratios (D/G); and S, the integrated mass distribution index. The number of revolutions, N(rev), corresponds to Halley-type orbits.

to 100 meters. Festou et al. (1987) report also on very large particles from outbursts in connection with the nucleus dust cloud. Using data from the Lunar Seismic Network, Oberst and Nakamura (1989) measured strong clustering of meteoroids with masses m < 1 kg. Banaszkiewicz et al. (1989) showed theoretically the possibility of long resident orbits around cometary nuclei.

2. The mass-loss is a very irregular process. However, for the very long-term evolution, we can calculate mass-loss using mean outburst rates or splitting rates, with the latest mass-loss estimated to about 3% per revolution, the same for young long-period comets or old short-period comets (Stefanik, 1966; Pittich, 1972; Kresák, 1981; Delsemme, 1982). If the irregularity of the cometary mass-loss process is to be applied to the evolution of the

stream, then stream structures with different mass distributions should be observed. Observations do seem to confirm this behavior (Šimek, 1987).

3. The Stream-Forming Process and the Change of Physical Quantities Characterizing the Stream

Large particles, released from the comet and moving in individual orbits slightly different from that of the comet, quickly form an expanding cloud and are spread along the whole orbit, creating a closed elliptical filament (Babadzhanov et al., 1987). In an idealized case of a nonperturbed orbit of the parent comet, this would represent an innermost core of the toroidal stream. However, a number of dynamical and physical factors strongly influence the stream-forming process, and the combination of these factors often creates complicated stream structures with separate belts, branches, mass concentrations, etc. (McIntosh and Hajduk, 1983; Porubčan and Štohl, 1987; Olsson-Steel, 1987).

The dynamical aspects of the stream formation, including the orbital evolution of the parent body and the orbital evolution of individual particles, have been studied and summarized by McIntosh (1989). There are, however, physical factors causing superposition of these effects. First of all, each new return of the comet leads to the superposition of new and old ejecta within the stream, as the orbital diffusion is quicker for smaller particles ejected with higher velocities. When the mass-loss, and hence the supply to the stream, is irregular, the particle mass distribution will vary through the observed shower period. However, it is difficult to distinguish between the real variation of the mass index and its measured scatter due to the differences in observational techniques or reduction methods (Hughes, 1971 and 1987). On the other hand, reliable differences in S values can be deduced from systematic and simultaneous observations of meteor showers: Two populations of meteors with S values of 0.8 and 1.2 have been found in this way for the Halley meteor showers (Hajduková et al., 1987). Very pronounced variations in particle flux and mass index have been recorded during meteor swarms, such as in the Leonids' 1966 display (McIntosh, 1973 and 1989).

Erosion processes tend to shift the mass distribution of ejecta towards higher S-values with time, as a consequence of the gradual disintegration of different-size meteoroid particles. We do not include in our discussion micrometer- or submicrometer-size particles, since they leave the comet-like orbit much earlier than the stream phase or even than the filament phase. Considering over 20 different erosion factors, Kapišinský (1987) concluded that the combined effect of impact erosion and of corpuscular sputtering was most important on the larger particles. According to Grün et al. (1985a and 1985b), catastrophic collisions dominate the small mass scale up to 10^{-8}-kg particles. Moreover, the efficiency of such erosion is inversely proportional to the particle bulk densities. According to Dohnanyi (1978), the maintenance of the mass distribution in the stream in a steady-state condition requires a stable source of larger particles, replacing those destroyed by collisions. However, the steady-state condition is rather a transitional stage in the evolution of a meteor stream. Recent results from radar observations (Šimek, 1987) indicate that showers without an active parent comet, such as the Geminids or the Quadrantids, are characterized by the lack of larger particles. This means that an originally flat particle size distribution, including large cometary fragments identified as dark matter from infrared and radio observations (Hanner et al., 1985; Goldstein et al., 1984), changes to a steeper distribution through collision-caused fragmentation, but also by further vaporization of volatiles from grains or fragments, as deduced from the fading rate decrease of cometary comas (Baum and Kreidl, 1986), or by grain sublimation (Hanner, 1981). A consequence of such erosion, together with a quicker dynamical spread of the orbits of high-velocity small particles, leads to a gradual shift with time of the mass interval of the maximum mass contribution (M_{max} in Figure 1) in the evolving stream towards the smaller masses. M_{max} of most meteor showers is between 10^{-6} and 10^{-4} kg (Hajduk, 1987a and 1987b). This is also confirmed from lunar cratering data (Grün, 1987), while M_{max} of background meteors has been determined to be about 10^{-9} kg (McDonnell, 1978).

