SOURCES OF INTERPLANETARY DUST

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ABSTRACT : It is generally assumed that ejections from active cometary nuclei are the major source of replenishment of the interplanetary dust complex. Conjectures against this concept are usually based on comparison of the quantitative efficiency of the dust production by comets with the efficiency of all the dissipative processes involved. The present paper discusses this problem from the dynamical point of view, tracing the evolution of swarms of cometary ejecta as they pass through different evolutionary stages. It is concluded that the contribution of the present population of active comets, of all revolution periods, is not only inadequate to explain the abundance of interplanetary particles, but also inconsistent with the distribution of their orbits. Other potential sources and their implications for the equilibrium problem are reviewed.

1. INTRODUCTION

Since almost every solar system object is able to liberate interplanetary dust, identification of its exact sources is essentially a problem of the relative contribution of individual types of parent objects. These differ in frequency and mechanism of dust release (outgassing drag, ejection at cratering impacts, collisional fragmentation, rotational or tidal disruption, electrostatic breakup, volcanic activity), in the size distribution of the solid particles produced (limits set by the momentum transfer and gravity), and in the ability to inject them into elliptic circumsolar orbits (binding energy versus radiation pressure depending on the composition and orbit of the parent body).

Fresh dust, most indicative of its immediate source, would produce temporary local enhancements of the dust population in the environment and along the orbit of the parent body, including comet tails, meteor swarms, and meteor streams. Major planets, severely handicapped in dust release by high escape velocities and atmospheres, would produce local concentrations by gravitational focussing, temporary satellite captures, dust exchange with their satellites, and dissipative effects of their external magnetic fields. Once orbiting in interplanetary space, the particles begin to evolve in every respect. Erosion and fragmentation processes make them proceed down the size scale at a pace depending both on their composition and structure and on their orbital environment. While the dispersion

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of larger particles is mainly controlled by their initial orbits and by planetary perturbations, dynamical effects of solar radiation become increasingly important with decreasing particle size. In the micron range the peak efficiency of the radiation effects is superseded by their damping due to light scattering, which gives rise to a division into two separate populations of dust grains - a conclusion supported by the lunar microcrater data (LeSergeant and Lamy, 1978). The submicron population has not yet been explored adequately, especially as regards its dynamics, and its origin will not be discussed here. The bulk of mass of the over-micron population falls within, or very close to, the size range detectable as meteors, so that dependable data on earth-crossing orbits are available. In Whipple's (1967) model of the interplanetary dust complex, three quarters of the total mass are confined to particle sizes of 0.1 to 1 mm. Recent data (Giese et al., 1978) lend support to the conclusion that this size range is also the dominating one in the zodiacal light.

The only observable mechanism of dust release into the interplanetary space is the ejection from cometary nuclei by the momentum transfer from the escaping gas; and the only known one-to-one associations of the parent objects with their débris are those between active comets and shower meteors. The comets are also held to be a strongly dominant source of the sporadic component of the dust population (Whipple, 1967; Dohnanyi, 1976; Millman, 1979). The devolatilization lifetimes of many of them are evidently shorter than the lifetimes of isolated dust particles. Thus the lack of active parent comets for a considerable proportion of the dust population does not seem surprising. On the other hand, the present input of cometary ejecta does not appear high enough to ensure a balance between source and sink. Although there is still a considerable margin of uncertainty as to the total dust content, the distribution of particle sizes and lifetimes, and the dust production rates of comets, recent estimates (Delsemme, 1976; Röser, 1976) suggest that short-period comets can account for only some 2 or 3% of the required mass. And it appears more likely that the requirements will have to be adjusted upwards rather than downwards, due to additional dissipative processes disregarded in the lifetime estimates (Paddack and Rhee, 1976; Fechtig et al., 1979). But the problem is not simply a quantitative one. The crucial question is whether or not both the observed abundance and the motion of interplanetary particles is consistent with the assumption that all (or most) of them have been ejected from active comets. And, unless this is the case, what other parent bodies would meet these requirements for the other portion of the dust complex.

