7

METEOR STREAMS IN THE MAKING

Z. SEKANINA

The well-known associations of meteor streams with periodic comets and the probable cometary origin of the zodiacal dust cloud point to the importance, in the cometary debris, of particles with masses exceeding roughly 10^{-6} gram. It is shown that these large particles dominate in the sunward-oriented anomalous tails of comets. Their study is essential for meaningful estimates of the mass of meteor streams and of the injection rate of the cometary debris that contributes to the zodiacal cloud. Favorable conditions for the detection of anomalous tails can be recognized in advance, as demonstrated by the successful predictions for comets Kohoutek (1973 XII) and Bradfield (1975p). To answer the question as to whether short-period comets can support the zodiacal cloud, a study of anomalous tails at future returns of these comets is considered indispensable.

METEOR STREAMS

More than a century ago it was first recognized that close dynamical relationships exist between the Perseid meteor stream and Periodic Comet Swift-Tuttle (1862 III) (Schiaparelli 1867), between the Leonid stream and Periodic Comet Tempel-Tuttle (1866 I) (Peters 1867, Schiaparelli 1867, Oppolzer 1867), between the Lyrid stream and Comet Thatcher (1861 I) (Weiss 1867), and between the Andromedid stream and Periodic Comet Biela (1852 III) (Weiss 1867, d'Arrest 1867). Further associations have been established since, and the understanding that many meteor streams are disintegration products of comets is now generally accepted.

The recent progress in the physical theory of meteors and experiments with artificial meteors made it possible to improve our knowledge of the luminous efficiency of meteoroids (solid particles giving rise to the meteor phenomenon) in the earth's atmosphere (Verniani 1965, Ayers *et al.* 1970), and to derive the meteoroid initial masses from the observed optical effects. It turns out that visual meteors, comparable in light with the brightest stars, are produced by meteoroids whose masses are within one or two orders of magnitude of 1 gram (Jacchia *et al.* 1967). Their corresponding diameters are therefore in the vicinity of 1 cm. The exact size depends on a number of circumstances, such as the relative velocity of the object, its composition, density and shape. Fainter and faster photographic meteors are products of smaller meteoroids, whose masses are typically around 10^{-2} gram (Jacchia *et al.* 1967) and their diameters amount to a fraction of 1 cm. A number of radar detectors, developed intensively after World War II, and modern television techniques (Cook *et al.* 1973, Naumann and Clifton 1973) can reach still smaller meteoroids, down to 10^{-4} gram in mass or to somewhat less than 0.1 cm in dia-

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meter. Finally, very powerful radar systems, such as the one that until recently operated at Havana, Ill., can reach meteoroids down to 10^{-6} gram in mass (Southworth 1972), corresponding to approximately 0.01 cm or 100 microns in diameter.

Quantitative analysis of the physical data on meteors leads to very low bulk densities of meteoroids. Verniani (1967, 1969) finds that the mean bulk density of the meteoroids that give rise to bright photographic meteors (mean mass of 0.8 gram) is only 0.3 g cm^{-3}, while for the meteoroids producing radio meteors (mean mass of 2 x 10^{-4} gram) the corresponding average is 0.8 g cm^{-3} (Verniani 1973). Although the bulk density appears to be independent of the mass within each sample (photographic and radio), the difference between the two samples (mass ratio of 10^3 to 10^4) may be statistically significant. There also seems to exist a correlation between the bulk density and the orbit size (Verniani 1967, Lindblad 1976).

