DEBRIS FROM COMETS: THE EVOLUTION OF METEOR STREAMS

BRUCE A. MCINTOSH
Herzberg Institute of Astrophysics
National Research Council Canada
Ottawa, Canada, K1A 0R6

ABSTRACT. The evolution of meteor streams is controlled basically by: (a) the initial velocities with which the particles were ejected from the parent body; (b) gravitational perturbations by the planets; (c) radiation forces; and (d) collisions. This review focuses mainly on recent numerical modelling dealing with (b) and (a).

Ejection velocities spread the particles around the orbit, closing the ring in a few tens of revolutions. The greater ejection velocities of smaller particles cause more rapid dispersion both around the orbit and in the cross section.

A determination of the effects of gravitational perturbations must take into account the distributed properties of the stream. The stream's evolution is dependent on the short-term impulse nature of planetary perturbations, as well as on long-term secular effects. The combined effects produce complex stream cross-sections as in the ribbon-like form of the Halley stream (Orionid and η Aquarid showers) or as in the changes in the annual position of peak shower activity shown by the Quadrantids. Perturbations may cause the orbit of a parent body to sweep rapidly across the orbit of the Earth. But the associated particle stream may not be lost as a meteor shower because it tends to become dispersed in a manner that ensures a continuing supply of particles in Earth-crossing orbits. The nodes of the observed meteoroid orbits may show very little motion compared with the rapid motion of the nodes of the orbit of the parent object.

Radiation effects contribute to size separation of particles. Very small particles are blown out of the stream or spiral in toward the sun because of Poynting–Robertson drag. Older meteor streams usually show a predominance of large particles.

1. Introduction.

It is now well over a century since the inference (usually attributed to Kirkwood about 1861) was made that a meteor stream was associated with a comet. As the quality and precision of meteor observations improved, most of the major meteor showers came to have an identified parent comet.

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However, improved precision was a two-edged sword since some associations that had been accepted on the basis of crude data were later rejected on the evidence of more precise orbits. Such rejections (Porter 1952) resulted from a lack of understanding of the dynamical evolution of meteor streams.

It was accepted that meteor particles were the debris of comets, and the development of the debris into a continuous loop which resulted in an annual shower was reasonably well understood. Spectroscopic observations determined the major constituents of the particles. Double-station photographs produced precise orbits of meteors, and radar observations generated an abundance of data on meteor rates and less precise orbits. Whipple's (1951) icy-comet theory and calculation of the ejection velocities of the particles allowed a quantitative explanation of the formation of meteor streams. It was thought by many that most of the interesting research had been done.

A resurgence of interest in meteor showers over the past decade or so has been due to several factors: access to high-speed computers which allow the detailed numerical modelling of meteor streams with a number of particles that is sufficient to inspire confidence in the macroscopic reality of the result; the return of Halley's comet; and the question of whether some portion of the meteor complex may derive from asteroids rather than comets (or, the corollary, that the meteor—parent-body association implies that such bodies are dormant comets).

This paper will review recent developments in the theory of the dynamical evolution of meteor streams, emphasizing the effects of planetary perturbations. Historical observational material on meteor streams will be discussed only insofar as it relates to the evolution of the streams. Such material has been dealt with in many earlier reviews and recently very extensively by Kronk (1988).

2. Identification of Meteor Showers with Comets.

2.1. Recognition of a Shower.

A meteor shower is recognized by an increase in meteor rates at a particular time over the 'normal' rates. In Fig. 1 (Millman and McIntosh 1964), strong increases in meteor rates stand out clearly at specific times of the year. The data in the figure are counts of meteor radar echoes, but relative visual or photographic rates are similar. There are smaller peaks for which it is not clear whether they are weak showers or only random fluctuations in the background. Since these radar rates are five-year averages, much of the random fluctuation has been smoothed out. One notes also that some of the shower peaks that are prominent in the counts of long-duration echoes, i.e., larger meteoroids, are less prominent or non-existent in counts comprising mostly small particles (upper curve in the figure).

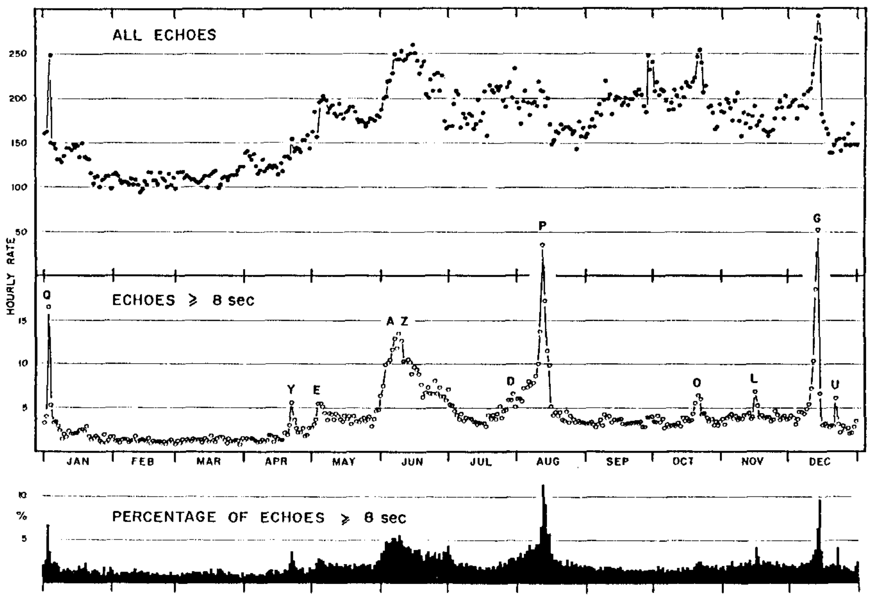

Figure 1 Meteor rates through the year as observed by the Ottawa meteor radar: upper curve, total echo count; middle curve, counts of echoes having durations ≥ 8 s; lower curve, percentage of echoes ≥ 8 s. Showers are: Q = Quadrantid; Y = Lyrid; E = η Aquarid; AZ = Arietid–Zeta-Perseid complex; D = δ Aquarid; P = Perseid; O = Orionid; L = Leonid; G = Geminid; U = Ursid.

2.2. Radiant of a Shower.

The next refinement in defining or identifying a meteor shower is the determination of its radiant—the position on the sky from which all of the shower meteors appear to originate. It was recognized (Olmstead 1834) that the meteors were in fact travelling toward the Earth along parallel lines and therefore on similar orbits in space. A.S. Herschel (1875) conducted a search for comet-meteor associations by calculating hypothetical radiants for comets that approached the vicinity of the Earth. He immediately noted the close correspondence between the 'radiant' for comet Halley and that for the η Aquarid meteor stream. Drummond (1981b) has more recently carried out a similar study.

A young meteor stream is thought to be characterized by a compact, well-defined radiant, while older streams seem to show broader, diffuse radiants. Whereas radiants determined from visual observations are not very accurate, those determined from precisely measured photographic meteors suffer from a paucity of data. More recent observations using sensitive TV-type cameras (Clifton 1973, Hawkes and Jones 1975) provide better data. Duffy *et al.* (1987) have demonstrated that sophisticated analysis methods allow shower parameters to be determined from single-station observations. Morton and Jones (1982) developed an ingenious method of determining radiant structure from single-station radar observations, which has been further developed by Poole and Roux (1989).

2.3. Orbital Parameters.

It is clear that every meteoroid that strikes the Earth must be travelling on an orbit such that one node (either ascending or descending) must intersect the Earth's orbit, and the longitude of the node is given by the longitude of the Earth at the time of collision. But no existing comet has a node exactly at the Earth's distance. What then are the criteria for associating comets and meteor streams? Why do the orbits differ? How can meaningful comparison of orbits be made? Research of the past few decades has led to a better understanding of the dynamical evolution of orbits and why large differences can occur between the orbit of the parent comet and its debris stream.

It was expected that the particle orbits in a stream would spread. But how much? A rule of thumb that became current stated that, if the node of a comet orbit was within 0.1 AU[1] of the Earth, a meteor shower would be possible. There were anomalies, such as for comet Halley, where the ascending node lies 0.85 AU outside the Earth's orbit, the descending node lies 0.15 AU inside, and yet there was evidence that the Earth encountered particles near both nodes. In this case, the closest approach between Earth orbit and the comet orbit is not at the nodes, but at points where the comet orbit passes the Earth orbit above and below the ecliptic. These distances are 0.07 AU and 0.15 AU (1910 orbit) for the Orionid shower and the η Aquarid shower, respectively. One falls within the 0.1 AU rule-of-thumb, but the other does not. It is still true that observed meteoroids have nodes at the Earth's orbit. McKinley (1961) comments, "The relation between either the η Aquarids or the Orionids and Halley's striking comet is tenuous and uncertain, though still an attractive possibility." The orbital parameters for Halley's comet and the two showers are listed in Table 1. Values for the showers are those given by Cook (1973). It is seen that the major differences in the orbits are in the values of longitude of the node, Ω, and argument of perihelion, ω. However, the similarity of the differences ω-Ω listed in the final column is indicative of the greater similarity of the orbits than the individual values seem to imply. This is discussed further below.

The reasons for past uncertainties in comet–stream associations are mainly twofold. First, measured parameters of meteor orbits tended to be inaccurate. Taking the Halley showers again as an example, Kronk (1988) lists values of semimajor axis for observed η Aquarid and Orionid meteors ranging from 2.8 AU to infinity, compared with 17 AU for Halley's comet. This extreme spread is due largely to errors in the measurement of meteor velocities. Second, the dynamical evolution of a stream may be considerably different from that of its parent comet, so that simple comparison of their present orbits may be misleading.

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[1] A convenient, if arbitrary, value whose origin is unknown. See Porter (1952), p. 89.