4. Bulk Densities of Particles and Parent Bodies

The physical evolution of particles released from comets depends strongly on the erosion processes, discussed above, and hence on the physical properties of the particles; in the mass interval of meteoroids, it depends mainly on the fragmentation index, which is associated with the bulk density. We thus now consider the derived bulk densities of particles as a function of mass, as shown in Figure 2. Each reference has been placed into the position as close as possible to the corresponding mass interval and density. References from the mass interval of about 10^{-5} to 10^{10} g correspond to the radar or photographic observations of meteors and fireballs, or to meteorite investigations; densities of smaller particles have been obtained from collection experiments or *in situ* measurements. Some of the references in the lower left of Figure 2 correspond to spectrographic or mass spectrometric data without any direct indication of bulk density values, but they recognize the chondritic nature of many particles, which may, however, have fluffy structures as well as compact ones.

The first impression from Figure 2 is that we may choose what we want. Unfortunately, we can scarcely consider the majority of results as observational errors or errors in the detection techniques. Moreover, in the laboratory we can study meteorites with densities of 7.0 $g \cdot cm^{-3}$ as well as collected particles of 0.1 $g \cdot cm^{-3}$. The general trend that is present ranges from parent bodies (on the right side in Figure 2) to fragments (in the middle) to dust grains (on the left), and, of course, also gaseous material. We now try to reconstruct the composition and structure of the parent bodies from this debris and smog. This is a starting point for making nucleus models.

The discussion on the bulk densities of the interplanetary dust particles has been renewed in connection with attempts to determine, from ground-based and spaceborne data, the mass and density of the nucleus of comet Halley. Rickman's (1986) determination of the mass of the nucleus of Halley from its acceleration by nongravitational forces, yielding a nucleus density between 0.1 and 0.3 $g \cdot cm^{-3}$, created much recent interest. Whipple (1986) later showed the uncertainties connected with the latter method, which make models of cometary nuclei themselves highly uncertain. If comets are inhomogeneous as suggested by Delsemme (1985), a series of models over a broad scale of densities will be required.

Fortunately, we have a large number of meteoroid-size fragments to study, and, using a sufficiently reliable physical theory, we can derive the density distribution of meteoroids in different mass regions. The revision of earlier work of Verniani by Ceplecha (1987 and 1988) led to a recognition of the proportional distribution of fragments of