2. FRESH COMETARY EJECTA: METEOR SWARMS AND STREAMS

A unique opportunity for studying the input of solid particles into interplanetary space is provided by the passages of the earth through meteor swarms of recent origin, occupying the vicinity of active comets. Table I presents statistical estimates of the average frequency and duration of such events, which are rare indeed. The chances are even that the closest encounter of the earth with a comet in a century will occur at a distance smaller or larger than 0.04 A.U., and that the object encountered will be a short-period or long-period comet; the closest misses on record are those of 1770I P/Lexell, $D_0 = 0.0151$, 1743I Grischow, $D_0 = 0.0275$, 1806I P/Biela, $D_0 = 0.0366$, and 1927VII P/Pons-Winnecke, $D_0 = 0.0394$. Since the frequency of passages varies with the square of D_0, very small miss

TABLE I

Occurrence rates R of different types of encounters (number of events per century) and their mean durations t (in days) for comets of different revolution periods P (in years). D_0 is the distance limit (in astron. units), E the particle density relative to the mean sporadic background in the environment of the earth's orbit.

Configuration	Limit	$P<20$ R/t	$20<P<200$ R/t	$P>200$ R/t	All R/t
Comet - Earth	$D_0<0.1$	3/20	0.2/10	3/6	6/13
Comet - Earth orbit	$D_0<0.1$	75/25	5/15	70/10	150/18
Earth - Comet orbit +)	$D_0<0.1$	500/25	300/15	8000/10	9000/11
Earth - Meteor swarm	$E>1$	12/0.30	6/0.15	2/0.05	20/0.23
Earth - Meteor swarm	$E>10$	6/0.15	2/0.05	-	8/0.12
Earth - Meteor swarm	$E>100$	2/0.05	-	-	2/0.05

+) for comets passing perihelion during one century

distances are quite exceptional. A passage through the optically detectable coma would occur once in 400,000 years and a collision with an active cometary nucleus once in 6,000,000 years (Kresák, 1978). Since the ejected particles tend to disperse predominantly along the comet's orbit, the distance between the two bodies becomes progressively less important than that between their orbits. The data of the second line are applicable when the spread in the time of perihelion passage attains one year, and the data of the third line when a complete ring, furnishing annual showers, is formed. The lower half of the table gives the estimates of the mean rates and durations of the earth's passages through meteor swarms in which the particle density exceeds that of the sporadic environment by a factor of E. As the underlying data (tentatively corrected for the incompleteness of observations) are of interest for identifying the individual parent comets, they are summarized in Table II.

This table lists the passages of the earth through the densest meteor swarms observed since 1800, and the current annual passages through major, ring-shaped meteor streams. Along with the name and year of the shower are listed: the name of the parent comet, its revolution period P, perihelion distance q, solar longitude at the time of encounter L_s, encounter velocity V (geocentric velocity V_g increased by the earth's gravity down to the meteor level), difference ΔM in mean anomaly between the comet and the swarm (in degrees; positive ΔM means a position behind the comet), minimum distance of the earth from the comet's orbit D_0, the width of the region of $E>1$ (applicable to the dense swarms), D, or the distance of the earth from the comet's orbit at the threshold of detectable meteor activity (applicable to the annual showers), D_e. All the distances are in astronomical units. The last two columns give the peak zenithal hourly rate of shower meteors for one visual observer under perfect atmospheric conditions (or, for the daytime showers, an equivalent radio echo rate), Z, and the maximum relative enhancement of the particle density against a mean sporadic background, E. This is defined as

$$E = Z v_g v^2 / 4 c f V_g V^2 = 100 Z V_g^{-1} V^{-2} \qquad (1)$$

TABLE II. The densest meteor swarms, $E > 1$, and the major annual meteor streams, $Z > 10$

