4.8 EVOLUTION AND DETECTABILITY OF INTERPLANETARY DUST STREAMS

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Sudden enhancements in responses recorded by micrometeoroid detectors flown on spacecrafts have been repeatedly attributed to encounters with streams of cometary debris similar to, or identical with, the meteor streams known from ground-based observations. For measurements made in the Earth-Moon environment, spacecraft effects, atmospheric fragmentation of larger particles, and possibly lunar ejecta can be misinterpreted as interplanetary streams. For deep space observations it is necessary to inquire whether a compact dust stream can persist under the dispersive and destructive effects which increase rapidly with decreasing particle size.

The reduction of solar attraction by direct radiation pressure is believed to produce a cutoff in the mass of the particles moving in circumsolar orbits - except for submicron grains where light scattering reduces the effect of radiation pressure. The size range of particles swept out of the solar system depends on the critical value of the radiation parameter $\beta = 0.93 \times 10^{-4} m^{-1/3} \varrho^{-2/3}$, where m is particle mass in grams and ϱ particle density in g cm^{-3}. There is a wide-spread misconception that the cutoff is governed by the condition $\beta = 1$ representing an equilibrium between gravitation and radiation forces. This applies only to fictitious particles of zero angular momentum. On the other hand, the critical value of β corresponding to emissions at perihelion (Harwit, 1963) is exceeded appreciably if the dust is released at a larger distance from the Sun.

The initial semimajor axis of the orbit of a dust particle released at a negligible velocity from a parent orbit of semimajor axis a_0 and eccentricity e_0 at a heliocentric distance r is

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

Consequently, the critical value of β for a parabolic escape varies between $\frac{1}{2}(1 - e_0)$, if the particle is emitted at perihelion, and $\frac{1}{2}(1 + e_0)$, if it is emitted at the aphelion of the parent comet. While the dust emission is obviously most abundant near perihelion, each comet spends most of a revolution in remote parts of its orbit, the contribution from which may not be disregarded for short-period comets. In fact, we have clearcut observational evidence of strong cometary activity beyond the orbit of Jupiter, ranging from sudden outbursts, to splitting of the nuclei, and to the presence of conspicuous tails, including indirect evidence from the tracing backwards of tail structures observed near the Sun. A rough model assuming that the mass loss is proportional to the radiative energy input, i.e. to the rate of change of true anomaly, was used by us to compute the variation of the mass population index for several comet-meteor associations.

The result is a break in the mass distribution function, with a progressive depletion beginning at $m = 6.5 \times 10^{-12}\,Q^{-2}(1 - e_0)^{-3}$, e.g. at $m = 1.8 \times 10^{-9}\,Q^{-2}$ for P/Encke or $1.0 \times 10^{-7}\,Q^{-2}$ for P/Swift-Tuttle, the parent comet of the Perseids. In a mass range which is about three orders of magnitude for short-period comets, a linear $\log n / \log m$ relation would only change its slope, until a final cutoff is produced by the absence of emission activity beyond a certain distance from the Sun. This limit is always above, but may be close to, $m = 0.8 \times 10^{-12}\,Q^{-2}$, i.e. in the region where scattering effects begin. Hence Soberman's conjecture (1971) that there is no cutoff at all may apply for some particle compositions, provided that the cometary emissions occur at large distances from the Sun. Maintaining fine dust within the solar system requires that the ratio a_0/r not be excessively large, so as to keep *a* positive for sufficiently high values of β. For comets of long period, and especially those coming from Oort's Cloud, the limited heliocentric region of activity moves both the break and the cutoff of the mass distribution curve into the size range of ordinary meteors. Hence no fine dust released from these comets remains in elliptic orbits, and a passage through the comet's tail is the only possibility of detecting a dust stream. For a nearly circular orbit of the parent body where the escape condition $\beta > \frac{1}{2}$ used by Zook and Berg (1975) applies the break and the cutoff coincide.