TABLE 1

Orbital parameters of Halley's comet and those of Orionid and η Aquarid meteors (a, semimajor axis; e, eccentricity; and i, inclination)

		a	e	i	ω	Ω	ω-Ω
Halley's comet	1986	17.94	0.967	162.24	111.85	58.15	53.70
	1404 BC	17.28	0.964	162.57	71.94	11.71	60.23
Orionids		15.	0.962	163.9	82.5	28.0	54.5
η Aquarids		13.	0.958	163.5	95.2	42.4	52.8

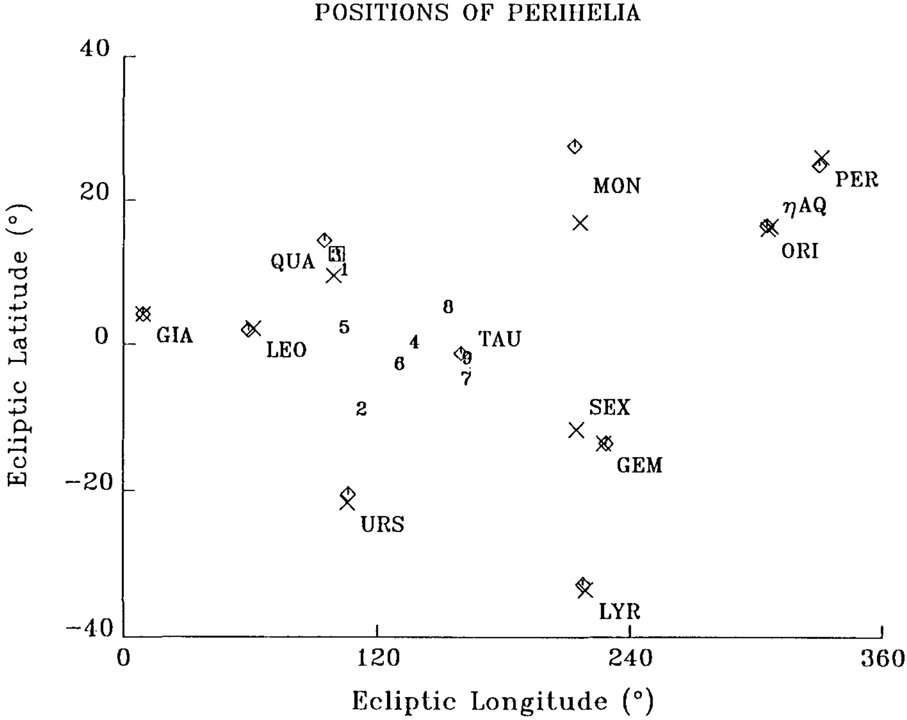

Figure 2. Positions of perihelia for major showers (× or number) and parent objects (diamonds). Labelling of the shower-parent associations is: GIAcobinid - Giacobini-Zinner; LEOnid - Tempel-Tuttle 1965 IV; QUAdrantid - comet 1491 I, Machholz 1986 VIII (square); URSid - Tuttle 1939 X; MONocerotid - Mellish 1917I; GEMinid, SEXtantid - 3200 Phaethon; LYRid - Thatcher 1861 I; ORIonid, η AQuarid - Halley; PERseid - Swift-Tuttle 1862 III; TAUrid (7 - daytime β Taurids, 8 - southern Taurids, 9 - northern Taurids) - Encke. Other showers: 1 - daytime Arietids, 2 - northern δ Aquarids, 3 - southern δ Aquarids, 4 - daytime ζ Perseids, 5 - southern Piscids, 6 - northern Piscids.

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A simple comparison that is usually indicative of association is that of positions of perihelion, as shown in Fig. 2. The positions of most of the meteor showers coincide nicely with the positions of their associated comets. This is especially evident for both the η Aquarid and Orionid showers and comet Halley. The Sextantid shower, frequently identified with the Geminids (Cook 1973), is seen to be somewhat offset. Similarly, the positions of the Monocerotid shower and Comet Mellish are offset (Kresáková 1974). A more recent determination (Ohtsuka 1988) of the mean Monocerotid orbit puts it much closer to the comet. The position of comet Encke corresponds closely with that of the northern Taurids (9) and reasonably closely with that of the β Taurids (7) and southern Taurids (8). More will be said about this complex later. Two other traditional groupings (Cook 1973)—1, 2, 3, and 4, 5, 6, on the plot—are seen to have a close pair and one outlier, and would seem to require further evidence to justify an association.

The Quadrantids are positioned reasonably close to the ancient comet 1491-I proposed by Hasegawa (1979) as a likely parent body. McIntosh (1990) has pointed out a possible association with comet P/Machholz 1986 VIII, which also links the group to the southern δ Aquarid and daytime Arietid streams also plotted in Fig. 2.

The general crowding of positions in this area cautions that, although divergence may be taken as lack of association, proximity is not necessarily evidence for a generic relation.

An orbit is completely defined by five parameters: two to determine its shape in its own plane, and three to determine its orientation in space. Southworth and Hawkins (1963) proposed a criterion for assessing the closeness of orbits in the five-dimensional space of the orbital parameters. Their D-criterion calculates a sum of squares of differences between the parameters of two orbits: eccentricities, perihelion distances, the angle between the lines of apsides, and the angle between the orbital planes. Drummond (1981a) suggested a modified D' criterion using normalized or fractional deviations rather than absolute ones. The D' values for the major showers and their parent bodies are graphed in Fig. 3. The value of D' acceptable for orbital pairing is usually taken as less than about 0.1. The Giacobinids, Perseids, Leonids, and Geminids have very small values of D'. The relation between the Sextantids and the Geminid parent body can be accepted only if a $D' > 0.2$ can be explained by the dynamics of its evolution. The same must be said for the Monocerotid–comet-Mellish association, although this may be only an example of the sometimes poor quality of meteor observations. The point plotted for the Monocerotids uses Cook's assessment of the data as of 1973, whereas the more recent determination by Ohtsuka (1988) moves the value of D' down to about 0.04. Hasegawa (1979) gives only parabolic elements for ancient comet 1491–I, and therefore a complete D' value for comparison of the comet and Quadrantid shower cannot be calculated. The D' value plotted in the figure includes the angular terms, which are small, and the difference in perihelion distances. The latter will be excessively large, since a parabolic orbit usually underestimates the perihelion distance. Considering the nature of the observations, the agreement is good.

Three sets of Halley relations have been plotted in Fig. 3. The lowest one shows the D' values between the 1986 orbit of Halley and the two showers. The middle one shows the relation between the comet orbit in 1404 BC (Yeomans and Kiang 1981) and the showers. The upper one shows D' for the two orbits of Halley—1404 BC and the present—which is nearly the largest among the three sets. Intercomparing Table 1, Figure 2, and Figure 3, it is apparent that although other aspects of the orbits have been considerably modified, the perihelion positions of Halley and its streams have changed very little.

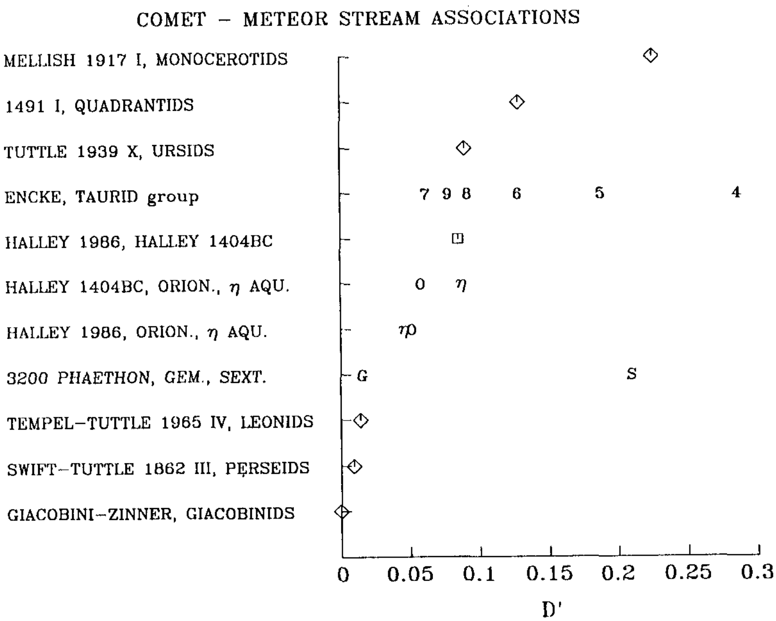

Figure 3. Values of the orbital-similarity criterion D' for the major comet–meteor-stream associations. Diamonds, parent body with one meteor shower. Letters and numbers, parent body with more than one meteor shower; G=Geminids, etc., and the numbers are identified in the caption of Fig. 2. Square, two different orbits of Halley's comet.

Although the D-criterion is a useful quantitative tool, it should be used with care. Kresák (1982) has carried out an interesting study of the probability of associations being predicted by the D-criterion by chance. He finds that for a sample of 1000 random orbits, there can be over 100 pairs with D < 0.3, and the minimum D will be about 0.07. Thus searches through databases comprising several thousand meteor orbits will turn up many 'minor-shower' pairs on the basis of pure chance. Southworth and Hawkins noted that the minimum acceptable D value should be adjusted for sample size[2]. Porubčan and Štohl have recently (1987) reviewed the use of the D-criterion, particularly as it applies to assigning membership in streams that are known to have undergone large orbital changes, such as the Taurid–Encke complex. Real associations may be overlooked. On the other hand, in searches among low-inclination direct orbits, there is a high chance of coincidental associations (Olsson-Steel 1988).

3. Development of Cometary Debris into a Meteor Stream.

When a comet becomes active on its approach to the Sun, momentum transfer to solid particles from escaping gasses needs only to accelerate the particles to velocities greater than the escape velocity, which, from a comet of 10-km diameter and density of 1 g m^{-3}, is about 3 m s^{-1}. An expression for the terminal ejection velocity was given by Whipple (1951). Rather than quote the formula, it is more instructive to examine the dependence on the parameters of the comet and the particles. Ejection velocity is proportional to:

$(\text{comet radius})^{1/2}$
$(\text{particle radius})^{-1/2}$
$(\text{particle density})^{-1/2}$
$(\text{solar distance})^{-9/8}$

The gravitational term has been assumed to be negligible.