Shower	Parent comet	P	q	L_s	V	ΔM	D_o	D/D_e	Z	E
Andromedids 1885	Biela	6.6	0.87	246.7	19	− 4	0.0004	0.0070	15000	230
Draconids 1933	Giacobini-Zinner	6.6	1.00	196.2	23	+ 12	0.0053	0.0025	20000	180
Andromedids 1872	Biela	6.7	0.87	248.1	19	− 4	0.0051	0.0070	8000	120
Draconids 1946	Giacobini-Zinner	6.6	1.00	196.3	23	+ 2	0.0015	0.0015	7000	60
Leonids 1966	Tempel-Tuttle	32.9	0.98	234.3	71	+ 17	0.0031	0.0008	150000	40
Leonids 1833	Tempel-Tuttle	33.1	0.98	232.4	71	+ 9	0.0012	0.0010	50000	14
Andromedids 1892	Biela	6.6	0.86	243.9	20	+ 18	0.0079	0.0010	400	6
τ Herculids 1930	Schwassmann-W. 3	5.4	1.01	77.3	18	+ 4	0.0055	0.0015	100	2.3
Andromedids 1847	Biela	6.6	0.86	245.4	20	+ 103	0.0095	0.0007	150	2.3
Bootids 1916	Pons-Winnecke	5.9	0.97	97.6	18	+ 49	0.0408	0.0003	100	2.1
Draconids 1952	Giacobini-Zinner	6.4	0.99	196.3	23	+ 30	0.0058	0.0002	200	1.8
Andromedids 1838	Biela	6.6	0.88	249.8	20	− 29	0.0003	0.0004	100	1.6
Andromedids 1899	Biela	6.7	0.86	243.9	19	+ 37	0.0089	0.0004	100	1.6
Lyrids 1803	Thatcher	415.5	0.92	31.2	48	− 50	0.0021	0.0005	1500	1.4
Leonids 1867	Tempel-Tuttle	33.5	0.98	232.3	71	+ 19	0.0065	0.0002	5000	1.4
Leonids 1965	Tempel-Tuttle	32.9	0.98	234.3	71	+ 6	0.0031	0.0030	5000	1.4
Geminids	?	1.6	0.13	261.0	37		small	0.14	90	0.19
Quadrantids	?	5.4	0.98	282.8	43		small	0.03	130	0.17
ξ Perseids	?	2.0	0.34	76	29		?	0.12	25	0.11
β Taurids	Encke	3.3	0.34	97.8	31		0.1779	0.20	20	0.07
Arietids	?	2.0	0.09	76	39		?	0.18	35	0.06
Taurids	Encke	3.3	0.34	224.3	31		0.1943	0.85	15	0.05
δ Aquarids	?	4.6	0.08	127	42		?	0.30	40	0.05
Perseids	Swift-Tuttle	120.0	0.96	138.7	60		0.0044	0.30	75	0.035
Ursids	Tuttle	13.8	1.02	270.7	36		0.0888	0.12	10	0.023
Lyrids	Thatcher	415.5	0.92	31.2	48		0.0021	0.04	15	0.014
η Aquarids	Halley	76.1	0.59	46.9	67		0.0652	0.20	30	0.010
Orionids	Halley	76.1	0.59	210.0	67		0.1541	0.25	20	0.007
Leonids	Tempel-Tuttle	32.9	0.98	234.3	71		0.0031	0.02	10	0.003

where the capital letters refer to the shower and small letters to the sporadic background. The factor of 4 reduces the zenithal flux to the omnidirectional flux of sporadic meteors, represented by their diurnal-and-annual mean rate f; the factor c takes into account the focussing effect of the earth's attraction. The right-hand side of equation (1) is obtained by assuming $f = 14.5$ meteors per hour, $c = 0.90$, $v_g = 15.0$ km/s, and $v = 18.7$ km/s.

This is admittedly some oversimplification, disregarding the differences in the particle size distribution and in their luminous efficiencies. However, correct values of Z are even more difficult to assess. The point is that the densest showers often appear unexpectedly; their short duration introduces geographic limitation of observability; hourly rates are too high and variable to be reliably estimated even by experienced observers; observations are often made under conditions much inferior to routine meteor counts; and sufficient documentation is often missing. Under such circumstances the adopted values of Z, though representing best guesses based on various sources, are subject to considerable uncertainty, in particular for the earlier events. Two great displays from the end of the eighteenth century, the Andromedids of 1798 and the Leonids of 1799, would undoubtedly range among the first few entries of Table II, with $E > 10$. The accuracy is generally much better for the peak rates of annual showers, but some of them exhibit appreciable variations from one return to another.