It is essential that the post-separation Poynting-Robertson spiralling begins from a starting orbit determined by the direct radiation pressure, with $a > a_0$, $\beta < \frac{1}{2}\, r\, a_0^{-1}$. This sets a definite lower limit of Poynting-Robertson lifetime, depending on the orbital elements of the parent body. The shortest time of inspiralling into the Sun is 1.4×10^4 yr for perihelion emissions from P/Encke, 1.9×10^3 yr for aphelion emissions from P/Encke, and as high as 1.0×10^6 yr for perihelion emissions from P/Swift-Tuttle. The role of the Poynting-Robertson effect seems to have been overestimated in most of the current comparisons of the competitive evolutionary processes. Due to the initial blowing off by direct radiation pressure, the time for complete inspiralling may become comparable with the destruction lifetime, and a considerable proportion of the particles may not survive.

Now, each reduction of the particle size by fragmentation or abrasion reinforces the radiative repulsion. For a particle of radius s eroded at a heliocentric distance r we have

$$da = -\beta\,(1-\beta)^{-1}\,(2\,a\,r^{-1} - 1)\,a\,s^{-1}\,ds \qquad (2)$$

which may be compared with the inspiralling rate determined by Wyatt and Whipple (1950). The solar wind sputtering rates, as estimated by Wehner et al. (1963) and by Ashworth and McDonnell (1974) are entirely inadequate to compensate for the Poynting-Robertson drag. Rotational splitting (Radzievskij, 1954; Paddack, 1969) would require the bursting speed to be attained every 10^3 yr for the ejecta from P/Encke. The impact erosion rates estimated by Whipple (1967) would be sufficient to convert the inspiralling into a prevailing drift outwards for cometary debris of loose structure. 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 a high destruction rate, irrespective of the exact mechanism (Kresák, 1968). However, the model of McDonnell and Ashworth (1972) predicts a steep drop of the erosion rate below $m \sim 10^{-5}$g, which would permit inspiralling for most of the cometary dust starting from short-period orbits.

Just as the heliocentric distance of the point of separation determines the efficiency of the radiation pressure in changing the size of the starting orbit, the distribution of the eroding medium governs its efficiency in offsetting the inspiralling motion. For example, for P/Encke the same erosion rate is about 150 times more effective if applied at perihelion than at aphelion. Apart from the dispersion by planetary perturbations, which is accelerated by the rapid radiative dispersion in mean anomaly, it appears that compact streams of dust particles released from normal comets can never pass inside their orbits, as claimed by Alexander et al. (1970) for P/Encke or by

Berg and Gerloff (1971) for the two comet associations already criticized by Levin and Simonenko (1972).

It has been definitely established by optical and radio observations that all permanent meteor showers become less prominent with respect to the sporadic background as the particle mass decreases (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 smaller sizes by hyperbolic escape of the dust component emitted near perihelion; 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. Therefore, showers of cometary dust should not be detectable in deep space, unless the probe enters a comet tail which still contains fresh hyperbolic ejecta. Such encounters, however, should be rare.

Recent in situ measurements of impact velocities and directions seem to be at variance with the identification of normal comets as a principal source of interplanetary dust. In this connection, two types of hypothetical parent bodies, unconfirmed by direct observation, deserve attention. If Harwit´s (1967) interplanetary boulders revolve in orbits of low eccentricity in the region of terrestrial planets, a low total energy would protect even very fine dust from being ejected and from being destroyed before arriving close to the Sun. During the inspiralling phase the particles 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 (Belton, 1967), the mass range should be relatively narrow, with geocentric velocities near 40 km s^{-1}. The erosion and light-scattering effects would act selectively according to the particle composition. A definite concentration to the plane of ecliptic would follow from a general correlation between inclinations and eccentricities of the parent bodies.

Another intriguing possibility is the existence of intermediate boulder-type products of disintegration in cometary orbits of very small perihelion distance. A unique example is the Kreutz group of sungrazing comets, where progressive disintegration of the nuclei seems to have produced at least one hundred separate comets (Kresák, 1966). The orbital ellipse of this system of comets may be occupied by numerous sizeable fragments which, at each sungrazing passage, can liberate dust without building up visible comas and tails. The dust would move away from the Sun at velocities exceeding 100 km s^{-1} at r = 1. Since the Kreutz group is apparently of recent origin (Marsden, 1967), 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. These streams may fail to show an ecliptical concentration, but may contribute to collisional interaction with the low-inclination low-eccentricity component. The orbits of the dust particles released at small heliocentric distances would be nearly the same as those of the particles of solar origin suggested by Hemenway et al. (1973), but the two sources would be distinguishable if reliable mass and velocity measurements were made.

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