ORBITAL EVOLUTION OF THE DUST STREAMS RELEASED FROM COMETS

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The orbital evolution of cometary dust grains with characteristic sizes of 1 to 100 μ is discussed. It is shown that the nongravitational perturbations produced by solar radiation strongly depend on the progressive abrasion and fragmentation of individual particles. The ejection of very small particles along hyperbolic orbits does not imply a sharp cutoff in particle size; a distribution of dust emission along the parent comet's orbit only produces a progressive depletion, with the mass limit decreasing with increasing heliocentric distance of the point of separation. Since each particle starts inspiralling from an orbit which is determined by the initial blowing-off by direct radiation pressure, the Poynting-Robertson lifetimes have a definite lower limit depending on the orbital elements of the parent body. Even for short-period comets, this limit is relatively high compared with the survival against destruction and perturbational dispersion.

Progressive fragmentation and abrasion reinforces the repulsion by direct radiation pressure at each reduction of the particle size, with an efficiency depending on the distribution of the eroding medium in heliocentric distance. Hence the inspiralling is controlled by the rate of mass loss, and can change into a drift outwards in special cases.

Some quantitative estimates of the dynamical evolution are made for the dust streams released from Comet Encke, and these are interfaced with the conditions in comets of longer revolution periods. There is apparently no way of maintaining a compact dust stream over a number of revolutions, or displacing it inside the orbit of its parent comet. The reality of the cometary associations suggested for some impact events on space probes is questioned. It is implied that the observed dust grains can hardly be immediate products of disintegration of comets; other possible sources are mentioned.

Эволюция орбит пылевых потоков выделенных из комет

Обсуждается эволюция орбит кометных пылевых зерн с размерами от 1 до 100 микронов. Показано что негравитационные возмущения, обусловленные солнечным излучением, строго зависят от постепенной абразии и дробления отдельных частиц. Извержение очень малых частиц по гиперболическим орбитам не дает никакого крутого отсекания по размерам частиц; распределение выбросов пыли вдоль орбиты родительской кометы приводит лишь к постепенному истощению, в котором предел массы уменьшается по мере увеличения гелиоцентрического расстояния точки сепарации. Так-как каждая частица начинает свое спиральное движение к Солнцу с орбиты определенной первоначальным оттолком вследствие прямого лучистого давления, возрасты Пойнтинг-Робертсона имеют нижний предел, определенный элементами орбиты родительского тела. Даже для короткопериодических комет этот предел кажется довольно высоким в сопоставлении с продолжительностю существования под действием разрушения и пертурбационного рассеивания.

Постепенное дробление и абразия усиливают отталкивание прямым давлением излучения при каждом уменьшении размеров частиц, с эффективностью зависимой от распределения разрушающей среды по гелиоцентрическому расстоянию. Сдедовательно, спиральное движение к Солнцу определено скоростью потери массы и в особых случаях может превратиться в дрейф направленный наружу.

Некоторые количественные оценки динамической эволюции пылевых потоков выделенных из кометы Энке сопоставлены с условями в кометах с большим периодом обращения. Очевидно что нет возможности сохранения компактного потока пылевых частиц в течении несколких оборотов вокруг Солнца, или-же его перемещения внутрь орбиты родительской кометы. Подвергается сомнению реальность связей с кометами, предложенных на основании некоторых наблюдений космических зондов. Показывается что регистрируемые пылевые зерна едва ли можно считать прямыми продуктами распада комет; приводятся другие возможные источники.

1. Introduction

A number of investigators have reported sudden increases of dust particle fluxes on satellite-borne detectors (Dubin et al., 1973; Nazarova, 1967 and 1968; McCracken et al., 1967; Hoffmann et al., 1975, etc.), enhancement of impact rates when meteor streams known from ground-based observations are crossed (Dycus, 1969; Alexander et al., 1970, 1971, 1972 and 1973), or coincidences of individual impact events with the passages through orbital planes of different comets (Alexander et al., 1970; Berg and Gerloff, 1971; Gerloff and Berg, 1971). These phenomena, if real, would suggest that a considerable proportion of interplanetary dust is concentrated in streams similar to the meteor streams known from optical and radio observations of larger particles, and that enhanced fluxes can be predicted from the orbits of known comets (Poultney, 1972).

The validity of most of the earlier results of this type has been questioned because of inconvincing noise rejection techniques (Mazets, 1971; Sitte, 1971; Soberman, 1971) and because of untenably high fluxes obtained (Shapiro et al., 1966). It appears that experiments in the near-earth environment (balloons, sounding rockets, low satellites) are most liable to spurious flux variations. This is because the contamination of terrestrial origin (see e.g. Farlow and Lem, 1973) and contamination by the carrier of the experiment significantly add to the noise problems. Even real accumulations of extraterrestrial particles need not come from interplanetary dust streams but from ablation and fragmentation of larger particles in the earth environment, or from secondary ejecta from the Moon. The results from Skylab (Nagel et al., 1975) indicate that products of recent fragmentation may be detected as high as 450 km above the earth surface, and the counts on Heos 2 (Hoffmann et al., 1975) put this limit still higher.

Nevertheless, non-random variations in particle fluxes and individual comet-micrometeoroid associations have also been reported from deep-space experiments in circumsolar orbits (Alexander et al., 1970; Gerloff and Berg, 1971). This contrasts with the finding of other authors that the time distribution of the impact events is commensurate with a purely random Poisson distribution (Roosen and Berg, 1973; McDonnell et al., 1975). The aim of the present paper is to discuss the dynamical conditions under which an interplanetary stream of fine dust can originate, evolve, and be detected.

2. The Escape Limit and the Mass Cutoff

The tentative identifications of individual comets as parent bodies of the observed dust particles are based on the theoretical evidence that a particle which is small enough to be strongly perturbed by solar radiation can essentially reach any point within its orbital plane in a relatively short time. It can either pass outward of the original orbit having been blown off a larger body by direct radiation pressure, or it can pass inwards having been decelerated by the Poynting-Robertson drag. It is unfortunately often overlooked that these two effects are closely tied together. The spiralling inwards has to start from an orbit which may substantially differ from that of the parent comet, because it is *always* preceded by a sudden disturbance of opposite sign at the moment of separation.

From that moment on, the direct radiation pressure reduces the central force attracting the particle to the Sun in a ratio of $1 - \beta$ where

(1)
$$\beta = 5{\cdot}8 \times 10^{-5} s^{-1} \varrho^{-1} = 9{\cdot}3 \times 10^{-5} m^{-1/3} \varrho^{-2/3} .$$

A spherical particle of radius s (in cm), density ϱ (in g cm^{-3}), and mass m (in grams) is assumed. For a non-spherical shape the effective value of β will become higher; on the other hand, if all incident radiation is not effective in transferring momentum to the particle, it will become lower. The resulting orbit is elliptic or hyperbolic according to the conditions set by the energy integral,

(2) $$\beta \lessgtr \tfrac{1}{2} r_0 a_0^{-1}$$

(3) $$m \gtrless 6{\cdot}5 \times 10^{-12} \varrho^{-2} r_0^{-3} a_0^3 ,$$

where a_0 is the semimajor axis of the orbit of the large parent body (e.g., a comet), and r_0 is the heliocentric distance of the point at which the particle was released, both in astronomical units. The simple relations (1) to (3) lose their validity due to light scattering, if s becomes comparable with the wavelength of the pressure-applying radiation.