3. THE INITIAL RATES OF DISPERSION

The marked concentration of meteor swarms in mean anomaly towards their parent comets suggests an important role of the dispersion rates in their survival times. The initial dispersion is controlled by two mechanisms: differential velocities imparted to the particles leaving the cometary nucleus, and augmentation of their orbital ellipses by solar radiation pressure.

Table III compares these two effects for a representative sample of meteor streams of different revolution periods. It is supposed that the particles are released at the comet's perihelion where strongest outgassing takes place. The column $P_e = \infty$ refers to an immediate escape from the solar system on a parabolic orbit. The column $P_e = P + 1$ refers to an increase of one year in the revolution period - a condition of observability of the shower at each return of the comet starting with the next perihelion passage, provided that D_0 remains unperturbed. The column $P_e = 1.05\,P$ refers to a 5% time lag, $\Delta M = +18^\circ$, typical for the dense swarms of Table II. For each case the following quantities are listed: the tangential component of the ejection velocity u (in m/s) necessary for reaching the required value of P_e; the particle diameter d (in mm) and the corresponding meteor magnitude m for which an equal effect is produced by the solar radiation pressure. The particle diameters are computed from

$$d = 1.16 \times 10^{-3} \rho^{-1} (2\,q^{-1} P_e^{2/3} - 1)(P_e^{2/3} P^{-2/3} - 1)^{-1} \qquad (2)$$

(Kresák, 1976), assuming that all incident solar radiation is effective in transferring momentum to a spherical particle of $\rho = 1$ g/cm^3. The main source of uncertainty is that in ρ, but appropriate values for other densities can be easily found by multiplying the listed values of d by the relative density. Meteor mag-

TABLE III

Tangential component of ejection velocity u (in m/s) required for increasing the revolution period from P to P_e (in years); particle diameter d (in mm) for $\rho = 1$ g/cm^3, and the corresponding meteor magnitude m, at which the same effect is produced by solar radiation pressure

Stream	P	q	$P_e = \infty$ u/d/m	$P_e = P + 1$ u/d/m	$P_e = 1.05$ P u/d/m
Geminids	1.6	0.13	3100/0.025/16	880/0.09/13	100/0.73/6
Taurids	3.3	0.34	2800/0.015/18	460/0.09/13	90/0.44/9
Draconids	6.6	1.00	3100/0.008/21	290/0.08/15	100/0.22/12
Leonids	33	0.98	1000/0.024/14	21/1.17/3	33/0.72/4
Orionids	76	0.59	450/0.071/11	4/8.1/-3	14/2.2/1
Perseids	120	0.96	430/0.059/12	2/10.4/-3	14/1.8/2
Lyrids	415	0.92	180/0.14/10	0.3/87/-9	6/4.3/0
Aurigids	2500	0.68	50/0.6/5	2000/0.01/-20	1.5/20/-5

nitudes are referred to the scale of Jacchia et al. (1963), putting

$$m = 19.2 - 6.75 \log d - 8.75 \log V \tag{3}$$

This relation is admittedly valid in a limited brightness range, and the calculated extreme values indicate only that the critical diameter is well outside this limit. The actual ejection velocities, increasing with decreasing solar distance, particle size and density, can amount to tens of m/s at the most (Whipple, 1951; McIntosh, 1973). Both mechanisms should separate the particles by sizes, with a tendency of smaller particles to disperse more rapidly. The difference should be more clearcut, and asymmetric with respect to the mean anomaly of the comet, for the radiation pressure. But even here ejections at different heliocentric distances would mix up particles of different size from the very beginning.

4. COMETARY SOURCES: LONG-PERIOD COMETS

Long-period comets undoubtedly are the most lavish source of interplanetary dust. On the other hand, the spectrum of particle sizes retained within the solar system is very narrow, being limited at the upper bound by the maximum size of particles which can be released from the nuclear surface (Whipple, 1951), and at the lower bound by the minimum size of those which avoid deflection into hyperbolic orbits.