Thus ejection velocities are greater for smaller, fluffier particles from larger comets ejected closer to the Sun. Table 2 illustrates the order of magnitude of the ejection velocities predicted by this formula for two values of comet diameter and two values of particle mass. Showers that have very small perihelion distances, for example, the Geminids at $q = 0.14$ or the δ Aquarids at $q = 0.07$, will have experienced ejection velocities ten to twenty times greater.

TABLE 2
Ejection velocities for particles of density 1 g/cm^3 released at at 1 AU

Comet diameter (km)	VELOCITY (m/s) 1 g	10^{-4}g
10	19	400
1	6	127

The discovery that gas and particles escape from Halley's comet as concentrated jets suggests that the Whipple formula might be only a lower limit for ejection velocities. However, observations of large particles in the coma of Comet Halley seem to support the contrary view, that escape velocities may be lower (Hajduk and Kapišinský 1987).

On escape, each particle becomes an independent body with an orbit that differs from that of the comet in two major respects, the first due to its velocity increment and the second due to radiation pressure. Since light pressure acts radially outward, it has the effect of reducing the

[2] $\propto N^{-1/4}$, where N is the sample size.

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solar gravitational constant μ by a factor $(1-\beta)$. The dependence of β is as:

(particle radius)$^{-1}$
(particle density)$^{-1}$

Both the ejection velocity and radiation pressure change the period of the particle orbit through the change in value of the semimajor axis. Separating the two effects, one can write the differential of the semimajor axis as:

$$da = a^2 \cdot d\left[\frac{V^2}{\mu}\right] \quad \text{ejection velocity; and}$$

$$da = -a^2 \cdot \beta \cdot \left[\frac{V^2}{\mu}\right] \quad \text{radiation pressure;}$$

where V is the comet velocity.

For meteor-sized bodies, the two effects are frequently of similar magnitude. McIntosh (1973) has discussed this for the Leonid meteor shower. Very small particles will be blown out of the solar system. For some representative meteor streams, Table 3 lists the maximum particle size that would escape if ejected at perihelion. The mass values would be smaller for ejection at other points on the orbit and would be smeared out by finite ejection velocities. A full discussion has been given by Kresák (1976).

TABLE 3
Representative maximum particle sizes that may be expelled from the solar system if ejected at perihelion
(Particle density = 1 g cm^{-1})

SHOWER	PARTICLE MASS (g)
Monocerotids	2×10^{-5}
Halley stream	1.5×10^{-7}
Geminids	5×10^{-9}
Quadrantids	2×10^{-10}

Meteor-sized particles will both lead and lag the comet and eventually form a continuous belt. If the period P has been changed by an amount dP, a belt will be formed when, after n revolutions, $n \cdot dP$ has accumulated a half-period difference. Thus

$$n = \frac{1}{2}\frac{P}{dP}$$

Since $P = a^{3/2}$, it follows that

$$n = \frac{1}{3}\frac{a}{da}$$

Then, from the relations for da given above, it is easily shown that

$$n = \frac{5000}{V_{mod}} a^{-1} (2/r - 1/a)^{-1/2}$$

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where r is the solar distance at which particles are released;

$v_{mod} = v - \frac{1}{2}V\beta$, with v being the ejection velocity, and V the comet velocity at r.

Velocities are expressed in m/s, and it is understood that the absolute value of v_{mod} is to be used.

Since $\frac{1}{2}V\beta$ is frequently of the same order as v, the calculation is not simple. To illustrate the range of n values, we calculate n for particles emitted at perihelion for a number of meteor streams, neglecting β. Assume a particle such that its ejection velocity at $r = 1$ AU is 10 m/s. Then

$$n = 500\ q^{5/8}(1-e)(1+e)^{-1/2}$$

Some calculated values are given in Table 4.

TABLE 4
Number of revolutions n to close a loop assuming ejection at perihelion

SHOWER	n	years
Geminids	12	18
Quadrantids	120	650
Orionids	9	675
Leonids	35	1100

These values are lower limits, since not all of the particles are expelled at perihelion. But this will be partially compensated by radiation pressure. The stream-formation time for the Geminids is unusually short because the parent body has a short orbital period and approaches to within 0.14 AU of the Sun.

3.1. Observed Factors to be Explained.

Any theory of the dynamical evolution of meteor streams must account for the following factors observed in meteor showers: variation of the mass distribution among the showers, and differences in the rate profiles among the showers. Mean profiles may be symmetric or asymmetric; in detail there may be fine structure and year-to-year variability indicating population density or structure variations around the orbit.

3.1.1. *Mass Population in a Shower.* The frequency of occurrence of particle masses tends to obey a power law of the form

$$dn = C_1\ m^{-s}\ dm$$

where dn is the number of particles having masses between m and m+dm, C_1 is a constant, and the parameter s is called the mass index or population index. Observations are usually presented in the cumulative form: N = number of particles having masses m or greater, i.e.,

$$N = C_2\ m^{-(s-1)}$$

The observed parameter is usually either meteor luminosity or radar echo duration, and one must apply many conversion factors and make allowance for observational selection before a mass population index is determined. Treatment of radar data is described by Šimek (1987) and other papers referenced therein. One of the most promising methods of obtaining better values of the mass index for meteor showers is through observation by low-light-level TV systems (Clifton 1973, Hawkes and Jones 1975).

The total mass, M, between mass limits m_1 and m_2, is given by the integral of $m.dn$

$$M = \frac{C_1}{2-s}\,[m_2^{2-s} - m_1^{2-s}] \qquad \text{for } s \neq 2$$

and

$$M = C_1 \ln(m_2/m_1) \qquad \text{for } s = 2.$$

When a large range of masses is under consideration, for $s > 2$, the total mass M is dominated by the small-particle end of the range, and for $s < 2$, by the large-particle end. These relations are useful in attempting to calculate the total mass in a meteor stream to compare it with the mass loss of the parent body.

The mass structure of the meteor complex was examined extensively by Dohnanyi (1970). He determined that stream populations could have a stable mass distribution in terms of the source supply of particles versus the loss processes when the population index took on a specific value. But some showers may not have arrived at a steady-state condition. Furthermore, it is reasonable to expect that the mass distributions of the original sources will differ, particularly if some of the supply is from asteroidal bodies.

Observations of the mass index of the background meteor population and of specific showers show much scatter because of the difficulty, as noted above, in allowing for selection factors and poorly determined conversion factors. The background is usually assumed to have an index value near 2, while most showers show values smaller than 2. These values must break down at the extremes of the mass range; few large particles (≈ a few hundred kilograms. Hajduk 1987, Jones *et al.* 1989) are given off by comets, and very tiny particles are removed from streams by radiation forces. In spite of the difficulty of obtaining accurate measures of mass indices, there are semi-quantitative effects to be explained. As noted in Fig. 1, some showers, for example the Perseids, seem to show a depletion of small particles (Šimek and McIntosh 1986). The Leonid showers of 1965 and 1966 differed considerably in their proportional content of large and small particles (McIntosh 1973). The rate profiles of some showers come to a peak at times that are dependent on the size of particles included in the count. In other words, there is 'size sorting' of the particles.

3.1.2. *Rate Profiles*. The durations of meteor showers vary from tens of days, as for Taurid meteors, to less than one day, as for the Quadrantid shower (McIntosh and Šimek 1984), and the brief but spectacular visitations of the Leonid showers (McIntosh 1973, Yeomans 1981) and Giacobinid showers (Kronk 1988). The very consistent Perseid shower is known to have an unusually dense core in an otherwise diffuse stream (Kaiser *et al.* 1966, Lindblad 1986, Šimek and McIntosh 1986). The Orionid and η Aquarid showers exhibit a double peak in bright meteors and up to five peaks in fainter radar meteors (Štohl and Porubčan 1978, Hajduk 1980, Cevolani and

Hajduk 1987). Quadrantid shower rates vary from year to year (McIntosh and Šimek 1984).

Rate profiles for the Geminid meteor shower are shown in Fig. 4 for combined meteor echo observations from Ottawa and Ondřejov radars (Šimek and McIntosh 1989). The rate profile for smaller particles (echo durations T_A between 1 and 4.5 s) is more asymmetrical and peaks before that for larger particles (T_A > 8 s).

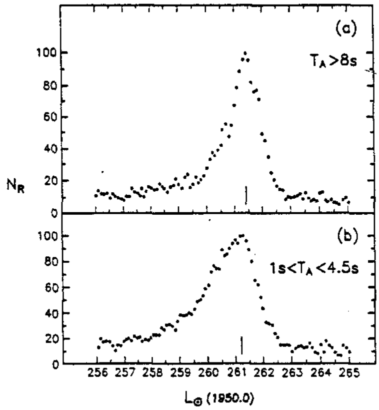

Figure 4. Rate profiles from the Geminid meteor shower: combined meteor echo rates observed by radars at Ottawa, Canada, and Ondřejov, Czechoslovakia, as a function of solar longitude (epoch 1950.0): (a) for particles producing echoes having durations greater than 8 s; (b) durations between 1 s and 4.5 s. Ordinate values are relative, and the data are averaged over many years.

3.2. The Dispersion of Meteor Streams.

A meteor stream, the belt of freely orbiting particles, is subject to many dispersive and degenerative effects, with the main ones being gravitational perturbation by the planets, collisional erosion, and radiation pressure and Poynting–Robertson drag. It is proposed to deal with these in reverse order.

3.2.1. *Radiation Forces and Collisions.* Although radiation pressure and Poynting–Robertson drag are usually considered separately, they are both manifestations of solar energy forces on a particle. The Poynting–Robertson (P–R) force is not so easily understood as is the radially directed force. Most of the mystery has been taken out of the concept in the review paper by Burns *et al.* (1979), which includes references to the earlier work by Poynting, Robertson, and others. The reemission of the absorbed solar energy in a moving reference frame introduces a transverse drag. This acts to shorten the major axis and reduce the eccentricity of the orbit of a small particle, causing it to spiral in toward the Sun. The changes to the orbital parameters are (Wyatt and Whipple, 1950):

$$\frac{da}{dt} = -\Gamma \frac{(2+3e^2)}{a(1-e^2)^{3/2}}$$

$$\frac{de}{dt} = -\Gamma \frac{5e}{2a^2(1-e^2)^{1/2}}$$

where

$$\Gamma = 3.55\times10^{-8}/b\rho \ \text{AU}^2\ \text{yr}^{-1}$$

with b being the particle radius and ρ its density (in cgs units).