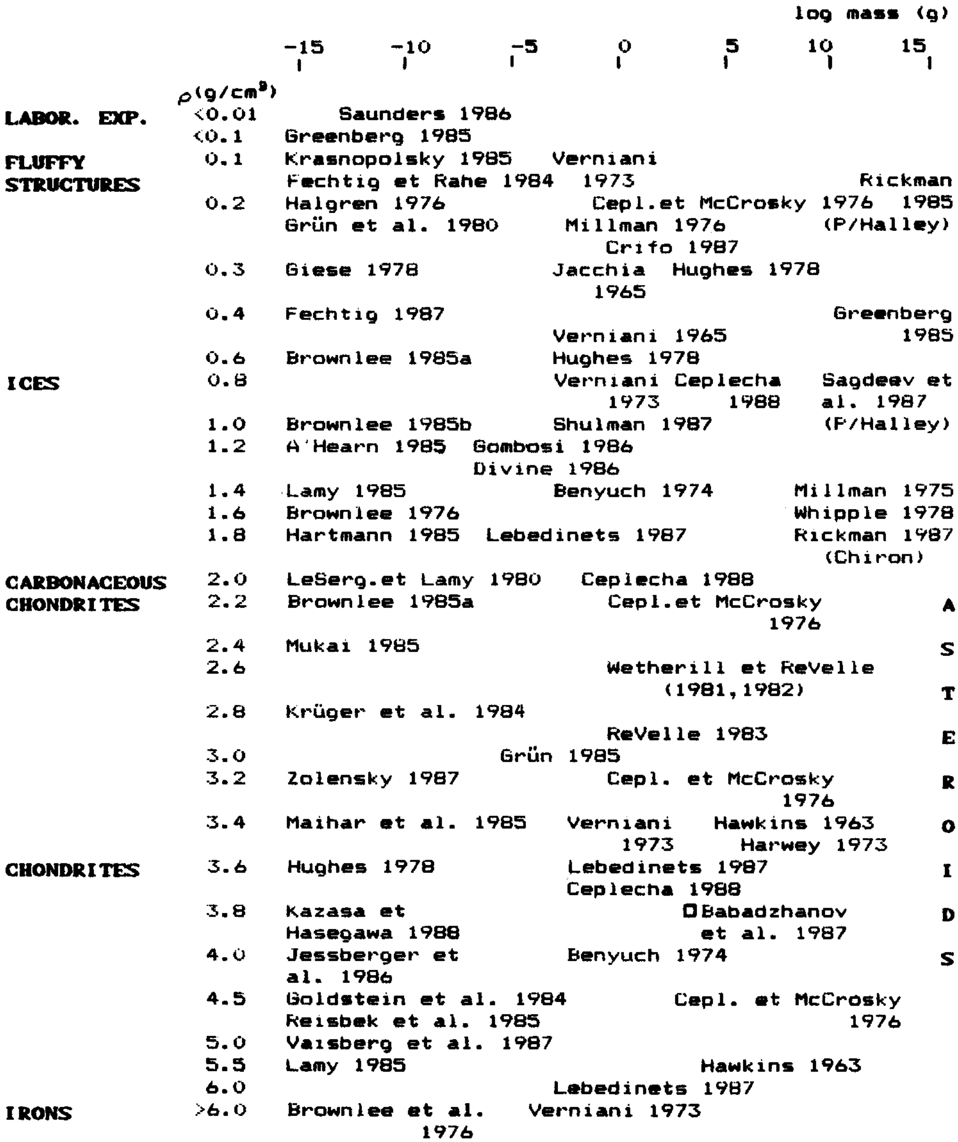

Figure 2. Bulk densities derived by different authors for the corresponding mass interval of particles or bodies.

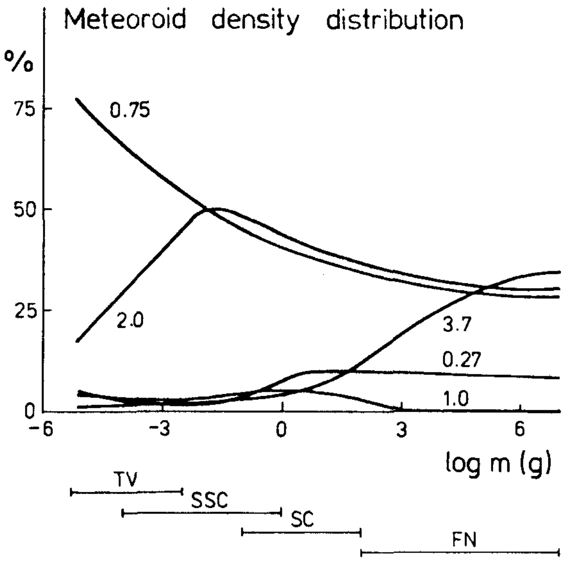

Figure 3. Relative distribution of meteoroids with different bulk densities (the numbers in the figure) from television observations, Super-Schmidt cameras, small cameras, and the Fireball network. (Constructed from data given by Ceplecha, 1988.)

different bulk densities, as seen in Figure 3, adapted from Ceplecha's results and strongly supported by Lebedinets' (1987) data. As photographic methods are relatively free from selection effects (but highly depend on the theory) in comparison with meteorites or atmospheric collections, they may more reliably represent the true composition of parent bodies.