The minimum size of ejecta from the "new" comets ($P = 2\times10^6$ to 5×10^6 years, $r = q = 0.5$ to 1.0) which are not expelled by the solar radiation pressure ranges from a few centimeters for high-density particles to decimeters for fluffy particles. Ejections in the direction opposite to the motion of the comet would reduce the critical size by one order of magnitude at $u = -5$ m/s, and by two orders at $u = -50$ m/s; however, these particles would remain in orbits of very long period. Any later fragmentation would reinitiate removal by radiation pressure, so that a progressive decay would lead to the same ultimate fate. The only protection is that the particles are transferred by planetary perturbations into smaller orbits before the next fragmentation occurs. A clear analogy with the orbital evolution of long-period comets (Everhart, 1972) shows that this process is extremely ineffective. Strong perturbations are very rare, and essentially limited to original perihelion distances of $q = 4$ to 6, excluding any previous appreciable activity in the critical size range. With decreasing period of revolution of the comet the conditions tend to improve, and a small fraction of the particles ejected from comets with periods of ~1000 years can remain in the inner solar system.

The orbits of about 18% of the known long-period comets approach the earth within $D_0 = 0.10$ in one node and 3% in both nodes; 2% approach the earth within $D_0 = 0.01$. These numbers are high enough to cause spurious associations when meteor observations are interfaced with extensive lists of predicted cometary radiants. Nonetheless, in several cases the relationship appears well established. In addition to the clearcut identification of 1861I ($D_0 = 0.003$, $P = 415$ years) as the parent comet of the annual Lyrids, particularly good matches are those of 1862II ($D_0 = 0.014$) and ξ Arietids, 1911II ($D_0 = 0.033$) and Aurigids, 1944I ($D_0 = 0.034$) and σ Hydrids, 1739 ($D_0 = 0.058$) and Leo Minorids, 1931IV ($D_0 = 0.062$) and δ Cancrids, 1919V ($D_0 = 0.102$) and o Draconids, 1964VIII ($D_0 = 0.122$) and ε Geminids. The longest period for a well established comet-stream association is that of 1911II Kiess, 2500 years, 1919V Metcalf being the only other case where a very long period seems to be certain. For the other comets the periods are either less than 400 years or rather indeterminate.

The ejecta from long-period comets are apparently scarce, and mostly restricted to distances of less than 0.1 A.U. from the comet orbit at $r = 1$. Their small contribution to the dust complex is consistent with the distribution of meteor orbits in inclination. The orbital planes of long-period comets are randomly distributed in $1/\sin i$, which should reflect in a random distribution of inclination angles of their ejecta encountered by the earth. While the most extensive catalogue of photographic meteor orbits (McCrosky and Posen, 1961) lists 20% of retrograde orbits, their proportion drops to 1% when a selection of the 10% of objects largest by mass is made. Accordingly, no more than 2% of the objects may belong to a random distribution, and this already includes the contribution of high-inclination orbits of shorter period.

5. COMETARY SOURCES: INTERMEDIATE-PERIOD COMETS

Table III demonstrates that for this type of orbit high-density particles down to a 10-micron size and fluffy particles down to a 100-micron size remain within the solar system. 16 comets of this type are known, and four of them approach the earth's orbit within $D_0 = 0.10$. Three of these, P/Tempel-Tuttle ($D_0 = 0.0031$), P/Swift-Tuttle ($D_0 = 0.0044$), and P/Halley ($D_0 = 0.0652$), produce major annual showers represented in Table II and the fourth, P/Mellish ($D_0 = 0.0616$), produces a minor but well confirmed shower of Monocerotids. Accordingly, every intermediate-period comet has an associated meteor stream which is steadily being replenished. This is evident from the observation of dense swarms at $D_0 < 0.01$. In Table II they are only represented by the Leonids. However, ancient records mention, in spite of unfavourable observing geometry, brilliant η Aquarid displays at the time when the orbit of P/Halley was passing close to the earth (Imoto and Hasegawa, 1958). The same source mentions a great Perseid shower in the year of the last perihelion passage of P/Swift-Tuttle, 1862. There are good prospects for rich Perseid showers in connection with the forthcoming perihelion passage of the comet which should occur in 1980 to 1982 (Marsden, 1973). According to Table III, a persistence of considerably increased activity over several years can be anticipated.