The study of meteor streams is complicated by their superposition on the "background" population of sporadic meteoroids, which, in turn, are believed to be relics of disintegrated streams (Jacchia 1963). It is known that streams are more pronounced among bright meteors (Millman 1970). This is definitely confirmed by a comparison of the stream-search results among photographic and radio meteors. Jacchia and Whipple (1961) conclude that 65% of 413 precise-orbit photographic meteors can be placed in associations, and Lindblad (1971a, 1971b), using a different, more conservative approach, finds that 43 to 50% of photographic meteors are in streams. This contrasts with the result of a very complete stream search among radio meteors, which shows that only 16% of them belong to streams (Sekanina 1976a). Millman (1970) finds that the inconspicuousness of streams among dust particles below 10^{-6} gram in mass is caused by their lower mass indices (the negative slope of the log-log plot of the particle flux versus the particle mass), and Dohnanyi (1970) confirms that the steady-state mass distribution in streams should indeed be relatively flat, if the streams replenish the mass in the sporadic population lost by collisions.

Particles below 10^{-6} gram can only be detected by space probes. Reports on swarms associated with periodic comets and/or meteor showers appear to be conflicting (Alexander *et al.* 1961, Dubin *et al.* 1963, McCracken *et al.* 1967, Silverberg and Poultney 1969, Silverberg 1970, Alexander *et al.* 1970, Alexander and Bohn 1974, Hoffmann *et al.* 1975a, 1975b).

THE ZODIACAL CLOUD

Whipple (1967) suggests that comets are probably also a major, if not the sole, source of dust that keeps the self-destructive zodiacal cloud in a steady-state condition, and that Periodic Comet Encke might have been the most significant contributor to the cloud in the past. The cometary origin of the zodiacal particles appears to be reinforced by the measurements on board of Pioneers 10 and 11 (Zook and Soberman 1974, Hanner and Weinberg 1974, Soberman *et al.* 1974, Humes *et al.* 1975, Hanner *et al.* 1976). While the results from the three experiments are discordant (Soberman *et al.* 1976), Dohnanyi (1976) finds that the contribution of asteroidal particles to the dust in the asteroidal belt is in any event small compared with the cometary contribution.

Giese and Grün (1976) conclude that the contribution to the zodiacal light from particles much larger than 10 microns in radius was strongly underestimated in the past. From the recent measurements of particle fluxes by various spacecraft they derive probable limits to the particle-size distribution function. They find that the contribution to the total brightness of the zodiacal light from submicron particles ($<10^{-13}$ gram) is negligible, while particles move massive than 3 x 10^{-7} gram contribute 42% of the total brightness. Their distribution function also indicates that 33% of the total mass is concentrated in particles heavier than 10^{-5} gram, 60% in particles heavier than 10^{-6} gram and

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89% in particles heavier than 10^{-7} gram. Thus, at an assumed density of 1 g cm^{-3}, the median zodiacal-particle diameter comes out to be near 160 microns. Very recently, Giese *et al.* (1976) have pointed out that the difficulties with fitting the observed polarization curve of the zodiacal light can apparently be removed, if the scattering particles are fluffy. Many of the extraterrestrial particles collected at high altitudes by Brownlee *et al.* (1976) are, indeed, complex porous aggregates of submicron-sized grains.

Giese and Grün's (1976) distribution function leads to a total space density of dust of 4 x 10^{-23} g cm^{-3} in the ecliptic near 1 AU from the sun. This value is still one order of magnitude smaller than Whipple's (1967) estimate, based in part on meteor data. It is therefore at least possible that the contribution from meteoroids in the submillimeter and larger size range is even more significant than indicated by the Giese-Grün distribution. Furthermore, it has been noted for some time (Whipple 1967, Millman 1976) that the most significant contribution to the total mass swept up by the earth appears to come from the particles of 10^{-6} to 10^{-3} gram in mass, or roughly 100 microns to 0.1 cm in diameter. Note that these particles are just of the right sizes to quality as "radio" meteoroids (Section I)

THE BIRTH OF A METEOROID STREAM

The recent theoretical studies and space experiments, briefly reviewed in the previous sections, tend to indicate -- at least qualitatively -- a fairly consistent picture for the evolution of the interplanetary dust population. The general consensus is that comets disintegrate into streams of meteoroids, which, under various forces, gradually disperse in interplanetary space and feed the self-destructive zodiacal dust cloud. Submillimeter-sized particles appear to be of key importance in the process. However, severe difficulties arise when a quantitative solution to the problem of the injection rate from comets is sought. In order to apprehend the substance of the controversy, we summarize first our understanding of the dust-emission process in comets and the dynamics of cometary dust particles.