On a double logarithmic scale, the escape condition (3) can be represented by the linear relation shown in Fig. 1 for five major meteor streams associated with known periodic comets (Taurids: P/Encke;

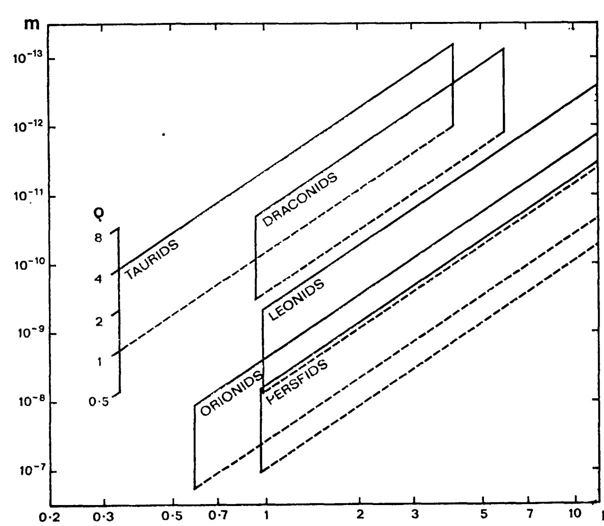

Fig. 1. Dependence of the critical particle mass m (in grams) on the heliocentric distance of the point of separation r_0 and particle density ϱ. Dashed lines, dustballs of $\varrho = 1$ g cm^{-3}; solid lines, stony grains of $\varrho = 4$ g cm^{-3}. The varying limit of parabolical escape from the solar system is shown for five comet-meteor stream associations: P/Encke — Taurids, P/Giacobini-Zinner — Draconids, P/Tempel-Tuttle — Leonids, P/Halley — Orionids, and P/Swift-Tuttle — Perseids.

Draconids: P/Giacobini-Zinner; Leonids: P/Tempel-Tuttle; Orionids: P/Halley; Perseids: P/Swift-Tuttle).

While the orbital element a_0 can be determined with ample accuracy, the other two factors on the right-hand side of Eq. (3) introduce a major source of uncertainty. Variations in the density of the particles produce a vertical displacement of the mass scale, with $\Delta(\log m) = 2 \log (\varrho/\varrho_{\text{adopted}})$. Two tentative values are plotted: $\varrho = 1 \text{ g cm}^{-3}$ (mass m_1) and $\varrho = 4 \text{ g cm}^{-3}$ (mass m_4). The correct values may even lie outside these limits, as indicated by the vertical scale for the Taurids. Whipple (1967) suggests $\varrho = 0{\cdot}44 \text{ g cm}^{-3}$ as a mean density of photographic meteors in the mass range of about 10^{-3} to 10^0 g; Verniani (1973) finds $\varrho = 0{\cdot}8 \text{ g cm}^{-3}$ for faint radio meteors in the mass range of 10^{-5} to 10^{-3} g. Most earlier papers use $\varrho = 3{\cdot}2$ to $3{\cdot}5 \text{ g cm}^{-3}$, drawing on a possible analogy with the meteorites recovered on the Earth. The depth-to-diameter ratios of the microcraters on lunar samples and their electron microprobe analyses indicate a silicate composition of the crater-producing particles (Hörz et al., 1975), and Smith et al. (1974) even claim a very significant proportion of iron particles of $\varrho = 7{\cdot}8 \text{ g cm}^{-3}$ in the mass range of 10^{-12} to 10^{-10} g. Advanced information on the orbits may improve these estimates, since the depth-to-diameter ratio may be rather sensitive to the impact velocity.

As regards the uncertainty in r_0, i.e. in the heliocentric distance at which the particles are liberated, we can obviously identify the absolute extremes as the preihelion and aphelion distance of the parent comet orbit. The total range of uncertainty depends on the orbital eccentricity,

$$(4) \qquad a_0(1 - e_0) \leqq r_0 \leqq a_0(1 + e_0)\,.$$

Since the initial value of the semimajor axis a' of a particle, released from an orbit of semimajor axis a_0, is

$$(5) \qquad a' = (1 - \beta)\, r_0\, a_0 (r_0 - 2\beta a_0)^{-1}\,,$$

the escape limits for a perihelion ejection and an aphelion ejection are defined as

$$(6) \qquad \beta_P = \tfrac{1}{2}(1 - e_0)\,,$$

$$(7) \qquad \beta_A = \tfrac{1}{2}(1 + e_0)\,,$$

respectively, provided that the relative velocity of separation can be neglected.

There is a widespread misconception that $\beta \geqq 1$ is necessary to let a particle escape from the solar system on a hyperbolic orbit. In fact, this statement only applies to fictitious particles of zero angular momentum. As already pointed out by Harwit (1963), Whipple (1967), and Dohnanyi (1973), very small values of β may be sufficient to make the circumsolar orbit open. In fact, Eq. (6) yields a critical value of $\beta_P = 0{\cdot}076$ for a perihelion ejection from Comet Encke, $\beta_P = 0{\cdot}016$ from Comet Halley, and β_P of the order of 10^{-5} for new comets coming from Oort's Cloud. On the other hand, it must not be overlooked that these figures only apply to the *perihelion* ejecta. The corresponding values from Eq. (1) cannot be interpreted as the minimum sizes of the grains retained in the solar system, as done implicitly by Harwit (1963). In general, Eqs (6) and (7) define two critical levels. The former is mostly slightly above $\beta = 0$ and indicates the onset of a partial escape; the latter is mostly slightly below $\beta = 1$ and indicates a total escape. For example, for the ejecta from Comet Encke the escape limits are $\beta = 0{\cdot}076$ ($m_1 = 1{\cdot}8 \times 10^{-9}$, $m_4 = 1{\cdot}1 \times 10^{-10}$) at perihelion, $\beta = 0{\cdot}226$ ($m_1 = 7{\cdot}0 \times 10^{-11}$, $m_4 = 4{\cdot}4 \times 10^{-12}$) at $r_0 = 1$, and $\beta = 0{\cdot}924$ ($m_1 = 1{\cdot}0 \times 10^{-12}$, $m_4 = 6{\cdot}4 \times 10^{-14}$) at aphelion. Only for a circular orbit of the parent body the two limits coalesce into a value of $\beta = 0{\cdot}5$ (used by Zook and Berg, 1975) which is then uniform throughout the orbit.