If τ is the time taken to spiral in to the Sun from an already circular orbit, then Burns *et al*. (1979) show that the relation between τ and the radiation pressure factor β is

$$\tau = 400\ r^2/\beta \quad \text{years}$$

where r is the radius of the orbit in AU.

For the general case, the time taken for a particle to spiral in to a circular orbit and then in to the Sun, the total P–R lifetime, τ_{P-R}, was calculated by Wyatt and Whipple (1950). In a later paper, Whipple (1967) approximates the P–R lifetime as a function of mass as

$$\tau_{P-R} = 1.5\times10^7\ m^{1/3} \quad \text{yr},$$

with m in grams.

The observed anomalies in the mass distribution in meteor streams, the so-called size sorting noted in Section 3.1.1, are frequently attributed to the P–R effect. It may be the cause for those showers in which the Earth traverses the stream along a line making a small angle with the orbital plane, since P–R drag will separate particles only in the orbital plane. This is the situation for the Geminid meteor shower. However, it is not always applicable in other cases—such as the Perseid shower.

But the actual effects of P–R drag are not easily determined, because they cannot be considered in isolation from other influences. Kresák (1976) points out that the inward spiralling must begin from an orbit enlarged by direct radiation pressure, so that lifetimes are usually underestimated. When particles in a stream collide with other particles in space, the effect may be total fragmentation of the particle or progressive erosion. This process is rapid (see, for example, Whipple 1967, Dohnanyi 1970), particularly for meteor-size particles, giving lifetimes of the order of 10^4 yr (Grün *et al*. 1985), i.e., shorter than the calculated P–R lifetimes. When considering collisions and erosion, it must be remembered also that the smaller fragments are subject to greater radiation pressure, which counteracts the P–R loss. There are other radiation influences, such as the Yarkovsky effect (Öpik 1961, Burns *et al*. 1979), which can be of the same magnitude but depends on the spin of the particle and may either add to or subtract from the P–R force. Then the combined (Y–P–R) force could be very different for each particle. Olsson-Steel (1987a) suggests that this may play a significant role in the dispersal of orbital energies. There are also transverse force components resulting from radiation pressure on anisotropic grains (Voshchinnikov and Il'in 1983). Since this theory applies to cylindrical, non-rotating grains, the process may not be very effective. Gustafson and Misconi (1987) have shown that the rates of P–R inward-spiralling cannot be divorced from gravitational perturbations, which may have a significant effect through changes to orbital eccentricities.

3.2.2. *Gravitational Perturbations*. The effect of the gravitational fields of the planets on comets and asteroids has always been of great interest to astronomers, but little attention was paid to the gravitational perturbation of meteor streams. Whipple (1940) examinined the influence of perturbations on Comet Encke and the Taurid meteors. The possibility of dramatic effects was not realized until Plavec (1950) suggested that the Geminid stream was not reported before the middle of the 19th century because it was being swept into the Earth's path (and out again in another few hundred years) by strong perturbations by Jupiter. Although our current high-capacity computers allow us to model meteor streams with hundreds of particles, we still need to reorient our thinking about the perturbation of streams. When considering a single body, even though its ***orbit*** may approach the ***orbit*** of Jupiter within a small distance, an actual close approach of the two ***bodies*** to that distance is rare. Not so with a meteor stream; there are ***always*** particles there when Jupiter comes by and therefore always some particles perturbed by the maximum amount (see also Levin *et al*. 1972). Also, the positions of the planets, particularly Jupiter, at the time the particles are released from the comet, are significant in determining the future dispersion of the stream (McIntosh and Jones 1988). Released particles are subject to differing planetary impulses during the critical period of their first few revolutions. Thus the debris will evolve into a band of orbits, which is difficult to predict, but which may be quite different from the orbit of the parent body.

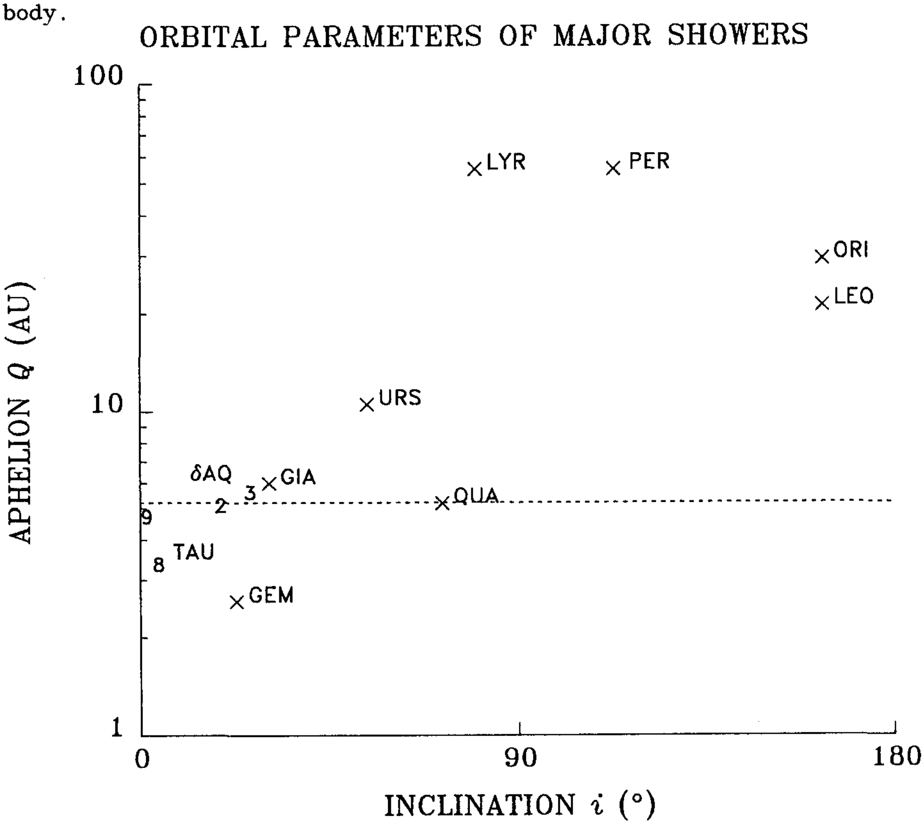

Figure 5. Aphelion vs. inclination for the major showers. The numbered positions for the Taurids and δ Aquarids are as listed for Fig. 2. The horizontal dotted line is at the position of Jupiter.

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In considering the dynamic evolution of a stream, the concept of the 'motion of the mean stream' may have little meaning and in fact may be misleading. Rather, attention should be focused on that portion of the stream that can be observed from Earth. For example, suppose one calculates the motion of the nodes of the comet due to perturbations and finds that the nodes are moving at, say, two degrees per century. One also calculates the secular perturbations on the 'stream' and finds again that the longitude of the stream nodes is moving at approximately the same rate. One asks: "How can that be, because it is quite clear that in the past century the node of the meteor stream has moved very little?" The explanation is that the stream is a very diffuse entity and our observations have selected only those particles that still have nodes at r=1 AU. The remainder of the stream will certainly have moved, but those nodes will be well away from the Earth and will not be observed. The Halley stream is a typical example (see Fig. 9).

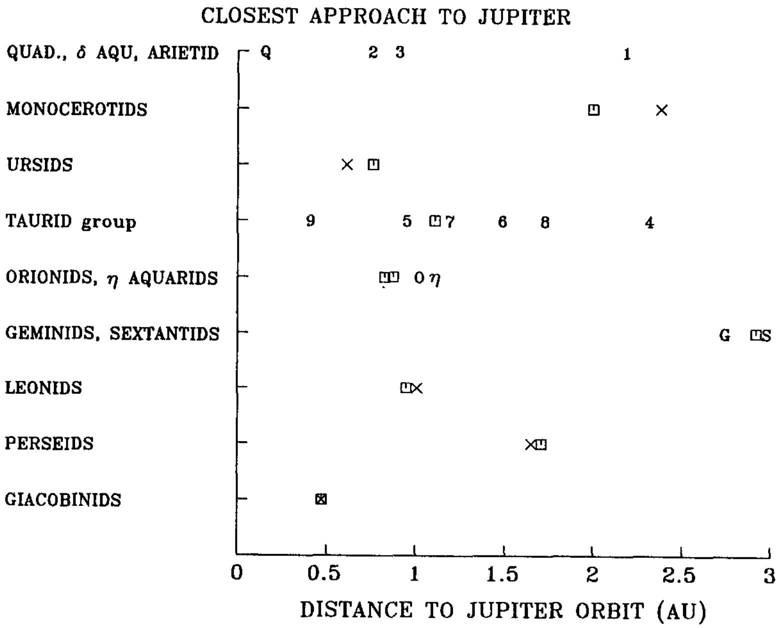

Figure 6. Closest approach to Jupiter for major showers and their parent objects: squares – parent object; ×, letter, or number – associated shower. Parent objects and numbers are listed in the Fig. 2 caption.

Next, we examine the general gravitational stability of streams, and illustrate the detailed effects using results of modelling the Halley meteor stream and summaries of similar work on the Geminid and Quadrantid streams.

Fig. 5 shows the aphelion distance versus inclination for the major showers. There appear to be two groups: at the upper right, the showers with elongated orbits either at 90° inclination or retrograde; and, at lower left, direct orbits with aphelia clustered about Jupiter. The

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Geminids, well inside Jupiter, would seem to be the most stable, but, as noted before, perturbations are sufficiently severe that the core of the stream may be lost[3] to Earth observation in a few hundred years. Fig. 6 sets out the closest approaches to Jupiter for the major streams and parent bodies. Many of the streams approach to within 1 AU of Jupiter and thus are not immune to fairly strong perturbations. Comparing this figure and the previous one, it is seen that the Perseid stream, with an inclination of about 90° and Jupiter distance of 1.7 AU, is likely to be the most stable. The Geminids never come any closer than about 3 AU, but the orbit happens to be in such a position that a small nodal regression rate sweeps it across the Earth's orbit. Most of the Geminid particles will be moved out of the way of the Earth because the planetary impulses at the time of particle ejection were not sufficient to develop a wide ribbon as in the case of the Halley stream.