The theory of the dust tails of comets had been largely empirical until the beginning of this century, when Arrhenius (1900) identified the long-known repulsive force, acting on the tail particles, as light pressure from the sun, and Schwarzschild (1901) subsequently recognized that the magnitude of the light pressure is related to the particle size and density. However, a sophisticated model interpreting the distribution of light in the dust tail in terms of the production rate of dust particles, the particle-size distribution and the separation particle velocity has been developed only recently (Finson and Probstein 1968a). Fluid-dynamics calculations by Probstein (1968), refining the earlier work by Whipple (1951), show that dust particles are dragged away from the surface of the comet nucleus by the force imparted by momentum transfer from the expanding gases. The significant dust-gas interaction is confined to the immediate vicinity of the nucleus, where the particles attain their "terminal" velocities. These are typically a few hundred meters per second for micron-sized particles, which rapidly accommodate to the ambient gas-velocity field, but only a few meters or a few tens of meters per second for large, slowly accommodating meteoroids. After the dust-gas interaction is terminated, the particles move independently of their parent comet. Their trajectories relative to the nucleus of the comet are determined by the magnitude of the light pressure, which varies inversely as the product of the particle size and bulk density, and amounts to less than 0.1% the solar attraction for the "photographic" meteoroids and to 0.1% to 1% the solar attraction for the "radio" meteoroids (Section I).

Because of the small cross-section-to-mass ratio of sizable meteoroids, their contribution to ordinary dust tails is suppressed to a considerable degree

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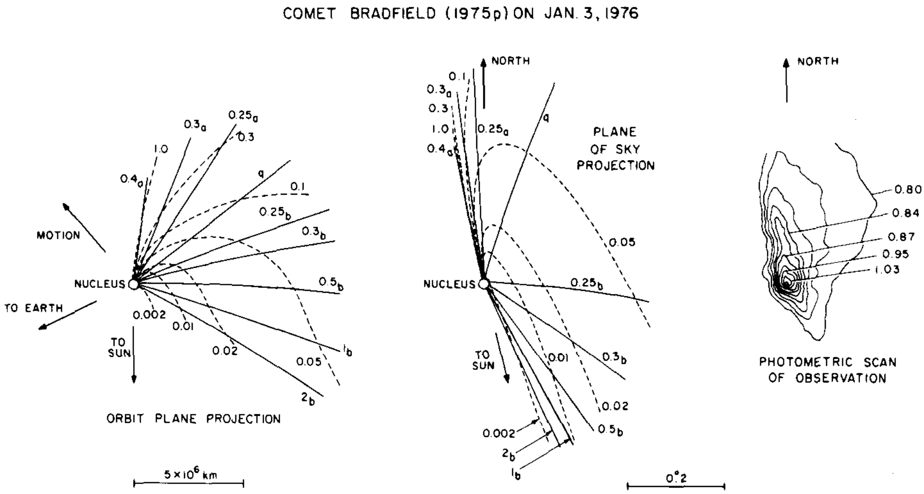

Figure 1. Dust emission from Comet Bradfield for January 3.733 UT, 1976. The unforeshortened projection of the theoretical distribution of dust particles onto the orbit plane of the comet is on the left, its projection onto the plane of the sky, at the center. The solid curves are the loci of particles subjected to all repulsive accelerations and emitted simultaneously; the locations in orbit of the emissions are given in terms of the heliocentric distance (in AU), subscripts b and a referring, respectively, to the preperihelion and postperihelion orbital arcs and q standing for perihelion. The dashed curves are the loci of particles emitted continuously and subjected to a constant repulsive acceleration by light pressure (in units of solar attraction). All particles are assumed to have separated at rest with respect to the comet. On the right of the figure is an isophotometric scan of the observed comet, oriented parallel to and reproduced on the same scale as the theoretical plane-of-the-sky projection. The numbers indicate the photographic density uncorrected for the sky brightness. Note that the orientation of the main body of the anomalous tail, toward south-southwest of the nucleus, matches perfectly trajectories of particles emitted before perihelion at heliocentric distances larger than about 0.5 AU and subjected to light pressure of less than 0.01 the solar attraction. (From Sekanina and Pansecchi 1976).