Thus the conjecture of Soberman (1971) that there is no cutoff by radiation pressure at all, because the light scattering makes relation (1) invalid just near $\beta = 1$, must also be taken with reserve. There is actually a gap between two critical particle sizes: the upper corresponding to a compensation of the difference between the parabolic and elliptic velocity by radiation pressure, and the lower to a recompensation of the parabolic excess by light scattering.

The presence and significance of the lower limit strongly depend on the dielectric properties of the particles. As shown by Shapiro et al. (1966), there is actually no lower limit for iron particles where β does not drop below 1·4 for infinitely small grains; on the other hand, β never reaches 0·8 for quartz. In general, the width of the gap, in which particles are swept out from circumsolar orbits, depends on the distribution of the heliocentric distances at which they become liberated from their parent bodies.

While it appears quite natural that, in accordance with Whipple's (1951) model, the process of dust release from comets is most efficient near perihelion, Eq. (6) alone cannot be used as a sound working approximation. This is both because the comets spend most of each revolution at much larger distances from the Sun, and because the mass distribution function of interplanetary dust strongly prefers the smallest sizes situated just above the cutoff.

To illustrate this effect, let us adopt a rough model, certainly oversimplified, which assumes that the amount of dust released per unit time is proportional to the radiative energy received from the Sun, i.e.

(8) $$\mathrm{d}m \sim r^{-2}\,\mathrm{d}t\,,$$

and that the mass loss is uniformly distributed into different intervals of log m, i.e.

(9) $$\mathrm{d}n(m) \sim m^{-2}\,\mathrm{d}m\,.$$

Since, due to the Law of Areas,

(10) $$r^2\,\mathrm{d}v = k[a_0(1 - e_0^2)]^{1/2} = \text{const.},$$

where v is the true anomaly, (8) and (10) yield

(11) $$\mathrm{d}m \sim \mathrm{d}v\,.$$

This relation, which is independent of (9), means that the amount of dust released is proportional to the range of the true anomaly covered. With this simple condition, the change of the mass distribution (9) due to partial loss into hyperbolic orbits can be easily determined. It must be borne in mind, however, that this change applies to the total population rather than to the flux through a fixed plane, which is, in addition, inversely proportional to the revolution period. Another effect which is not included is the different response of the detectors to different impact velocities, which is also related to the particle mass.

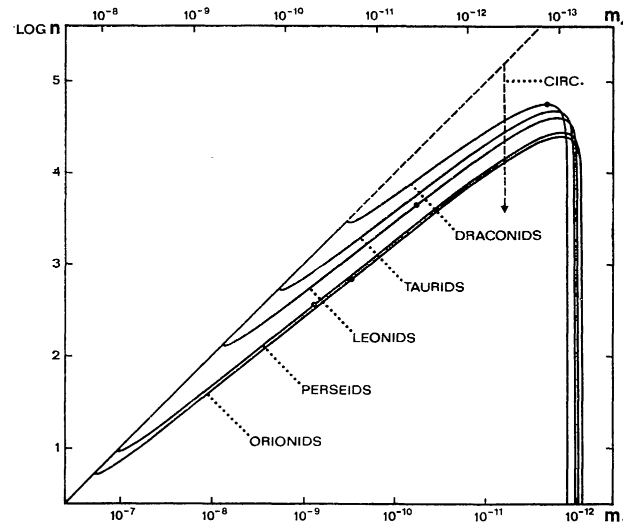

Fig. 3. Changes of an exponential mass distribution $\mathrm{d}n \propto m^{-2}$. $\mathrm{d}m$ ($\log n + \log m = 10^{-6}$) due to hyperbolic ejection by radiation pressure, for the five comet-meteor stream associations of Fig. 1. Lower scale, dustballs of $\varrho = 1\ \mathrm{g\,cm^{-3}}$; upper scale, stony grains of $\varrho = 4\ \mathrm{g\,cm^{-3}}$. The dots on the curves mark $r_0 = 5$ a.u. The break on the dashed line indicates a sharp mass cutoff for parent bodies moving in circular orbits.

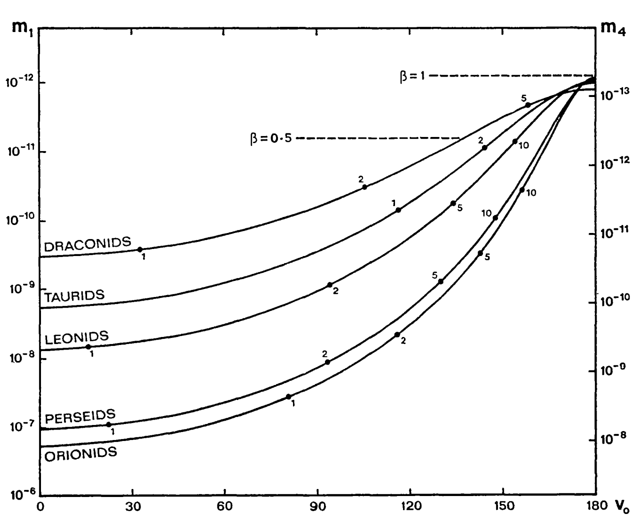

Fig. 2. Dependence of the critical particle mass m_ϱ (in grams) on the true anomaly of the point of separation v_0 for the five comet-meteor stream associations of Fig. 1. Left-hand scale, dustballs of $\varrho = 1\ \mathrm{g\,cm^{-3}}$; right-hand scale, stony grains of $\varrho = 4\ \mathrm{g\,cm^{-3}}$. Selected values of heliocentric distance r_0, in a.u., are labeled on the curves. Dashed lines: equilibrium between gravitation and radiation forces (linear escape), $\beta = 1$; parabolic cutoff for parent bodies moving in circular orbits, $\beta = 0{\cdot}5$.

Figure 2 shows the critical masses m_1 and m_4 as a function of the true anomaly of emission v_0 for the five comet-stream associations of Fig. 1. Figure 3 shows the logarithmic distribution of particle numbers for this simplified model. It is evident that while the depletion is appreciable even for relatively large particles, the population index merely exhibits a sudden reduction to

(12) $$\mathrm{d}n(m) \sim m^{-1.7}\,\mathrm{d}m \quad \text{to} \quad m^{-1.8}\,\mathrm{d}m\,,$$

followed by a rather sharp cutoff near $\beta = 1$, $m_1 = 10^{-12}$, $m_4 = 6 \times 10^{-14}$. Here the actual trend becomes definitely distorted by scattering effects. The observed value of the exponent in (12) would be even smaller because of the dependence of the flux on the periods of revolution.