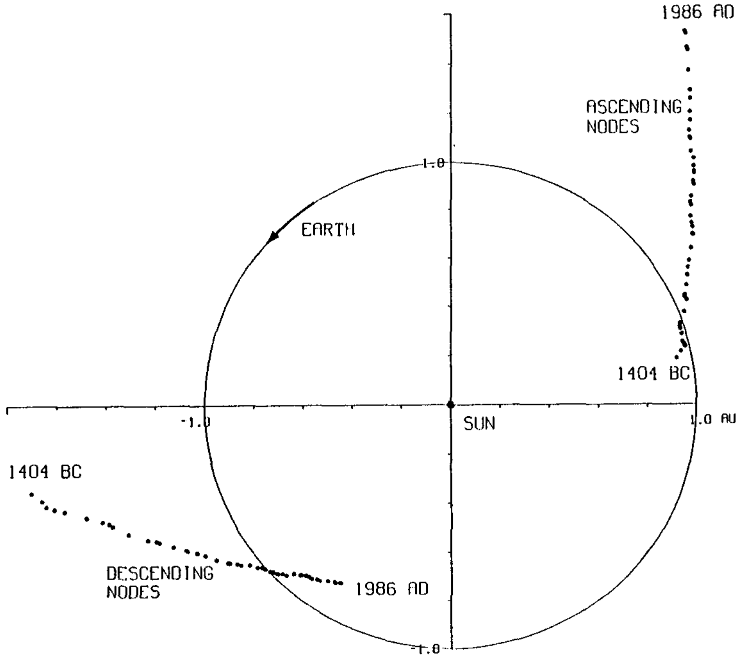

Figure 7. Crossing points in the ecliptic plane (nodes) of Halley's comet from 1404 BC to 1986. The vernal equinox is along the positive x-axis.

3.2.2.1. The Halley stream. The major effect of Jupiter on comet Halley's orbit is to shift the longitude of the node by an amount which can be as much as 2° per revolution of the comet for a close approach, or near zero in the most-distant case (Yabushita 1972, see also McIntosh and Hajduk

[3] A weak shower may remain; see Jones and Hawkes (1986).

1983). The rapid motion of the nodes and the varying amount of the motion at each return are shown in Fig. 7 (data from Yeomans and Kiang 1981). McIntosh and Hajduk (1983) realized that if a portion of the particle debris did not advance as rapidly as the comet, there would be meteoroids with nodes at the Earth's distance. The main motion of the orbits in this time period is a rotation about the major axis, producing a ribbon-like stream as shown pictorially in Fig. 8. Such a form explained the fact that the meteor showers observed at the two crossings of the Earth through the stream are of approximately equal intensity and duration. This theory was confirmed by McIntosh and Jones (1988) by numerically integrating the orbits of 500 particles released in 1404 BC. The nodes of the orbits of these particles in 1986 are shown in Fig. 9. McIntosh and Jones also demonstrated that the orbital dispersion depended on particle size and on the relative position of Jupiter at comet perihelion.

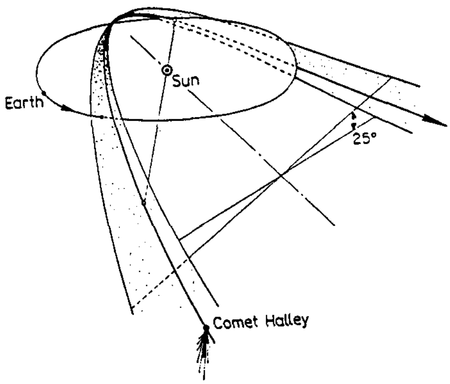

Figure 8. The Halley meteor stream as visualized by McIntosh and Hajduk (1983), showing the present orbit of comet Halley, the positions of the Earth crossings, and the hypothetical boundaries of the ribbon model.

Cross-sections of the calculated stream perpendicular to the ecliptic and containing the Earth's orbit are shown in Fig. 10. The dispersion is relatively more uniform for small particles (10^{-4} g) than for large (1 g). The diagram shows concentrations and structure, particularly among larger particles. Thus it seems likely that the fine structure seen in the Halley showers (Hajduk 1980, Cevolani and Hajduk 1987) does not require the 10^5-year lifetime postulated by McIntosh and Hajduk (1983), but can arise in a few thousand years due to bunching in the gravitational dispersion.

In Fig. 11, the small and large particles have been superimposed, and particle counts that might be seen by the Earth (counts within ± 0.02 AU of the ecliptic) are also plotted. The mean longitude for small particles is about 1° less (i.e., one day less) than the mean longitude for large particles. This indicates the possibility of size sorting due to the combined effects of mass-dependent ejection velocities and gravitational perturbations. However, the model is not adequate to make a more positive statement.

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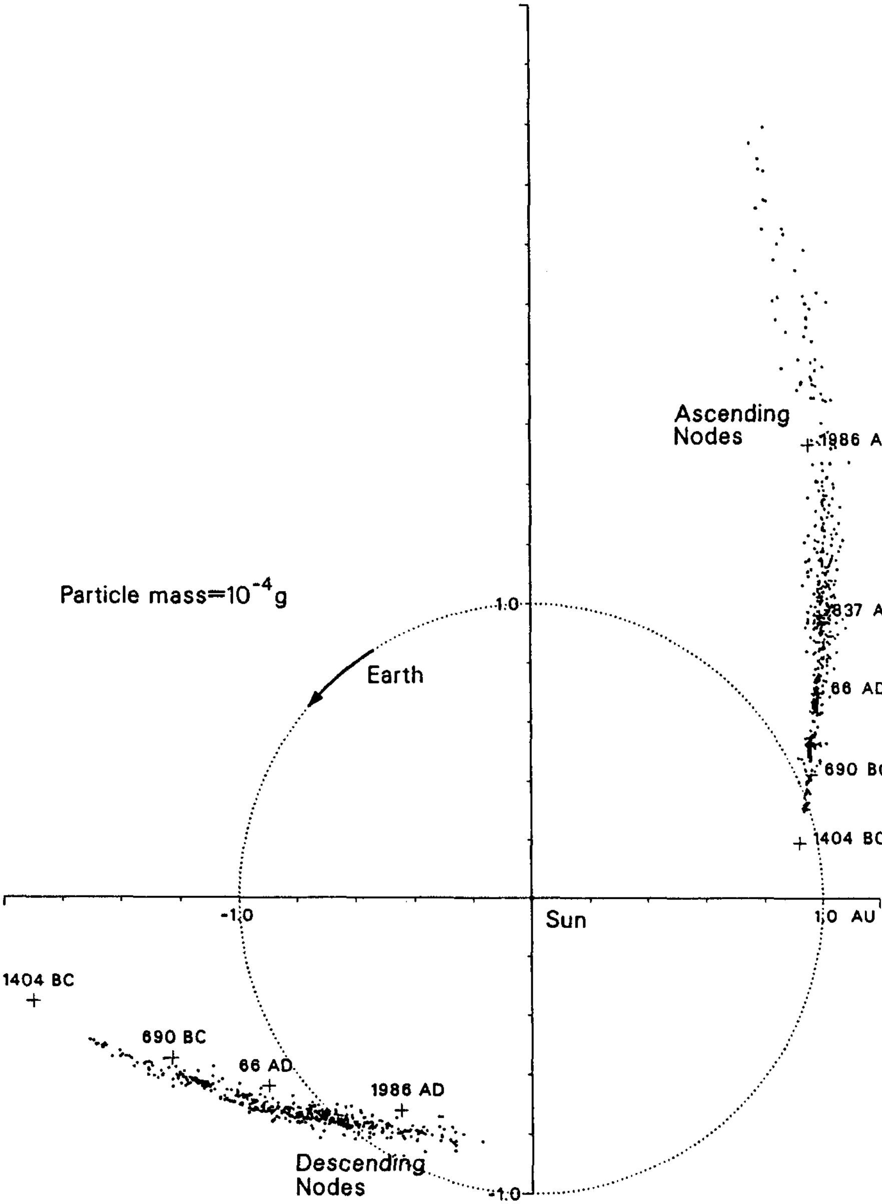

Figure 9. Present positions of the nodes of 500 10^{-4}-g particles ejected from comet Halley in 1404 BC. The Orionid meteors are observed at the ascending nodes, and the η Aquarid shower at the descending nodes. The vernal equinox is along the positive x-axis.