The lists of photographic meteor orbits include 24% of periods exceeding 20 years. Again, if only the 10% of largest objects are sampled, the contribution drops to 5%, and a correction for measuring errors reduces this to less than 3%. The total contribution by intermediate- and long-period comets cannot exceed this figure, and should decrease towards smaller sizes. For about 20% of the intermediate-period meteors the parent comet can be readily identified among the four objects mentioned earlier. This would set the mean lifetime of such streams at 20% of the mean lifetime of individual particles, which, compared with Whipple's (1967) model, yields a reasonable value of about 10,000 years.

6. COMETARY SOURCES: SHORT-PERIOD COMETS

Table III shows that unrealistically high ejection velocities are needed for an immediate escape from the solar system of any particles released by short-period comets. Particles with diameters of microns to tens of microns are eliminated by radiation pressure; this size range is of interest for detection in situ but irrelevant to meteor observations. At the same time, the selective effect of radiation pressure makes the swarms of ejecta disperse rather rapidly along the orbit, with the smallest particles lagging the most behind. While for intermediate-period comets occurrence of optically detectable showers is predicted for a few years after the comet's return immediately following the ejection, for comets of the Jupiter family a similar extension can only appear in the range of faint radio meteors. This finding is consistent with the observed difference between the Leonids and the Draconids, some separation by size being also evident from the Leonid radio data (McIntosh, 1973).

Short-period comets of the Jupiter family constitute a clear majority of the parent objects of dense meteor swarms, but are absent among the parent objects of the major annual showers (see Table II). A swarm of recent ejecta apparently accompanies every active short-period comet, as short intense showers nearly always appear when $D_0 < 0.01$ and $\Delta M < 30^\circ$. The only exception from this rule was P/Grigg-Skjellerup in 1967 ($D_0 = 0.0027$, $\Delta M = +18^\circ$), and again in 1972 ($D_0 = 0.0043$, $\Delta M = +10^\circ$). However, this is fully consistent with the general picture. These two encounters were preceded by a close approach to Jupiter in 1964 which perturbed the comet's perihelion distance by +0.15 A.U.; hence, there was apparently not time enough for a sufficient dispersion of the ejecta along the orbit. Current D_0-values of active short-period comets are: P/Giacobini-Zinner, 0.0013; P/Grigg-Skjellerup, 0.012; P/Tuttle, 0.089; P/Finlay, 0.102; P/Boethin, 0.102; P/Haneda-Campos, 0.135; P/d'Arrest, 0.151; P/Denning-Fujikawa, 0.152; P/Encke, 0.178 and 0.194; P/Tuttle-Giacobini-Kresák, 0.197. There are only two additional comets of $q < 1.2$ and ten of $1.2 < q < 1.4$ which pass at larger distances. At $D_0 = 0.1$ to 0.2, about one half of the short-period comets display a weak, hardly discernible meteor activity. This is easily understandable, as a complete diffusion of a typical new swarm into the volume of a typical annual stream would be concurrent with dilution by a factor of 10^{-5} to 10^{-6}. Even if a swarm of E = 2 is the result of a single perihelion passage, a level of E = 0.05 at D_0 = 0.20, as displayed by P/Encke, would require 10,000 revolutions of the comet. This requirement is in conflict not only with the frequency of major perturbations by Jupiter, but also with the average rate of mass loss by short-period comets. The loss is estimated at 1/1000 of the total mass per revolution on the basis of the nongravitational effects in their motion (Marsden and Sekanina, 1971). The fact that all the dense swarms produced by short-period comets constitute about 1/8000 of the circumterrestrial meteoroid population makes it very difficult to believe that later evolutionary stages of such swarms could contribute a significant fraction of the dust complex. The lack of narrower, ring-shaped, short-period streams identifiable as the next stage of dispersion, can be explained by the character of planetary perturbations dominated by Jupiter. While the displacement of the orbit by secular perturbations is typically 0.01 A.U. per century (Galibina, 1979), that by random perturbations amounts to 0.15 A.U. per century. Almost invariably the displacement in a single revolution exceeds the width of young swarms. Moreover, ring-shaped streams would be periodically depleted by Jupiter passing near their aphelia at a low relative velocity.