It may be conjectured that any emission of dust from comets is unlikely beyond a certain heliocentric distance, e.g. beyond the region of persistent envelopes of ice crystals suggested by Delsemme and Wenger (1970). Nonetheless, we have clearcut observational evidence of cometary activity at $r_0 = 5$ to 10. This includes frequent violent bursts of P/Schwassmann-Wachmann 1 (Vsekhsvyatskij, 1966), splitting of P/Biela, P/Brooks 2 and 1957 VI Wirtanen (Pittich, 1971), appearance of conspicuous tails of some comets, such as 1927 IV, 1954 V, 1955 VI, 1956 I, 1957 VI, 1962 VIII or 1971 I, at unusual distances

(Roemer, 1962), or the backward tracing of the synchrone and syndyne tail structures observed near the Sun (Sekanina, 1973a). Although the dust emissions at such distances may be far from continuous, their contribution cannot be disregarded entirely. Even the present simplified model involves a significant disproportion between the dust supply from the perihelion and aphelion, e.g., about 150 : 1 per unit time for Comet Encke, and a dominant contribution from the inner part of the orbit, e.g., one half from within $r_0 = a_0(1 - e_0^2) = 0{\cdot}626$ for Comet Encke.

It is obvious that the escape limit is somewhat smeared out by the contribution of the emission velocities. However, for small dust particles the velocity requirements to counter with the radiation pressure are rather severe. In order to compensate for the momentum imparted by radiation fully, the tangential component of the emission velocity ΔV_T must be

$$\Delta V_T = [(1 - \beta)^{1/2} - 1]\,(2r_0^{-1} - a_0^{-1})^{1/2}\, V_0$$

$$(13) \qquad \simeq \tfrac{1}{2}(2\, r_1^{-1} - a_0^{-1})\,\beta V_0 \qquad (\text{if } \beta \ll 1)\,,$$

where V_0 is the circular velocity at $r_0 = 1$, $\beta = 0$. For a perihelion emission from Comet Encke, a velocity component ΔV_T exceeding 1 km/s would be necessary for $m_1 < 3{\cdot}5 \times 10^{-8}$ g, $m_4 < 2{\cdot}2 \times 10^{-9}$ g; 0·5 km/s for $m_1 < 2{\cdot}8 \times 10^{-7}$ g, $m_4 < 1{\cdot}7 \times 10^{-8}$ g, etc. Such high velocities are clearly at variance with the present concepts of processes in cometary nuclei, not to mention their impact on the initial dispersion of orbits, and a small proportion of the particles emitted in a suitable direction. For an aphelion emission the velocity requirements become reduced in a ratio of $(1 - e) : (1 + e)$, i.e. by a factor of $\frac{1}{12}$ for P/Encke. Thus the aphelion emissions, with the escape mass limit three orders of magnitude lower, and critically dependent on the physical properties of the individual particles, would imply a wider scatter of individual particles of uniform mass for a constant velocity of separation. There are good reasons to believe that the emission velocity at aphelion is considerably lower than at perihelion (Whipple, 1951) which would remove or even invert this disproportion.

3. The Orbital Evolution of Non-fragmenting and Non-eroded Particles

The interplay of all destructive and non-destructive effects in the motion of individual dust grains is enormously complicated, and a number of poorly known parameters are involved. Any model that assumes a physical integrity of the particle (constant s, m and β) can hold good as a working approximation only in the event that the time scale of the non-destructive effects is short enough to make fragmentation improbable, and erosion and sputtering negligible.

The relevant time scale is determined by: (1) the size and shape of the orbit into which the particle is injected by direct radiation pressure immediately after separation, (2) the speed of the Poynting-Robertson spiralling to the Sun, and (3) gravitational perturbations by the planets. One point which was not observed in some previous analyses is that a rapid operation of the Poynting-Robertson drag is precluded by the escape of those particles to which it would apply. Moreover, for the particles maintained it takes some extra time before an orbit coinciding with that of the parent comet is nearly restored. Small size and density, which is a prerequisite of an efficient operation of the Poynting-Robertson effect, implies a precedent injection into a larger starting orbit, and hence an extended period of spiralling.

The situation is illustrated in Figure 4 showing the radiative perturbations in aphelion distance for different sizes of dust grains released at low velocities from the perihelion of Comet Encke. Particles of $m_1 < 1{\cdot}8 \times 10^{-9}$ g or $m_4 < 1{\cdot}1 \times 10^{-10}$ g are ejected at once on hyperbolic orbits. Larger particles start spiralling inwards at a different speed, but also from a different distance which increases with decreasing particle size, as

$$(14) \quad a' = (1 - \beta)\,(1 - e_0)\,(1 - e_0 - 2\beta)^{-1}\, a_0\,.$$

Subsequent evolution can be determined using the formulae of Wyatt and Whipple (1950). Inclusion of the corpuscular drag would accelerate the changes a little, by about 22% according to Whipple (1955). In the present computations this was neglected because an equivalent adjustment of the densities, to $\varrho = 0{\cdot}8$ for m_1 and $\varrho = 3{\cdot}2$ for m_4, would bring them even closer to the probable values for icy dustballs and stony grains, respectively. A wider margin of uncertainty is set by the variety in shape factors and reflectivities.

The most important feature illustrated by Fig. 4 is that the Poynting-Robertson lifetimes have a lower limit. For low-velocity ejections from Comet Encke this is 14 000 years, irrespective of ϱ. Particles which would arrive first to the Sun have $\beta = 0{\cdot}047$, corresponding to $m_1 = 7{\cdot}6 \times 10^{-9}$ g and $m_4 = 4{\cdot}8 \times 10^{-10}$ g, respectively. They start at $a' = 5{\cdot}5$, $Q' = 10{\cdot}7$, i.e. from first-revolution aphelia just beyond the orbit of Saturn (dashed line).

During the first few thousands years the differen-

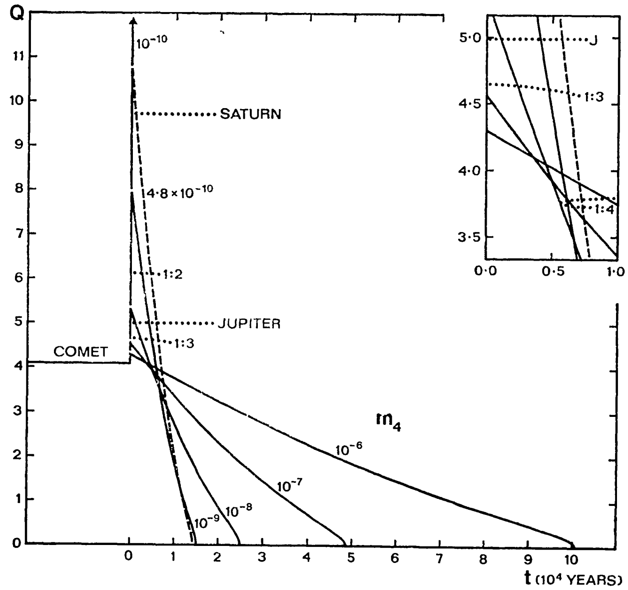

Fig. 4. Progressive variations in aphelion distance Q due to the Poynting-Robertson effect, for particles of different mass m_4 (in grams: $\varrho = 4\ \text{g cm}^{-3}$) released at time $t = 0$ from the perihelion of Comet Encke. Crossing of the orbits of Saturn and Jupiter and passages through simple resonances with Jupiter are indicated by dotted lines. The inlet on upper right is a three-fold enlargement of the region near the aphelion of the comet.