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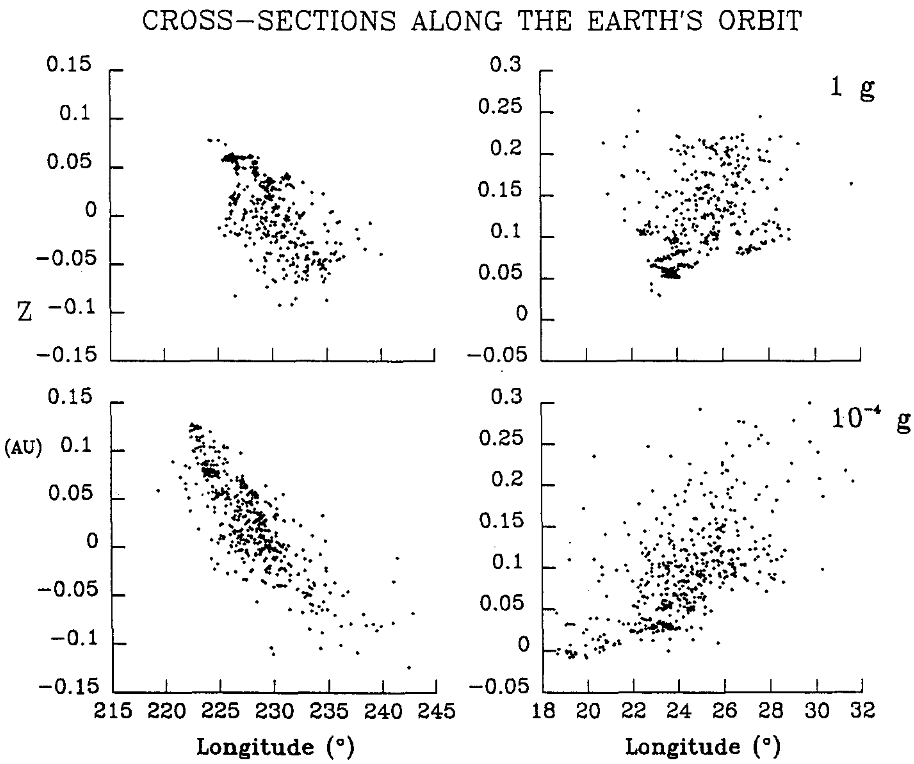

Figure 10. Predicted cross-sections perpendicular to the ecliptic plane of particles ejected from comet Halley in 1404 BC and observed in 1986: ordinate – distance, Z, perpendicular to the ecliptic, in AU; abscissa – longitude along the Earth's orbit. Left side – near the descending node; right side – near the ascending node.

3.2.2.2. Geminids. The Geminids have always been an enigma. The orbit is outside the bounds of short-period comets, and the particles are known to have a density value higher than those of other showers (Jacchia *et al.* 1967, Halliday 1988). The discovery of a parent body—3200 Phaethon—posed as many new questions as it answered. The orbit of 3200 Phaethon is very close to that of the Geminids (Fig. 12), but most evidence leads to its classification as an asteroid (Hartmann *et al.* 1987). Nevertheless, it is not the classification of the body that is important, but rather its origin (Wetherill 1988).

The rate profile is asymmetrical, as shown in Fig. 4, exhibiting, particularly for small particles, a slow rise, and then a rapid fall after the maximum. Also, the rates for small particles come to a maximum about one day sooner than do the rates for large particles (Plavcová 1962, McIntosh and Šimek 1980). Because the period is so short, the particle number density around the orbit can be studied and appears to vary by a factor of two (Hajduk *et al.* 1974).

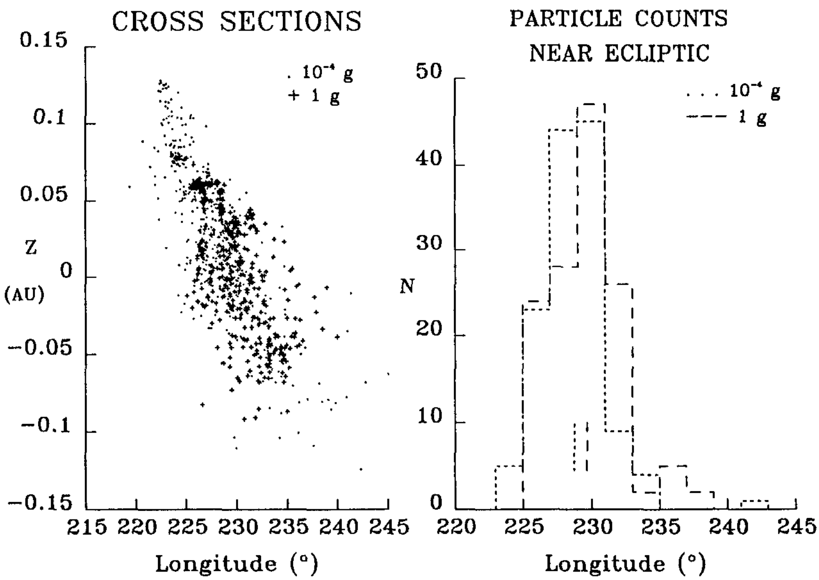

Figure 11. Left side: The same as the left side of Fig. 10 but with 10^{-4}-g and 1-g particles superimposed. Right side: Particle counts along the Earth's path—within ± 0.02 AU of the ecliptic. Mean values are indicated by short vertical line segments.

McCrosky (1975) derived a total mass of the Geminid stream of 4×10^{13} g. Multiplying this by four to allow for lost gas and using Halliday's (1988) preferred value for density, 1 g/cm^3, gives an equivalent body of 0.8-km diameter. This will be an underestimate, since the stream shape is probably ribbon-like rather than cylindrical (see below). Hughes and McBride (1989) have made similar calculations.

Beginning with Plavec (1950), a number of workers (Babadzhanov and Obrubov 1980, Fox *et al.* 1982, 1983, Belkovich and Ryabova 1987) examined the effect on the Geminid orbit of secular planetary perturbations. They agreed that the orbit node regresses at about 1.6°/century. Fox *et al.* (1982, 1983) derived an elongated cross-section for the stream. They calculated that there would be a high-density core immersed in a broader background that could account for the skewed nature of the rate profile. However, the theory predicted a distribution that was much too narrow, and whose asymmetrical shape reversed itself in a period of a few decades. Both features are contrary to the observational evidence.

Jones and Hawkes (1986, also Jones 1985) numerically integrated the motion of particles ejected from a parent body 1000 years ago, taking into account initial ejection velocities and Jupiter perturbations. Although

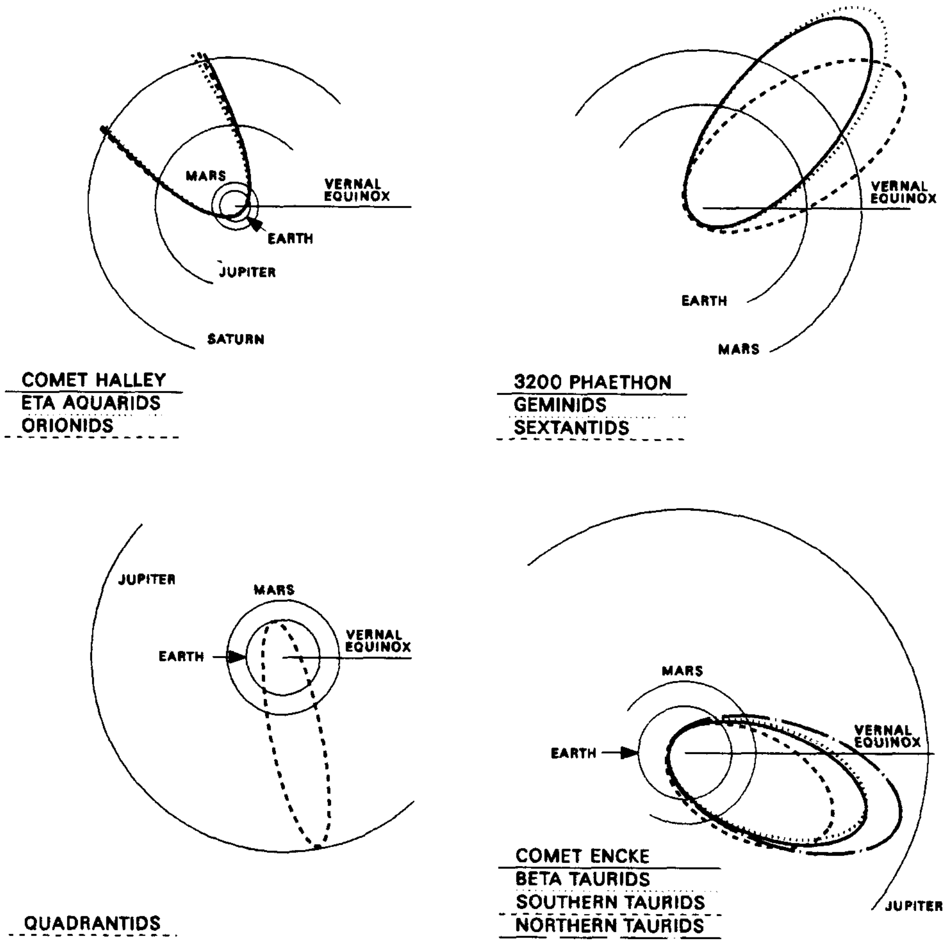

Figure 12. The orbit of the Quadrantid stream and three combinations of orbits of a parent body and its associated particle streams: Halley's comet and the Orionids and η Aquarids; 3200 Phaethon and the Geminids; Comet Encke and three Taurid streams. All orbits are projected on the ecliptic plane.

they found that gravitational perturbations caused the dispersion of the shower to increase with time, a stream lifetime of many thousand years would be required to explain the shower width. On the basis of P–R size sorting, Jones also estimated the stream age at about 4000 years. This is close to the value calculated by Babadzhanov and Obrubov (1980) based on P–R drag and secular perturbations for a particle density of 1 g/cm^3. Olsson-Steel (1987b) suggested that dispersion in the Geminid stream is explainable by radiation forces, including the Yarkovsky effect.

In their more recent study, Babadzhanov and Obrubov (1989) state that secular perturbations are constrained by two relations:

$$(1-e^2)\cdot\cos^2 i = C_1$$

and

$$e^2(0.4 - \sin^2 i\cdot\cos^2\omega) = C_2$$

where C_1 and C_2 are constants. The first is a modified version of the Tisserand criterion; the second is stated to be an integral of the motion developed by authors referenced by Babadzhanov and Obrubov (1989).

Since we observe meteors only if their orbital nodes lie at the Earth's orbit, a third relation is

$$a(1-e^2) = 1 \pm e\cdot\cos(\omega)$$

where the + sign denotes the ascending node and the − sign the descending node. These relations define four possible streams:

	northern branch	southern branch
nighttime pre-perihelion	Geminids	Canis Minorids
daytime post-perihelion	δ Leonids	Sextantids

Whether this is indicative of a generic relationship is not clear. Kresáková (1974) suggests that the Canis Minorid shower is a southern branch of the Geminids and that an evolutionary history involving comet Mellish is indicated.