The single exception from this point of view is P/Encke, which is quite peculiar in many other respects as well: in shortest perihelion distance and period on record; in aphelion decoupled from Jupiter, ensuring motion of relative stability. The estimated contribution of P/Encke to the meteoroid population around the earth's orbit is about 0.4%, or five times that of all other active comets taken together. Even this is a conservative lower limit, including only those particles which are still recognizable as stream members by their motion. The detectable width of the stream, more than 1 A.U., is quite abnormal, indicating a uniquely rich source. Whipple (1967) had already suggested that P/Encke over the past several thousand years had been the major support for maintaining the quasi-equilibrium of the zodiacal cloud.

7. OTHER SOURCES AND CONCLUSIONS

The results of the foregoing paragraphs suggest that the contribution of the present population of active comets to the present meteoroid population is less than 1%, and that most of it is supplied by P/Encke. Another 1% constitutes the major annual streams of unknown parent bodies - the Geminids, Quadrantids, ξ Perseids, Arietids, and δ Aquarids. Their orbits are unlike those of short-period comets. In four cases the perihelion distance is very small; in the fifth (Quadrantids) the inclination is high, implying a very small perihelion distance 1700 years ago, when the inclination was low (Hughes et al., 1979). It would appear logical that comets of small perihelion distance decay rapidly and are no longer observable. On the other hand, normal evolution from long-period to short-period comets can only very rarely result in an orbit of Quadrantid or δ Aquarid type, and never in one of Geminid, ξ Perseid or Arietid type.

The above data apply to the size range from 100 microns to several milimeters, producing photographic meteors. There is both theoretical expectation (see

Tab.III) and observational evidence (Kresák, 1964) that the proportion of comet-like orbits tends to decrease with decreasing particle size. Radar measurements of fainter meteors are strongly biased against low-velocity particles. They reveal a significant enhancement of retrograde orbits, but their aphelia are almost invariably situated far inside the orbit of Jupiter (Davies and Gill, 1960; Kashcheev and Lebedinets, 1967). The only mechanism capable of moving the aphelion into this position is a long-term operation of nongravitational forces associated with the mass loss by a nucleus in retrograde rotation. Even for P/Encke this requires an extraordinary original size of the nucleus, 20 to 60 km according to Sekanina (1972). Yet the 10% sample of largest photographic meteors includes 55% of aphelion distances smaller than that of P/Encke, and 65% smaller than that of any other known comet. There are even 40% of aphelion distances below 3.0 A.U. For such orbits the mean secular change of the perihelion and aphelion is 0.0004 A.U. per century (Galibina, 1979). Encounters with Jupiter producing large random perturbations are absent, and encounters with the inner planets are rare.

It is often believed that the Poynting-Robertson drag can explain the preponderance of small orbits. This interpretation, however, overlooks the fact that Poynting-Robertson inspiralling does not start from the orbit of the parent body but from an orbit augmented by direct radiation pressure. At particle sizes for which the Poynting-Robertson drag is effective enough, the radiation pressure is strong too. For example, in the absence of planetary perturbations it would take more than 1000 revolutions of P/Encke before this effect can reassemble the dispersed ejecta of different size into the vicinity of the orbit in which the ejection took place; it is not until then that the real inspiralling begins (Kresák, 1976). The stay inside the original orbit would not be much longer than outside it, notwithstanding further fragmentation, erosion, and depletion by Jupiter at the time when the aphelia cross its orbit.

The only larger bodies with dynamical properties similar to those of a majority of meteoroids are the Apollo objects (for their relationships to comets and asteroids see Kresák, 1979). The surface properties of most of these objects make them a plausible source for meteorites, but not for low-density meteoroids. As to the carbonaceous asteroids which apparently originate from the outer region of asteroid accretion, it is not out of the question that their interiors are rich in volatiles (Chapman, 1979). Collisional fragmentation of this type of body could supply interplanetary space with a vast amount of dust, and possibly also with a number of progressively decaying pseudo-comets. However, an asteroidal origin of the dust complex presents serious difficulties as well. Just as the reduction of the aphelion distance is the main problem for the comets, the analogous problem for the asteroids is the reduction of the perihelion distance. Mean elements of the asteroids passing through the region of highest collision risk are $q = 2.27$, $Q = 3.05$, $i = 7^{\circ}$, and the mean collision velocity is 5 km/s. Since this is about the same as the differential velocity necessary for placing the fragment into an earth-crossing orbit, the particles liberated by collisions should remain predominantly within the main asteroid belt. But there, no appreciable increase of impact rates was recorded by Pioneers 10 and 11 (Humes, 1976). Other arguments against the asteroidal origin of meteoroids have been presented by Dohnanyi (1976).