tial Poynting-Robertson drag tends to contract the stream and diminish the mass separation of the particles which had been ejected simultaneously. The crossing region is not far from the aphelion of the parent comet but, as seen from the enlarged inlet on upper right, the aphelia of all particle sizes never come close together. Moreover, during the 4000 to 6000 years which are necessary to restore the concentration near the orbit of the parent comet, dispersive effects of planetary perturbations must get overhand. While Comet Encke cannot approach Jupiter to within 0·9 a.u., all ejecta from near its perihelion do so. All particles of $\beta > 0{\cdot}016$ (i.e. $m_1 < 2 \times 10^{-7}$ g, $m_4 < 10^{-8}$ g) have to cross Jupiter's perturbational barrier, at a characteristic speed $\mathrm{d}Q/\mathrm{d}t = -0{\cdot}015\beta$ per year, or $-0{\cdot}05\beta$ per revolution. In view of the escape mass limit, the shift of the aphelion cannot exceed 0·004 a.u. per revolution. As a consequence, Jupiter will deplete the stream considerably by accelerations and collisions, and set some of the remaining particles into temporary libration (resonance 3 : 1 near $Q = 4{\cdot}6$; resonance = 4 : 1 near $Q = 3{\cdot}8$), thus increasing their dynamical lifetimes.

The radial dispersion will be accompanied by a considerable spread perpendicular to the initial orbital plane. Due to the differences in revolution periods, even the particles which have been released simultaneously will occupy a closed ring within two or three revolutions of the parent comet. Deformations of the kind described by Levin et al. (1972), produced by random perturbations, will make the larger particles overtake the smaller ones in different planes, and the nodal difference will determine the duration of the shower recorded by a passing detector. A simple statistics of the variations of nodal longitudes of short-period comets in one revolution makes it possible to roughly estimate this time interval. For the comets with aphelia near or beyond the orbit of Jupiter, Δt exceeds 1·3 hour in 50% of cases, 6 hours in 20%, and 2 days in 10%. For the less perturbed Comet Encke the corresponding figures are 0·3, 0·5, and 4 hours, respectively. By comparison with the duration of the swarms ($\Delta t < 0{\cdot}25$ hour) and groups ($\Delta t < 12$ hours) detected on Heos 2 by Hoffmann et al. (1975) we see that the ages of such formations cannot exceed a few years and a few decades, respectively. Even these limits require a superficial assumption that the particles are of uniform size, have been released simultaneously, and move in an environment free of products of earlier emissions.

During the subsequent evolution, the rate of dispersion by random planetary perturbations will tend to slow down, but the difference in secular perturbations for different revolution periods will make the stream expand at a constant pace. Since the contraction of the orbit to the size of that of the parent comet would take thousands of years, any compact stream must be dissolved completely by perturbations long before having spiralled inside the orbit of the parent comet. This conclusion applies even in a more obvious form to the streams of longer revolution period, where the size limit for hyperbolic escape is higher and the Poynting-Robertson lifetime is longer. For example, the lower lifetime limit for perihelion emissions from P/Swift-Tuttle, the parent comet of the Perseid stream, is as high as 10^6 years.

The conditions are only a little more favourable for the emissions from the aphelion of the comet. In this case equation (14) transforms into

$$a' = (1 - \beta)(1 + e_0)(1 + e_0 - 2\beta)^{-1} a_0 . \tag{15}$$

The aphelion distance remains unchanged, and the perihelion recedes from the Sun. For Comet Encke the lower limit of the Poynting-Robertson lifetime reduces from 14 000 to 1900 years, and applies to a broader size range of particles around $m_1 = 10^{-11}$ g, $m_4 = 7 \times 10^{-13}$ g. It may be noted that these particles are much smaller than all those retained from the perihelion emissions. For larger particles the dependence of the Poynting-Robertson lifetime on the emission point (r_0) becomes immaterial.

A conspicuous feature of the aphelion emissions is that they preserve a moderate radial dispersion of the orbits. The same particle which would escape on a parabolic orbit if released at perihelion, would only increase its perihelion distance from q_0 to

$$q' = q_0[1 + \tfrac{1}{2}(e_0^{-1} - 1)] \tag{16}$$

if released at aphelion. For Comet Encke, e.g., this would mean an increase of 0·03 a.u., or 9%.

Relatively narrow streams may originate in this way, but these will certainly vanish in the strongly predominating, widely dispersed background from the near-perihelion emissions. It may seem that the aphelion emissions become prominent at the lowest size level where the dust released from other parts of the orbit is eliminated by hyperbolic escape. However, here the dispersion by planetary perturbations will proceed most rapidly, because large values of β imply different revolution periods in similar orbits, and a rapid transport of individual particles along the orbital ellipse.

4. The Effects of Fragmentation, Erosion, and Sputtering

Even the lower limit of the Poynting-Robertson lifetimes for the particles retained in elliptic orbits at the time of separations is apparently too long compared with their rate of destruction. The most straightforward evidence of a rapid operation of the destructive effects is the abundance of shower associations among ordinary meteors, which indicates that the shower meteors must vanish before they completely diffuse into the sporadic background (Whipple, 1967; Kresák, 1968). Optical and radio observations of meteor showers consistently indicate a relative lack of faint shower meteors (Millman and McIntosh, 1963; Kresáková, 1966; Millman, 1970), which complies with the assumption that the depletion is due to a destructive effect accelerating with decreasing particle size (Kresák, 1960). The progressive decay of short-period comets suggests that the time during which any of them can produce coma and tail is limited; the fact that the parent comets of most of the major meteor showers are still active puts another constraint to the possible lifetimes of individual meteoroids. The rate of dispersion of meteor showers is controlled by planetary perturbations, and can hardly exceed 10^4 years for associations like Comet Encke/Taurid meteors (Hamid and Whipple, 1951). If the destruction is a result of progressive abrasion, the lifetime should be proportional to the cube root of particle mass, and amount to not more than several years for the dust grains detected by deep-space probes.

Unless the probe moves through a dust tail of a comet, in which case the hyperbolic component of fine dust should be dominant, we must visualize the grains encountered as remnants of particles which were originally larger. Under these conditions not only the Poynting-Robertson drag but also the direct radiation pressure exerts a permanent, or at least recurrent, influence on the motion of the particles.

The potential modes of mass loss include rotational disruption by the windmill effect (Paddack, 1969) or by the reflectivity effect (Radzievskij, 1954); incomplete collisional destruction (Piotrowski, 1953; Wetherill, 1967; Dohnanyi, 1972), erosion by impacts of smaller particles (Whipple, 1965), and erosion by corpuscular sputtering (Kresák, 1960;, Wehner et al., 1963; McDonnell and Ashworth, 1972). Thus the process may be either due to separate major events, or may be more or less continuous. Anyway, every mass loss not only accelerates the Poynting-Robertson spiralling but also blows off the particle into a larger orbit. It is the rate of destruction which determines the resulting trend – a drift inwards or outwards. The conditions of the intermediate case of hovering are of particular interest.