by the much more efficiently scattering micron-sized particles. Thus the distribution of light in ordinary tails does not provide any meaningful information on the population of submillimeter-sized and larger meteoroids. Fortunately, insignificant emission velocities and low light-pressure accelerations prevent large meteoroids from getting dispersed far away from the parent comet's nucleus even months after ejection, and the progressive lagging behind the comet's radius vector (due to light pressure) discriminates the trajectories of the "old" sizable meteoroids from the paths of "fresh" micron-sized particles. If the geometric conditions are favorable, early emissions of large meteoroids can project in the sky sunwards to form a separate, anomalous tail or anti-tail (for one example, see Fig. 1). Not only were anomalous tails reported on a number of occasions in the past, but the possibility of their appearance can even be predicted (Sekanina 1974a). Such predictions have so far been provided for two comets, Kohoutek (1973 XII) and Bradfield (1975p). Since in both cases the presence of the anti-tail was confirmed by observations -- and in the case of Comet Kohoutek the presence of large particles in the anti-tail was independently established from infrared measures (Ney 1974) -- we feel confident that anomalous tails are indeed sections of meteoroid streams seen just a fraction of a year after their separation from the parent comet. Studies indicate (Finson and Probstein 1968b, Sekanina 1974b, 1976b, Sekanina and Miller 1976, Sekanina and Pansecchi 1977) that the main body of the anti-tail consists typically of particles that are in the size range of "radio" meteoroids, although the situation varies, primarily because of the diversity of projection conditions, from comet to comet.

Because the ejection velocities of large meteoroids are very low, the anomalous tail is basically a flat formation in the orbit plane of the parent comet. When the earth crosses the orbit plane and the projection circumstances are favorable, we can see the sheet of the meteoroid debris edgewise in the form of a "spike." A brilliant spike was displayed by Comet Arend-Roland (1957 III) on April 25, 1957 (Fig. 2), and its nature was immediately recognized by Whipple (1957a, 1957b) and by others.

Micron-sized particles never form a long spike. Being subjected to high accelerations, they are swept away through the tail in the matter of days or weeks at the most, dispersing rapidly. The short period if visibility does not provide time necessary for the dominant *systematic* component of their motions (imparted by light-pressure) to depart significantly from the direction of the prolonged radius vector, and so they rarely project on the sunward side of the nucleus (beyond the limits of the coma). However, thanks to the extremely favorable projection conditions and other lucky circumstances, the effect of particle size on the dispersal rate of cometary debris was convincingly demonstrated by Comet Arend-Roland, as described briefly in the following.

Besides the anti-tail, which was visible for more than one week, Comet Arend-Roland also displayed -- just for one or two days around April 25 -- another sunward reature (Fig. 2). Called a "beard" by Porter (1957), it was substantially fainter and broader than the anti-tail. Recent calculations have shown (Sekanina 1976b) that the beard consisted of the dust expelled during an outburst, about 6 days before perihelion, whose existence was established by Finson and Probstein (1968b) from the presence of a "bulge" in the comet's ordinary dust tail two days after the beard had vanished (see Fig. 5 of Finson and Probstein). Our Figure 2 shows that the beard particles must have been typically several microns in diameter and about 10 times smaller in size than the spike particles. From the measured edge-on breadths of the beard and the spike (Larsson-Leander 1961) the component of the average ejection velocity normal to the orbit plane of the beard particles comes out to be about 0.6 km sec^{-1}, more than 100 times higher than that of the spike particles.