Delsemme (1976) proposes three alternative conditions under which the cometary source may be sufficient to cover the permanent loss of dust: (A) the dust complex is not in a permanent equilibrium, most of its mass being supplied by rare bright short-period comets. (B) The estimates of the total dust production are in error, because a major fraction of the dust is dragged away from short-period comets by something more volatile than water, at large solar distances. (C) A major portion of the dust is supplied by long-period comets, in particles of considerable size. In fact, alternative (C) is inconsistent with the distribution of meteor orbits in inclination. Besides, any progressive diminution of the particles by fragmentation or erosion would lead to the same ends - escape from the solar system. Alternative (B) is incompatible with the distribution of the dust in heliocentric distance. Thus only alternative (A) appears plausible. It would imply a progressive decay of the whole dust complex continuing until another rich source of fresh dust appears.

The lack of active parent comets can be overcome if they leave, after devolatilization, unobservable remnants subject to further disintegration. There is indeed indirect evidence of continuing dust supply from inactive, sub-kilometer-sized objects - crusted fragments of extinct, or temporarily extinct, comets revolving in the inner solar system (Kresák, 1976 and 1978). This can be the ultimate fate of abnormally large cometary nuclei - a feature pointing to a very limited number of precursors of the intermediate parent objects. Yet the prevalence of very small orbits remains a difficult problem. If it is due to perturbational elimination of Jupiter-crossing objects, then a large mass input and long disintegration lifetimes would be required. The chance of a comet being transported by nongravitational forces into an orbit well inside that of Jupiter increases with its size. The extreme for known objects of possibly cometary nature is 2060 Chiron which may evolve from its present orbit into a short-period comet (Oikawa and Everhart, 1979), and eventually into an object of the type of P/Encke. Another example is the parent object of the present Kreutz group of sungrazing comets. This has apparently produced by progressive fragmentation more than 100 active comets, one of which (1882II) was possibly the second largest comet ever observed. An orbit of this type permits high-velocity ejections near the perihelion, and a moderate deceleration of 300 m/s (less than 0.1% of the orbital velocity) would be sufficient to place the aphelion inside the orbit of Jupiter. While evaporation near the Sun and escape on eccentric orbits would introduce an immense wastage, a fraction of the liberated particles could occupy orbits similar to those of the retrograde radio meteors.

The suggestion that a major portion of the interplanetary dust has been produced by a few exceptional parent objects is consistent with the size distribution of comets (Öpik, 1973) and asteroids (Kresák, 1977), with the seasonal variations of sporadic meteor rates (Millman and McIntosh, 1966), and with their expressed streaming pattern (Kashcheev et al., 1967; Štohl, 1969; Sekanina, 1973). It would imply that the dust complex is not in permanent equilibrium between source and sink, both its population and shape being variable on a time scale of 10^4 to 10^6 years. The nature and orbital history of the objects responsible for the present state is still rather obscure. Too much of our observational evidence is based on a single object - Comet Encke. A real touchstone for the problem of very small aphelion distances would be an explanation of the origin of the Geminid meteor stream. Its small dispersion makes it clear that the orbit of its parent object must have been similar to the orbit of the stream; but this is unlike that of any known larger, dust-producing object.

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DISCUSSION

Keay: Would you care to comment on the way that the Tunguska object fits into the picture which you have presented?

Kresák: It lends support to the idea that fragments of extinct cometary nuclei are one of the missing sources of interplanetary particles. On the other hand, the probable association of the Tunguska object with Comet Encke is consistent with the suggestion that a major portion of the dust complex has been supplied by a very limited number of parent objects, and that we do not have current state of equilibrium between source and sink.