Provided that the destruction process is a splitting into separate pieces of comparable size, an equivalent effect to that of the release from a sizeable parent body requires an increase of β to

$$\beta' = (2 - \beta)\,\beta \tag{17}$$

which, for $\beta \ll 1$, yields $\beta' \simeq 2\beta$ and, according to equation (1), $m' \simeq \frac{1}{8}m$. If the separation and disruption occur at the same heliocentric distance, and at the time when the orbit of the particle has shrinked to the dimension of the orbit of its parent body, initial conditions are restored for a number of eight fragments but, since $\mathrm{d}a/\mathrm{d}t \propto \beta$, the spiralling will now proceed twice as rapidly. Thus the condition of hovering would require $m' \simeq \frac{1}{16}m$, i.e. disruption into sixteen equal fragments. For example, if the particles emitted from the perihelion of Comet Encke would suffer progressive splitting into halves at later perihelion passages, an equilibrium interval between such events would be about 10^3 years (900 years for $m_4 = 10^{-6}$ g to 1400 years for $m_4 = 10^{-9}$ g), according to Fig. 4. At this rate of fragmentation the orbits would remain permanently outside that of the comet, until the particles become small enough to escape from the solar system on hyperbolic orbits. However, rotational disruption seems to be much less frequent (Paddack, 1969). Splitting into equal halves is obviously a superficial assumption and a full compensation of the drag would only require that the largest fragments remain below the critical size.

For a continuous process of erosion or sputtering, an equilibrium is attained if the Poynting-Robertson drag becomes compensated by an increasing effectivity of the direct radiation pressure. The formula for the Poynting-Robertson rate of change of the semimajor axis, derived by Wyatt and Whipple (1950), can be written as

(18)

$$\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)_{PR} = -6{\cdot}2 \times 10^{-4}(2 + 3e^2)(1 - e^2)^{-3/2}\, a^{-1}\beta =$$
$$= -5{\cdot}8 \times 10^{-8}(2 + 3e^2)(1-e^2)^{-3/2}\, a^{-1}\, m^{-1/3}\, \varrho^{-2/3}.$$

For a constant abrasion rate $\mathrm{d}^2s/\mathrm{d}t^2 = 0$, we have

(19) $$\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)_{E} = -\varepsilon a\beta(1-\beta)^{-1}\, s^{-1}\frac{\mathrm{d}s}{\mathrm{d}t} =$$
$$= -1{\cdot}60 m^{-1/3}\varrho^{1/3}(1{\cdot}07 \times 10^4 m^{1/3}\varrho^{2/3} - 1)^{-1}\, a\varepsilon\,\frac{\mathrm{d}s}{\mathrm{d}t},$$

where

(20) $$\varepsilon = 2ar_{\varepsilon}^{-1} - 1$$

and r_ε is the heliocentric distance at which the erosion occurs. Inserting for r_ε the aphelion and perihelion distance of the orbit, the extremes of ε are obtained:

(21) $$\varepsilon_A = (1-e)(1+e)^{-1} \leqq \varepsilon \leqq$$
$$\leqq (1+e)(1-e)^{-1} = \varepsilon_P\,.$$

The two effects counterbalance each other if

(22) $$\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)_{PR} + \left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)_{E} = 0\,,$$

which leads to a hovering condition of the form

(23)

$$\varepsilon\frac{\mathrm{d}s}{\mathrm{d}t} = C(3{\cdot}9 \times 10^{-4} m^{1/3}\varrho^{-1/3} - 3{\cdot}6 \times 10^{-8}\varrho^{-1})$$

where C is a function of the orbital elements,

(24) $$C = (2 + 3e^2)(1 - e^2)^{-3/2}\, a^{-2}\,.$$

For P/Encke (the Taurids) we have $C = 5{\cdot}63$, for P/Swift-Tuttle (the Perseids) $C = 0{\cdot}373$, etc.

The results of evaluation of the condition (23) for Comet Encke are presented in Figure 5. The equilibrium masses m_1 and m_4 near the orbit of the comet are plotted as a function of $\log \varepsilon$ and $\log(\mathrm{d}s/\mathrm{d}t)$, in which case the dependence is linear. Heliocentric distances r_ε corresponding to different values of ε are also indicated. The position of a particle (eroded at a characteristic heliocentric distance r_ε at a rate of $\mathrm{d}s/\mathrm{d}t$) to the right of its mass line means that drifting inwards, due to the Poynting-Robertson effect, prevails. The position to the left of it means that the dominating erosion makes the particle drift outwards by the progressive effect of direct radiation pressure. The result is shown not to be particularly sensitive to the particle density, but rather sensitive to the heliocentric distance at which most of the erosion takes place, and especially to the erosion rate. This obviously depends on the structure and composition of the particle, and hence implicitly on the density.

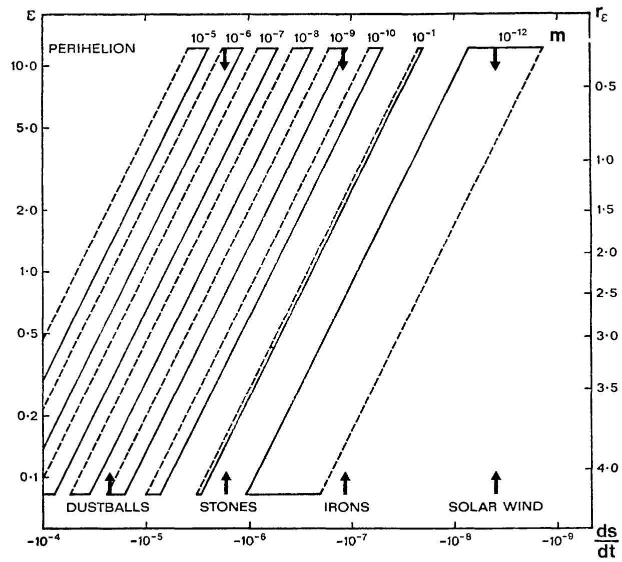

Fig. 5. The condition of equilibrium for dust particles released from Comet Encke, between a drift inwards (due to the Poynting-Robertson drag) and outwards (due to the reinforcement of direct radiation pressure by progressive abrasion). Horizontal scale, abrasion rate $\mathrm{d}s/\mathrm{d}t$ in centimeters per year. The arrows indicate erosion rates for irons, stones and dustballs according to Whipple (1967), and the sputtering rate by solar wind according to Wehner et al. (1963). Left-hand scale, erosion efficiency ε; right-hand scale, the corresponding heliocentric distance r_ε. Labeling at the perihelion extreme, particle masses in grams; dashed lines, dustballs of $\varrho = 1\ \mathrm{g\,cm^{-3}}$; solid lines, stony grains of $\varrho = 4\ \mathrm{g\,cm^{-3}}$.