There is a fundamental difference in the character of the dispersal effects induced on the particles by the light pressure and by the impulse at ejection. The former is systematic in the sense that it discriminates particles by their mass and by the emission time, while the latter contains a randomizing factor. The combined effect increases dramatically with decreasing particle dimensions (down to micron and submicron sizes) and results, on the one hand, in the quick loss of similarity between the orbit of the parent comet and individual orbits of tiny particles, and, on the other hand, in the quasi-stable preservation of a fairly close resemblance between the comet's orbit and the orbits of large meteoroids.

COMETARY DEBRIS IN INTERPLANETARY SPACE

The systematic effect of the light pressure on the particles is to increase the dimensions of their orbits compared with those of the comet's orbit. For a large meteoroid, for which the acceleration from light pressure, $1-\mu$, is a small fraction of the solar attraction, the perihelion and aphelion distances of its

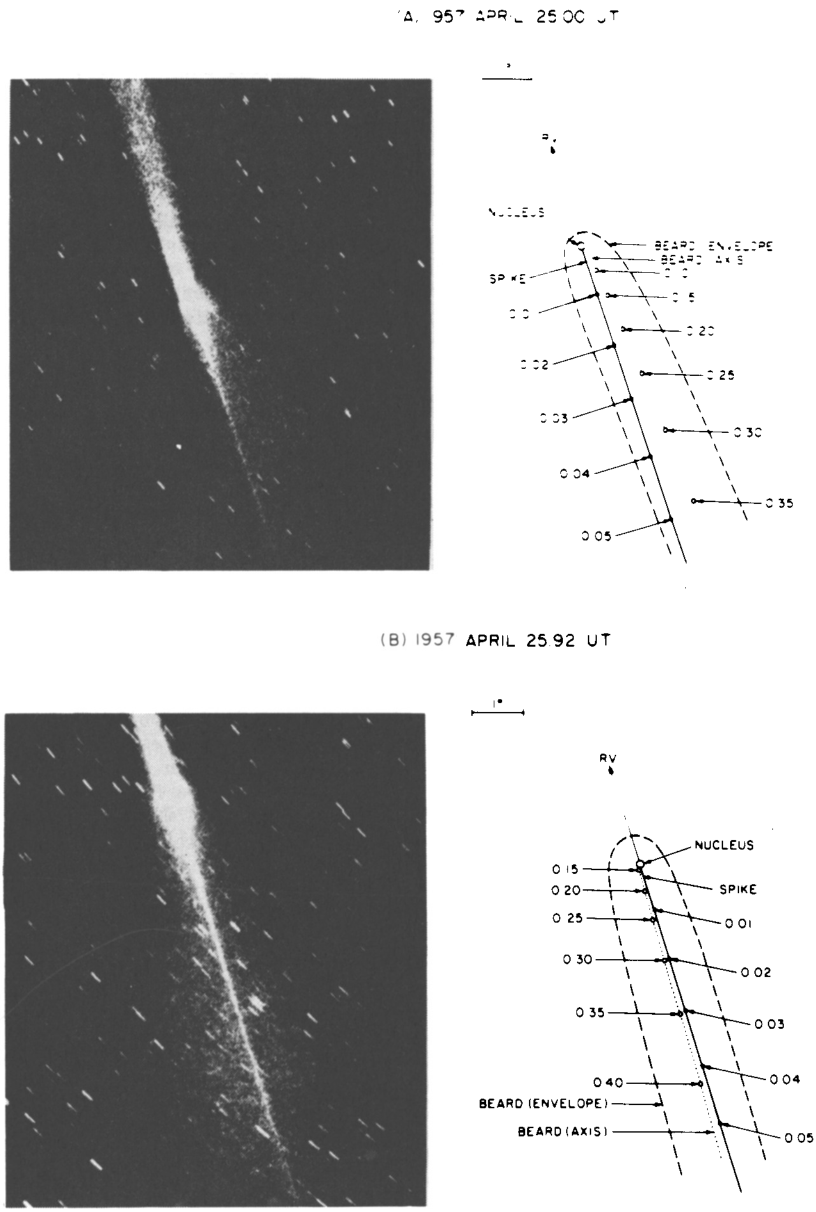

Figure 2. *The spike and the beard of Comet 1957 III on April 25.00 UT (top) and on April 25.92 UT, 1967 (bottom). The photographs taken by R. Fogelquist (left) are compared, on the same scale, with the outburst model of the beard (right). The calculated beard axis (dotted curve) gives several standard values of the acceleration by light pressure (in units of solar attraction) for dust particles emitted, with no initial velocities, at a heliocentric distance of 0.37 AU*

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before perihelion. Compare these with the accelerations exerted on the spike particles (solid line) emitted, with no initial velocities, at a heliocentric distance of 1.5 AU before perihelion. Note that, if of the same density, beard particles must be roughly 10 times smaller in diameter than are spike particles at about the same angular distance from the nucleus. The beard envelope (dashed curve) is determined by the isotropic distribution of initial particle velocities of about 0.6 km sec^{-1}. RV indicates the projected direction of the prolonged radius vector of the comet's nucleus. (From Sekanina 1976b; photographs courtesy of G. Larsson-Leander).

orbit (q, Q) can be approximately related to the orbital elements of the periodic parent comet (q_0, Q_0) thus:

$$q = q_0 \left[1 + (1-\mu)\ (1 - q_0/r_{em})\ (q_0+Q_0)\ /\ (Q_0-q_0)\right],$$
$$Q = Q_0 \left[1 + (1-\mu)\ (Q_0/r_{em} - 1)\ (q_0+Q_0)\ /\ (Q_0-q_0)\ \right], \qquad (1)$$

where r_{em} is the heliocentric distance at ejection. For example, for a "radio" meteoroid of $1-\mu = 0.01$, released from P/Encke at 1 AU from the sun, equations (1) give $q - q_0 = 0.003$ AU, $Q - Q_0 = 0.15$ AU.

Since the dimensions of a particle orbit increase with decreasing particle size, the quantity of considerable importance is the maximum size of the particles that, following their ejection from a comet, leave the solar system on hyperbolic orbits. This problem has been discussed on various occasions for particles released at rest with respect to the comet (Harwit 1963, Dohnanyi 1970, Jambor 1976). It follows that the particles escaping from the solar system are those whose diameters are smaller than d_{lim}, where

$$d_{lim} = 2.4\ (Q_{rp}/\rho)\ (a/r_{em})\quad \text{(micron)}, \qquad (2)$$

where Q_{rp} is the scattering efficiency of the particles for light pressure, ρ their bulk density (in g cm^{-3}), and a the semimajor axis of the comet's orbit (a and r_{em} in AU). Formula (2) indicates that lost from the solar system is virtually all the debris shed by the nearly-parabolic comets as well as all of those particles ejected from the short-period comets that are smaller than approximately 10 microns in diameter (the actual cutoff size depends on the particle material and the emission distance, and varies, of course, from comet to comet). These results point to two apparent conclusions. One, the zodiacal cloud cannot be maintained by nearly-parabolic comets (Harwit 1963, Jambor 1976); and two, if the required mass influx is supplied by the short-period comets, the relative deficit of particles with masses below 10^{-7} gram would tie in with the existence of the hyperbolic cutoff (Dohnanyi 1970).

In spite of the fact that the effect of ejection particle velocities has been neglected, the first of the two conclusions appears to be established with a fair degree of confidence, especially because it is supported by an independent body of evidence, such as the obvious conflict between the random distribution of orbital inclinations of nearly-parabolic comets and the sharp concentration of mass in the zodiacal cloud near the ecliptic.