Whether the Geminid stream could be generated by the collision between two rock-like bodies was investigated by Hunt *et al*. (1986). They found that a collisional mechanism was capable of explaining the cross-section of the stream. But in order to achieve this, the collision had to take place near aphelion, and the result did not model correctly the distribution of Geminid orbits at aphelion.

3.2.2.3. Quadrantids. The peculiarities of the Quadrantid shower have been summarized by McIntosh and Šimek (1984) and by Isamutdinov and Chebotarev (1987). The shower is only about one day in duration and is difficult to observe. Peak rates and the longitude of the peak vary from year to year. The rate profile is slightly asymmetrical. Size sorting is such that the peak rate for small particles in any particular year may occur either before or after the peak rate for large particles.

The orbit is nearly perpendicular to the ecliptic (i = 72°), but aphelion is quite close to Jupiter (Figs 5, 6, and 12). Three perturbation regimes must be considered: 1) long-term secular perturbations; 2) periodic effects, because some orbits may be in a 2:1 resonance with Jupiter; and 3) impulse effects, because some particles in the stream will be strongly perturbed on each of Jupiter's revolutions.

The effects of the long-term perturbations are most apparent in the regression of the nodes. Most studies (Hawkins and Southworth 1958, Hindley 1970, Babadzhanov and Obrubov 1980, Hughes *et al*. 1981, and other papers listed therein, Murray 1982) find the motion of the nodes to be about −0.004°/yr. In this case, the calculated variation agrees with that observed for the shower, because the motion is roughly parallel with the Earth's orbit. Because there is considerable spread in aphelion distances among Quadrantid orbits, a portion of the particles in the stream will have periods close to a 2:1 resonance with Jupiter. Murray (1982) finds that the motion of these particles will be dominated by the resonance perturbations. This has been studied also by Froeschlé and Scholl (1986, 1987). They find that the 2:1 resonance, over a period of 10^4 yr, will generate 'arcs' with significantly different orbits. Because the particles maintain slightly different velocities, the arcs would close into continuous streams. If these new branches are not observable from the Earth, then the process can only be considered as a secondary loss mechanism for the stream. The efficiency of this mechanism is small because the time period is of the same order as the lifetime of the particles under collision and P–R dissipation, and because the resonance region is narrow and would select only a small fraction of the particles from the stream. However, it is entirely possible that one of the 'particles' lost from the stream may have been the parent comet.

The rapid motion of the stream is illustrated by Fox's (1986) calculation of the position of the stream 1000 years ago. Had we been there, we would have observed it as a shower with a radiant in Aquarius in the month of August.

A cyclic variation of the orbital elements with a period of about 4000 years was indicated by the studies of Hamid and Youssef (1963) and Williams *et al*. (1979). McIntosh (1990) shows that two comets, P/Machholz 1986 VIII and 1491–I, and several meteor streams, all form a complex associated with the Quadrantids.

Babadzhanov and Obrubov (1989) note that, for Quadrantid-like orbits, their equations (see Section 3.2.2.2) have eight possible solutions. A number of major showers correspond to the solutions: the daytime Arietids; the northern and southern δ Aquarids; and the Ursids. McIntosh (1990) presents other evidence that the first three of these showers are associated with the Quadrantids. The Ursids are definitely associated with comet Tuttle 1939 X, and since this is a very young shower, one might speculate that the other showers are earlier streams associated with earlier quasi-stable orbits of comet Tuttle or a common larger parent object.

Since Jupiter passes through the stream on every revolution, it is clear that a fraction of the particles will be significantly perturbed every 12 years. Since the particles are constantly redistributing themselves around the orbit, the perturbed particles will form irregular filaments in the stream. Thus the impulsive effects combined with resonance perturbations are sufficient to explain, at least qualitatively, the fine structure in the stream, viz., irregular annual rates, position of the peak, and size sorting.

3.2.2.4. Comet Encke and the Taurid complex. Comet Encke has been considered a significant source of the particle distribution that gives rise to the zodiacal light (Whipple 1967). Also associated with Encke is a complex of meteor streams[4] (see Sekanina 1976 and Drummond 1981a) , and possibly a number of asteroids (Olsson-Steel 1988). Štohl (1986) suggests that a portion of the sporadic meteor background may in fact be an associated diffuse stream. The meteor complex begins in early summer with daytime showers (β Taurids and ζ Perseids) observed at nodes after perihelion. The autumn Taurid showers are observed pre-perihelion and extend over several months.

Whipple and Hamid (1952) deduced that Taurid meteors may have originated from more than one parent body. Clube and Napier (1984, also Clube 1987) postulate that the breakup of a giant comet 10^5 years ago has led to Encke (and other bodies now lost), the Taurid complex of meteoroids, and the zodiacal light particles; and that this was only the latest of similar events that can also account for ancient catastrophic extinctions on Earth.

Another interesting aspect of the study of this family of objects is a possible association, suggested by Kresák (1978), with the Tunguska exploding fireball of 1908. The evidence is not conclusive. For example, Sekanina (1983) prefers an asteroidal source for the Tunguska body.

The extent of the Encke–Taurid complex has been summarized by Porubčan and Štohl (1987); their final comment is "At present it is impossible to explain the origin of the whole Taurid complex in a unique way."

3.2.2.5. Leonids. The Leonid meteors are an example of a periodic shower with magnificent displays approximately every 33 years (Kronk 1988). However, the loop has been closed for some particles, since a low rate of Leonid meteors is observed annually. The stream shows a number of peculiarities (McIntosh 1973). In addition to the spectacular return of 1966, there were strong showers in 1962, 1965, and 1969. The position of comet Tempel-Tuttle at the time of these showers is shown in Fig. 13. Clearly, these particle concentrations are well spaced from the comet. The mass distributions of these concentrations differ significantly. The 1969 shower showed a high proportion of very small particles during its lifetime of a few hours. On the other hand, the shower in 1965 consisted of a higher proportion of large particles spread over several days. In fact, down to a limiting mass that produces an 8-second radar echo, there were more large particles in the 1965 return than in the 1966 return, in spite of the enormously high rate of the latter. Some of these data are illustrated pictorially in Fig. 14.

For periodic streams such as the Leonids, it is not clear whether the Earth is intersecting 'bunches' of particles not distributed around the orbit or whether we are observing narrow ribbons. If the former, it is difficult to explain how showers such as the Leonids of 1962 and 1969 have maintained coherence so far from the comet. Nor can one easily explain the

[4] Orbits of three of the streams, along with that of the comet, are shown in Fig. 12.

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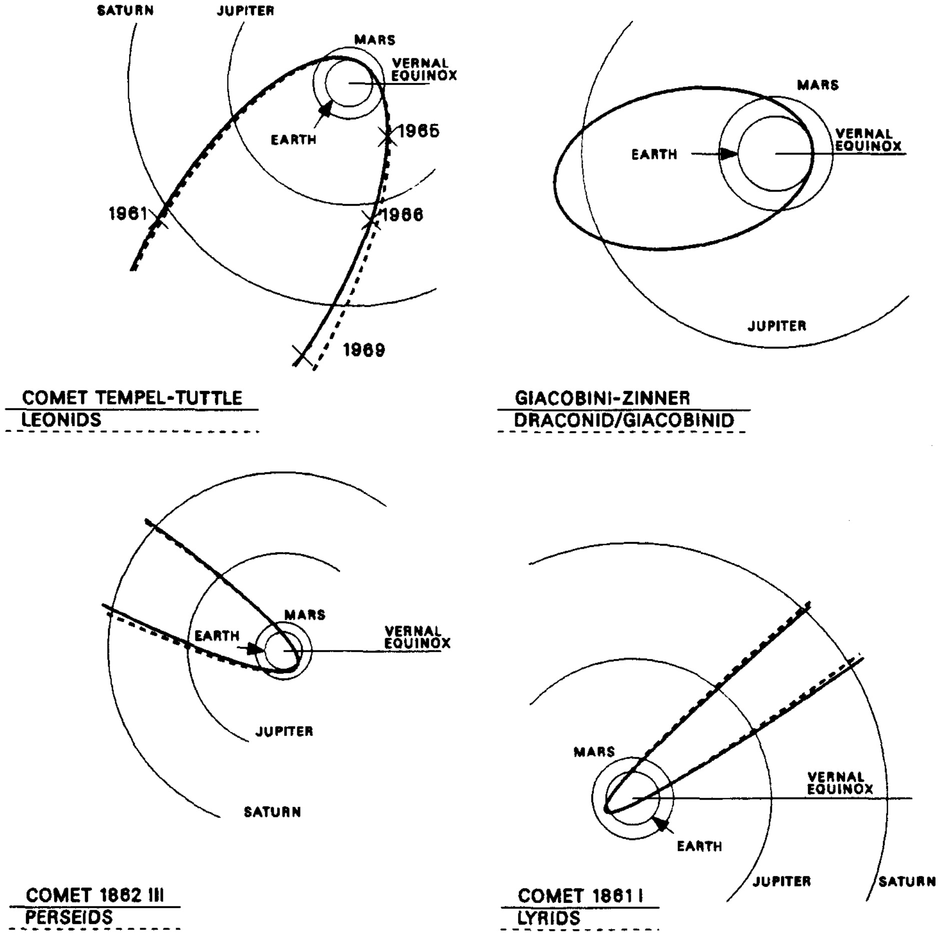

Figure 13. Two periodic showers, the Leonids and Draconid/Giacobinids; and two long-period showers, the Perseids and Lyrids. On the orbit of comet Tempel-Tuttle are marked the positions of the comet at the times of recent strong Leonid showers. The orbits of the Giacobinid meteoroids and the comet are identical.

large particles of 1965. They are obviously relatively old, because of the width of the group, yet they are closer to the comet than any particles from the other years noted. McIntosh (1973) suggested that this group may have 'lapped' the comet, making n±1 revolutions to the comet's n revolutions. But this number of revolutions, with a reasonable spread in ejection velocities, is more than sufficient to form a closed stream. Kresák (1968) notes that planetary perturbations are sufficient to shift a narrow ribbon out of Earth-crossing position in one revolution. But the Halley modelling studies (McIntosh and Jones 1988) have shown that perturbations combined with ejection velocities diffuse a stream quickly. The Leonid observations could be explained as either bunches or narrow ribbons, if the particle ejection was at unusually low velocity and prominent at only a few points on the orbit. This is in agreement with Yeomans' (1981) conclusions that the stream is basically controlled by perturbations.