Selected values of erosion rate $\mathrm{d}s/\mathrm{d}t$, which are indicated by the arrows, represent conservative upper limits. The solar wind sputtering rate of 4×10^{-9} cm yr^{-1} is taken from Wehner et al. (1963); more recent estimates by McDonnell and Ashworth (1972) and McDonnell et al. (1974) are considerably lower. Nevertheless, even for Wehner's sputtering rate the dynamical effect is insignificant. It would become comparable with the Poynting-Robertson drag until for particle masses $m < 10^{-11}$ g, i.e. for those particles which are expelled immediately after separation.

The impact erosion rates estimated by Whipple (1967) would be sufficient to convert inspiralling into outspiralling for cometary dustballs, and even for stony grains if the erosion takes place predominantly near the Sun. Whipple (1951) suggested that the dispersion among photographic Taurids was due to collisions in the asteroid belt rather than to ejections at perihelion. However, the data from Pioneer 10 (Neste and Soberman, 1974; Kinard et al., 1974) failed to show any significant concentration of dust in the asteroid zone, and it now appears that higher particle fluxes and velocities near the Sun should be responsible for a major part of the erosion. This would permit an overcompensation of the Poynting-Robertson effect by direct radiation pressure for most of the cometary particles detectable by space probes.

While the abundance of shower associations among ordinary meteors, combined with the rate of disintegration of periodic comets and the rate of perturbational dispersion of meteor streams, lends strong support to the high erosion rates estimated by Whipple, it appears questionable whether these values can be extrapolated to the finer dust. The mean erosion rate may well be strongly size-dependent. A cutoff, or a bimodal distribution of particle masses, like that suggested by Hörz et al. (1975), would reflect in parallel changes in erosion of masses several orders of magnitude higher, where the respective size of impinging particles is most efficient in non-destructive collisions. A depletion of the microparticle population by radiative repulsion would act in this direction, and a reduction of the mean erosion rate below 10^{-7} cm yr^{-1} would make the outspiralling practically impossible. In fact, the model of McDonnell and Ashworth (1972) predicts a steep drop of the erosion rate below $m \simeq 10^{-5}$ g.

For other cometary dust streams the situation may be similar. Selecting the Perseid stream of P/Swift-Tuttle as a representative of long-period streams, we can compare the requirements on the erosion rate with those found for the Taurid stream of P/Encke. Qualitatively, the effects are the same. Due to a different value of factor C in equation (22), which is a function of orbital elements, the requirements on the erosion rate $\mathrm{d}s/\mathrm{d}t$ to produce an equivalent dynamical effect are 15 times lower for P/Swift-Tuttle than for P/Encke. Also the maximum erosion efficiency is 4 times higher, $\varepsilon_P = 50$ as compared with $\varepsilon_P = 12$. On the other hand, the depletion of the smallest dust particles (which are most liable to drifting outwards) immediately after their liberation is stronger, and the time spent in strongly eroding environment is much shorter. P/Swift-Tuttle spends only 0·5% of each revolution within $r = 2$ a.u. (P/Encke: 20%), 1·8% within $r = 5$ a.u. (P/Encke: 100%), and 4·8% within $r = 10$ a.u. Unless more is known about the dependence of the erosion effects on the distance from the Sun, it is difficult even to guess which type of orbit is most affected.

Since the impact erosion is essentially a random process, its rate may be different even for two particles of equal mass and density, and identical initial orbit. Periods of drift inwards and outwards may alternate even for a single particle. A concentration of the eroding medium to the plane of ecliptic would imply a dependence of the erosion rate on the inclination and orientation of the orbit. A combination with planetary perturbations may give rise to a complicated pattern, as illustrated in a higher mass range by the double (northern and southern) meteor streams of Taurids, δ Aquarids, ι Aquarids etc.

The final escape of small dust particles along hyperbolic orbits needs not be only due to their separation from a sizeable parent body. It may also follow after a nearly destructive collision of two particles of comparable size, after an impact on a larger particle of loose structure, or after a partial vaporization near the Sun. The last process represents, according to Belton (1967), the termination of the Poynting-Robertson spiralling. However, in view of the present results it appears that most of the cometary dust is removed long before reaching the region of vaporization.

5. Conclusions and Discussion

The main results of this study can be summarized as follows:

(1) There is no definite cutoff of particle sizes by direct radiation pressure even for a system of particles released from the same parent body. The condition of equilibrium between solar attraction and radiative repulsion, $\beta = 1$, applies only to a specific case of linear escape, and not to the escape in general; the condition $\beta = \frac{1}{2}$ (Zook and Berg, 1975) applies only to parent bodies in circular orbits; the limit set by perihelion emissions (Harwit, 1963) is exceeded appreciably if the dust is liberated at a larger distance from the Sun. The effective limit stretches between $\beta = \frac{1}{2}(1 - e)$ at perihelion and $\beta = \frac{1}{2}(1 + e)$ at aphelion.

(2) The broad range of the escape limit for eccentric cometary orbits makes the mass distribution

function of the liberated dust markedly deviate from that of the original partition. If the amount of emitted dust is proportional to the radiative input from the Sun, and the original mass distribution is exponential, the mass distribution of the particles maintained in the solar system can be approximated by two regions of different mass exponent. The upper end of the second region nearly coincides with the critical size for which the scattering effects make the radiation pressure less effective and dependent on the dielectric properties of the particles.

(3) Since the Poynting-Robertson spiralling must begin from a starting orbit enlarged by direct radiation pressure, very short Poynting-Robertson lifetimes are virtually impossible. There is a definite lower limit of this lifetime for each parent body, and for the cometary debris this is generally long compared with their survival against destruction.

(4) Progressive fragmentation and erosion reinforces the operation of direct radiation pressure which counters the Poynting-Robertson drag. This can change the spiralling inwards into a hovering around the original orbit, or into a drift outwards for repeated splitting into halves in intervals of the order of 10^3 yr, or for erosion rates of the order of 10^{-6} cm yr^{-1}. A progressive increase of the relative mass loss at a constant erosion rate implies an additional decrease of the mass exponent with decreasing particle size. The exact mode of depletion of the smallest particles depends on the preceding activity and orbital history of the parent body.

(5) A prolongation of the dynamical lifetimes by radiation pressure applied at the time of separation from the parent body, and at the time of every subsequent reduction of the particle size, tends to increase the dispersive effects of planetary perturbations. Their operation is accelerated by a rapid building up of the dispersion in mean anomaly, as a result of the size-dependent reduction of solar attraction by radiation pressure.