According to these results for the mass interval from 10^{-6} to 10^{6} g, two populations of meteoroids, with bulk densities of about 0.75 $g{\cdot}cm^{-3}$ and 2.0 $g{\cdot}cm^{-3}$, are dominant, while particles with densities of about 0.3 $g{\cdot}cm^{-3}$ contribute less than 10% of the total amount. If this representation of density distribution is taken into account together with the fact that erosion is progressively more important for the low-density fragments and that large cometary fragments have been detected, it seems to be more difficult to accept very low-density cometary nuclei. As other physical properties such as porosity, permeability, shearing strength, and degree of chemical and mechanical homogeneity of nucleus material are not known well enough, we should probably agree with Wood's (1986) statement that the belief that cometary nuclei are low-density snowy masses is not a definitive result. The main arguments for the low-density models come from the measurements of the existence of fluffy particles in space and the experimental construction of such particles in the laboratory as well as from the low dust/gas ratios of comets that are measured by space probes and ground-based techniques. Some procedures, combining observational data with the physical theory, lead to the underestimation of densities. As shown by Wetherill and ReVelle (1981), these procedures imply densities of < 1 g·cm^{-3} even for recovered meteorites that have measured densities of about 3.7 g·cm^{-3}. This is a consequence of large uncertainties in such parameters as the effective meteoroid area, drag coefficient, heat transfer coefficient, and ablation coefficient, which are included in the drag equation and evaporation equation used in the physical theory of meteors (see Bronshten, 1981).

It also seems that the role of the porosity of meteoroids has been underestimated (ReVelle, 1983). The porous, fluffy microscopic particles from atmospheric collections are often considered to be representative of cometary material, without any analysis of the selection effects and their proportions to other meteoroidal materials. Recent spectroscopic data from Orionid meteors show clear evidence that 1-g particles from comet Halley survive to encounter the Earth's atmosphere (Halliday, 1987). Such particles cannot be too porous and fluffy. On the other hand, low dust/gas ratios have been derived from the limited range of very small particles (without extending the particle size or mass distribution to the larger debris). The acceptance of such dust/gas ratios without considering the mass limit for which the ratio was derived is probably the main error of all low-density cometary models.

5. Concluding Remarks

If we accept densities of cometary nuclei to be similar to the densities of 90% of those cometary nuclei whose debris has been observed, i.e., densities between 0.75 and 2.0 g·cm^{-3}, as derived by Ceplecha (1987 and 1988), then we can probably also solve the problem of the equilibrium between the source and sink of the interplanetary dust. If the mass distribution of fresh cometary ejecta (with $S \sim 0.5$) is also valid for large fragments released during outbursts or splittings of comets, then the estimated mass of the source particles for interplanetary dust would increase very significantly (100 times for 8 orders of mass—from 1-kg up to 10^8-kg bodies). The total mass of the interplanetary dust (IPD) cloud could be simply supplied by disintegration of large cometary fragments. This requires only the acceptance of heavier nuclei with a flat mass distribution of debris including larger masses. This conclusion is surely not outside of the possibilities set up by the uncertainties in estimates coming from comet decays, from past perturbing environments, and from a number of selection effects, as analyzed by Kresák (1985) in more detail. However, the question of whether the mass contribution to the IPD was caused gradually or by a single event of cometary swarms seems to be also within the same uncertainties.

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