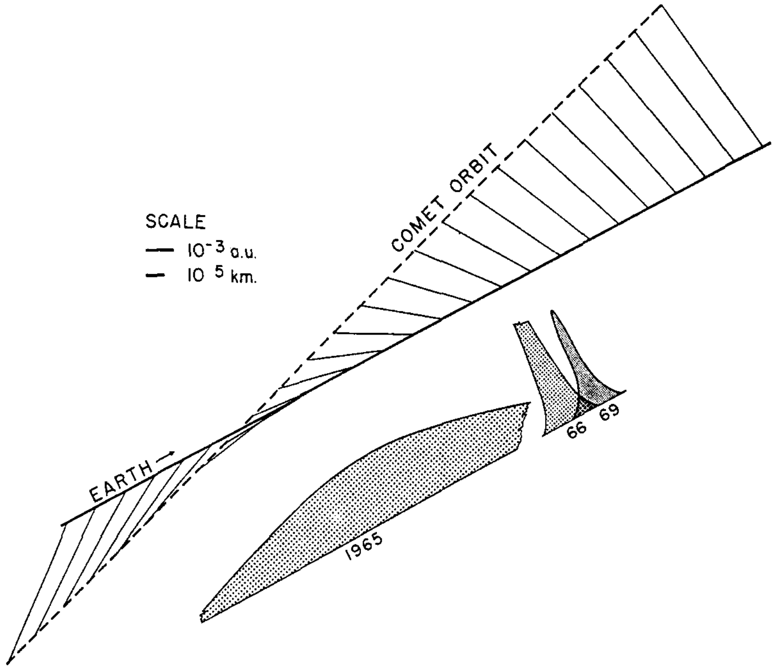

Figure 14. Relative positions and intensities of recent Leonid showers with respect to Earth passage. Shaded areas illustrate rate profiles in the years indicated. The 1966 profile has been cut off.

4. Age of meteor showers and streams.

It is necessary to distinguish among three valid concepts of 'age':

1) The first concept of age begins with the time when the parent comet is captured into the inner solar system and joins the ranks of short-period comets. Particulate debris is ejected in the vicinity of each perihelion passage, and contributes to the formation of 'a' stream. If the comet suffers no major planetary perturbations, the particle belt becomes 'the' stream and evolves under all of the influences discussed earlier.

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2) In the second concept of age, a close approach of the comet to one of the major planets, usually Jupiter, perturbs a fraction of the particles out of the stream, but, on the whole, leaves the stream intact. However, the comet is perturbed into a significantly different orbit, and, along this new orbital path, it develops a completely new stream (in the sense that a stream is defined by a similarity of orbital parameters). The age of this stream is clearly determined by the time of the major perturbation to the stream's parent comet.

3) The third concept relates to the age of a meteor shower. The Earth is a very tiny probe for sampling interplanetary space. It is fortuitous if the streams of 1) and 2) above are formed initially having particle orbits with nodes at the Earth's orbit to produce a meteor shower. Such cases do exist, e.g., the periodic showers such as the Giacobinids and the Leonids. However, many meteor showers began only when some particle orbits in a long-existing stream are perturbed into Earth-crossing nodes. Typical of this situation are the Geminid and the Quadrantid showers discussed previously.

Because of the ribbon-like structure of the Halley stream, it may be deduced that the Orionid and η Aquarid showers have been visible for many centuries, and ancient records bear this out (Imoto and Hasegawa 1958, Zhuang 1977). McIntosh and Jones (1988) found that the evolution of the stream has been such that particles now encountered by the Earth in the Orionid shower must have been ejected from the comet more than 4000 years ago. By contrast, η Aquarid meteors can be much younger. Jones *et al.* (1989) have recently assessed the age of the Halley stream and find it to be about 30,000 years. It appears to be an example of concept 2) above, since this value of age is in reasonable agreement with predictions that comet Halley suffered a major perturbation by Jupiter 150 to 200 revolutions ago (Yeomans 1986, Carusi *et al.* 1987, 1988, McIntosh and Jones 1988).

The age of a stream may be calculated:

1) By estimating the mass of the shower and comparing this with the mass of the comet. Our knowledge of the initial or current mass and rate of mass loss per revolution for specific comets is very meagre for all comets except comet Halley. Also, the procedure for calculating the mass of streams, as outlined in the next section, is fraught with difficulty. Hajduk (1987) used the mass of the stream calculated earlier (McIntosh and Hajduk 1983) to estimate the age of the comet as 2×10^5 yr, which he takes to be synonymous with the age of the stream. The value determined by Jones *et al.* noted above differs by an order of magnitude. This will be discussed further in Section 5.

2) From the mass population index of the stream, knowing the source population and the depletion rates as a function of mass. Since each of these factors is uncertain, a resulting calculation is at best a qualitative indication of age. Clearly this method would not work for a stream such as the Leonids in which the mass population index varies tremendously for different populations sampled.

3) From the dynamic evolution of the stream. The dispersion of a stream, as indicated in the rate profile by width, symmetry, and size sorting, is known to increase with age. Considerable progress has been made in the past few years in our understanding of these effects and in modelling them quantitatively, but results still seem uncertain.

5. Mass of meteor streams.

Historically, there are two methods of calculating the mass in a stream:

1) Lovell (1954) gives the mass of some meteor streams derived from estimates of the volume and mean volume density of the streams. But the volume is difficult to calculate, and the concept of mean volume density has little meaning.
2) The mass is more easily calculated by analogy with the physics of fluid flow. The total volume flow within any bounded surface is equal to:

$$F \times A \times t$$

where F = the flow per unit area per unit time in the direction of flow,
A = the cross-sectional area perpendicular to the flow, and
t = time.

This calculation is independent of the particular cross-section chosen.

The same relationship will apply to meteoroid flow, provided that the chosen cross-section includes most of the particles, and that the distribution of particles around the orbit is relatively uniform. To get the total mass in a stream, the 'time' is the period of the stream. The method is not applicable to periodic streams such as the Leonids.

A major assumption must be made concerning the shape of the cross-section of the stream and the position in it of the chord the Earth traverses during the meteor shower. In the past, for want of better information, stream cross-sections were assumed to be circular. It seems likely that many will have an elongated shape, as was found for the Halley stream (McIntosh and Hajduk 1983) and for the Geminids (Fox *et al*. 1983), which have a length:width ≈ 10:1. As noted in Section 3.2.2.2, the mass of the Geminid meteor stream calculated by McCrosky (1975) is probably an underestimate due to the assumption of a circular cross-section.

Calculation of the mass flux usually starts from raw counts of visual meteors or radar echoes and involves many assumptions. Two major ones are:

1) The efficiency factors for the conversion of particle mass to luminosity or to quantity of ionization along the trail. These values are still not well known, either in terms of absolute value or velocity dependence.

2) The range of masses to be included in the summation for the total mass flux. The range will be of the order of 10^{10}, with both the upper and lower bounds uncertain. As noted in Section 3.1.1, the integral depends primarily on the upper bound if the mass index < 2 and on the lower bound if the mass index > 2.

If the stream is old, it is necessary to correct for the loss of small particles. The final estimate of the total mass is still just the mass of the particulate, nonvolatile material. If one wishes to use the value for comparison with the parent body, for example, in order to determine the age of the stream, it is necessary to estimate the fraction of the mass lost from the comet as gas. The value of this fraction may be uncertain by a factor of about 3 (Whipple 1987, Lamy and McDonnell 1990).

As noted in the previous section, both Hajduk (1987) and Jones *et al.* (1989) have derived values for the age of the Halley stream, based on calculations of the stream mass, which differ by a factor of ten. In both cases, the authors used the same elongated cross-section. The major difference between the two treatments was in the factor used to convert meteor magnitudes to particle masses.

Hajduk's calculation would indicate that the Halley stream belongs in age concept 1) of Section 4. The present author considers that the evidence (Jones *et al.* 1989) favors classifying the age as an example of concept 2).

Hughes (1974) calculated the masses of several showers using Lovell's method. He has since revised his estimates using the second method described above (Hughes and McBride 1989).

6. Summary.

In this paper, we have stressed particularly the need to take into account the distributed properties of a meteoroid stream in determining its dynamic evolution. In some cases the long-term behaviour of a stream may be studied by considering it as an entity that is controlled by secular perturbations of the planets. But frequently a stream's structure depends on the short-term impulse nature of planetary perturbations, both during the first few revolutions after the particles are ejected from the comet and also later in the stream's life. After the meteoroids have formed a closed loop, there are always some particles that are subjected to the maximum perturbation on each planetary revolution. This can produce varying concentrations in a stream, as exemplified by the observed annual changes in the position of peak activity of the Quadrantid meteor shower.

The essential effect of secular planetary perturbations is to cause the pole of an orbit to precess around the pole of the ecliptic. This is most frequently seen as rapid motion of the orbital nodes in the ecliptic plane. In some cases, one node of a parent body may be swept rapidly across the orbit of the Earth. But the associated stream particles tend to become dispersed over the ***shell*** traced out by the motion of the ***orbit***, and hence the particle stream may not be lost as a meteor shower because there is a continuing supply of particles in Earth-crossing orbits. The

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nodes of the stream may show very little motion compared with the rapid motion of the nodes of the orbit of the parent object.

Older meteor streams frequently show a predominance of large particles. It is clear that small particles are dispersed more widely due to their greater initial ejection velocities and due to radiation effects. But it is difficult to quantify the combined effects of all forces on small particles, and hence difficult to determine the age of a stream from observed size sorting. Age may be calculated also from the mass of the stream, which requires a knowledge of the stream cross-section and the rate of mass loss of the parent body. It is apparent that some streams may have elongated cross-sections with a length:width ratio ≈ 10.

There is much productive work yet to be done in modelling the dynamic evolution of particle streams.

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