It has been definitely established by ground-based observations that all permanent meteor streams become less prominent with respect to the sporadic background as the particle size decreases (Millman and McIntosh, 1966; Kresáková, 1966; Millman, 1970). There are three reasons to expect that this trend is maintained, or even increased, in the range of smaller dust particles detected on spacecraft: the depletion of the smaller sizes by the hyperbolic escape of the dust component emitted near perihelion (see Fig. 3); increasing revolution periods with decreasing size, which reduces their encounter frequency relative to their numbers; and a size-dependent effect of abrasion which makes the relative mass loss increase with decreasing mass. It appears that no micrometeorite streams should be detectable unless the space probe enters the dust tail of a comet, or unless it moves in the vicinity of a large body (Earth, Moon) where remnants of recent grazing encounters or impacts may simulate interplanetary micro-showers. In particular, it appears quite impossible that a compact stream might spiral inside the orbit of the parent comet, as suggested by Alexander at al. (1970) for the shower event detected on Mariner IV in 1967. Inspiralling is rather improbable even for isolated particles like that detected on Pioneer 8 and tentatively attributed to Comet Grigg-Skjellerup by Gerloff and Berg (1971). It has already been shown by Levin and Simonenko (1972) that identifications of this type are unfounded. Predictions of enhanced fluxes of dust particles at the time of crossing the nodal lines of short-period comets of $q < 1$, like those published by Poultney (1972), have hardly a reasonable probability of being fulfilled.

The orbits of active short-period comets exhibit a definite cutdown around the perihelion distance of 1 a. u. (Kresák, 1973), which is consistent with the capture process. In view of the strong arguments against any efficient inspiralling of their debris, it is difficult to see how they could contribute to a concentration of dust near the Sun. The debris of long-period comets, on the other hand, should never return to the Sun, being only observable as hyperbolic streams in the vicinity of the comet. The rate of occurence of such comets is rather low: on the average, one observed object of $q < 0{\cdot}2$ passes perihelion every six years, and one of $0{\cdot}2 < q < 0{\cdot}5$ every three years. These comets are mostly bright, with conspicuous tails, and their rapid motion makes them observable at sufficient angular elongations from the Sun within a few weeks of the perihelion passage (Kresák, 1975). The rate of discovery of such comets has experienced no increase due to improving instrumentation during the last century (28 comets of $q < 0{\cdot}5$ between 1874 and 1924, 27 comets between 1924 and 1974), contrary to those of large perihelion distance (10 comets of $q > 2{\cdot}0$ between 1874 and 1924, 38 comets between 1924 and 1974). This also suggests that there are not many active comets passing near the Sun without being detected. The decay of the long-period comets can account for high particle fluxes of hyperbolic dust streams at the time when the space probe crosses a comet tail. However, such events should be exceedingly rare, and cannot contribute to a permanent sporadic background.

If we discard active comets, both of short and long period, we are faced with the necessity of assuming an unobservable kind of direct source for most of the interplanetary dust. Obviously, this may well be an intermediate product of disintegration of larger bodies. Harwit's (1967) interplanetary boulders, with a size of the order of 10 to 100 m, would meet these requirements. If they are so numerous as to produce erratic nongravitational disturbances in the motion of short-period comets at the rate suggested by Marsden and Sekanina (1971) and Sekanina (1973b) they can also supply large amounts of fine dust. In order to produce a sufficient concentration of dust near the Sun, the boulders have to revolve in low-eccentricity orbits in the region of the terrestrial planets. This is a necessary condition for a complete inspiralling, since a low total energy at the time of separation of small dust particles would protect them against destruction between the initial blowing off and the final contraction of the orbit, by reducing this time interval. Low eccentricities would probably imply low inclinations, i.e. a distinct ecliptical concentration of the dust, favouring an asteroidal origin.

Dust particles generated by the boulders would be detectable in two phases of evolution. During the inspiralling period they would cover a broad size range, and exhibit low impact velocities on space probes, perhaps 10 km s^{-1} and less at $r = 1$. At the terminal phase of escape, following a partial vaporization by the mechanism suggested by Belton (1967), they would move away from the Sun at geocentric velocities of the order of 40 km/s near $r = 1$. This escaping dust component would be confined to a relatively narrow mass range (around 10^{-12} g or 10^{-13} g depending on particle density), corresponding to $\beta \simeq 0{\cdot}5$.

It must be admitted that ground-based observations yield little evidence on the presence of larger particles moving in orbits of the type required for the parent boulders. A majority of the observed meteors cross the earth orbit at large angles, and a very low geocentric velocity, which is indicative of an orbit similar to that of the Earth, is rather an exception. The Cyclid meteors with masses of the order of 10^{-1} g, detected in the Harvard Super-Schmidt data (Southworth and Hawkins, 1963) is a good example. It is possible that this type of objects is much more abundant than suggested by the observational statistics, since both the optical and radio methods are rather insensitive to particles of low geocentric velocity. Furthermore, the earth-crossing condition restricts the observability to a narrow range of semimajor axes of nearly circular orbits, which may be depleted appreciably by previous encounters with the Earth. For all these reasons, the small values of Whipple's „Cosmic Weights" assigned to the Cyclids may be misleading. An interesting example of a boulder-sized object moving in an orbit almost identical with that of the Earth was presented by the „Canadian Fireball Procession" of 9 February 1913. Here, a sequence of tens of huge fireballs was observed to graze the atmosphere at a very low velocity, on an arc stretching from Saskatchewan to the Central Atlantic (Chant, 1913; Mebane, 1956). This exceptional phenomenon was apparently due to a recent disintegration of a body of considerable size. Several similar but less striking examples can be found in the book of Nininger (1952).

One more potential source of interplanetary dust deserves special attention. Even with a long revolution period, the disintegration of the parent body may become very efficient provided that its perihelion distance is very small. Since the condition $\beta \simeq 0{\cdot}5$ does not apply for this case, even larger particles can attain high hyperbolic velocities pointing away from the Sun, and the velocity of fine dust at the encounter with the Earth may considerably exceed 100 km s^{-1}.

A unique family of known bodies excellently meeting these orbital requirements is the Kreutz group of sungrazing comets. Eight members of this group were discovered during the last century and two of them, 1882 II and 1965 VIII, were observed to split into several separate nuclei near perihelion. With about one half of similar objects lost by adverse observing conditions and a mean revolution period of 10^3 years one can guess that the total number of active comets constituing this stream is one to two hundreds (Kresák, 1966). It appears probable that the orbital ellipse of the Kreutz group is occupied by a great number of cometary fragments of different size which, at each sungrazing perihelion passage, can liberate great amounts of dust without building up visible comas and tails. The position of the nodal line does not allow these bodies to cross the orbit of the Earth.

The Kreutz group of comets seems to be of relatively recent origin (Marsden, 1967), and one can speculate that there are similar older streams of cometary fragments which no longer contain active comets. These might represent a significant source of high-velocity particles with fluxes variable both in time and space, failing to show an ecliptical concentration, but contributing to collisional interactions with the low-inclination, low-eccentricity particles, especially near the Sun. The behaviour of the dust released at short heliocentric distances ($q < 10^{-2}$ for the Kreutz group) would essentially be the same as that of the particles of solar origin suggested by Hemenway et al. (1973), except for a difference in the velocity corresponding to the original momentum.

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