The hypothesis identifying the source of supply for the zodiacal cloud with the short-period comets is dynamically feasible and its chances depend essentially on whether the injection rate from these comets is sufficiently high to balance the losses. Recent estimates suggest that it is not.

The total mass of the zodiacal cloud within 3.5 AU of the sun is estimated by Whipple (1967) at 2.5×10^{19} grams and its mean lifetime at 10^5 years. The injection rate of dust from comets required to keep the cloud in steady state is calculated to range from 1×10^7 to 3×10^7 grams sec^{-1} (Whipple 1967, Dohnanyi 1970). The available estimates of the dust output from the short-period comets, based on very uncertain relations between the mass-loss rate and

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the intrinsic brightness, lead to injection rates that represent only 0.2% to 3% of the required influx (Delsemme 1976a, Röser 1976).

Alternative explanations for the source of the zodiacal cloud have been proposed (such as a quasi-equilibrium maintained by an occasional capture of an extremely massive comet; the contribution from periodic comets or other cometary-like objects of large perihelion distances; see Delsemme 1976b, Sekanina 1976c) and should be considered, including the possibility that the cloud is not at all in the steady state (Harwit 1963). It is felt, however, that the short-period comets should not be ruled out as a possible source, unless the results suggesting the inadequate production of dust, especially of the large particles that are most vital for the survival of the zodiacal cloud, are independently confirmed by more reliable determinations. Until cometary probes are launched, meaningful emission rates for the submillimeter-sized and larger cometary debris can only be derived from observations of anti-tails.

All undisputed observations of anti-tails refer, unfortunately, to nearly-parabolic comets. The only short-period comet that might have been observed to display an anti-tail was P/Encke in 1964 (Roemer and Lloyd 1966, Sekanina 1976b, 1976d). The apparent absence of anti-tails among the short-period comets seems to be in conflict with the existence of meteor streams known to be associated with a number of these comets. Thus, both the problem of the origin of the zodiacal cloud and the understanding of the relationship between the short-period comets and the meteor streams require that a thorough search for the anti-tails be undertaken. A study (Sekanina 1976e), listing favorable conditions for anti-tails at the future returns of the short-period comets, has very recently been completed to facilitate the search.

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DISCUSSION

HUEBNER: The change of particle diameter as a function of time due to vaporization of an icy mantle or vaporization of the grain itself (in the case of a sun-grazing comet) must add complications. Have these been solved in a satisfactory way?

SEKANINA: I have developed an approximate approach to handle vaporizing dust particles in comet tails; this has been applied in a paper on Comet Kohoutek I and Freeman Miller have published recently in Icarus. There is, however, no generaly solution available at present and the problem presents a severe complication for the Finson-Probstein model.

SMOLUCHOWSKI: Is the size distribution of particles and the resulting visible separation of various sizes the same for all comets? If not, why?

SEKANINA: The distribution definitely varies from comet to comet. Why, we do not know; it is presumably associated with the history of each comet. There seems to be a correlation with perihelion distance q; the smaller q is, the larger particles are observed. I would not comment on the significance of this result, except that particle evaporation might perhaps be one of several possible explanations.

SINGER: Can you give us an idea to what extent this method can be used as a spectrometer for particle size, and over what size range? What results are available on the spectrum of sizes of emitted particles?

SEKANINA: The discrimination of particles by 1-μ has been used as a "size spectrometer." Particle-size distribution appears to span over a number of orders of magnitude, the particle diameter varying inversely as the fifth power of size for larger particles (with a certain degree of uncertainty), less steeply for smaller particles and is more or less cut off somewhere near or below 1 micron. Variations from comet to comet are, however, significant.

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WHIPPLE: I suggest that a consequence of saturation irradiation of comets by cosmic rays is a loose binding of meteoroidal grains in the upper levels. The thermal spikes will redistribute heavier atoms between grains of radius ~0.1 μm to produce clumps of grains that could be ejected by the highly volatile damaged molecules at large solar distances. Hence new comets should show grain halos more than older ones.

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