SESSION 7

Chairman: V. Guth

37. STRUCTURE AND EVOLUTION OF METEOR STREAMS

(Survey Paper)

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Our present knowledge of meteor streams is based on three types of meteor showers:

(1) About one or two dozen major showers that recur annually in optical and radar records of meteor activity.

(2) An indefinite number of minor showers, hardly distinguishable from the sporadic background, which can be traced only by comparing individual meteor orbits.

(3) Rare appearances of temporary showers, sometimes producing extraordinary meteor displays. These include prominent concentrations of meteors within some of the annual streams, meeting the Earth under specific conditions.

While the temporary shower of Draconids, having produced the most spectacular displays of this century in 1933 and 1946, has been deflected by Jupiter's perturbations into an orbit missing the Earth, the dense temporary component of the Leonids renewed its extraordinary activity in 1965 and, in particular, in 1966. We shall have the opportunity to hear about these events later during this session.

Thanks to the improvement of photographic techniques (Harvard Super-Schmidt cameras) and to the application of simultaneous radar measurements from more stations for the determination of the complete orbital elements of meteors (Jodrell Bank, Adelaide, Kharkov, Harvard), information on the minor streams is growing rapidly. Surprisingly enough, the minor streams do not simply duplicate, as to the distribution of their orbits, the major streams but at a lower concentration of particles. This can be seen from Figure 1 where the logarithm of the semi-major axis is plotted against the orbital inclination. The 10 major night-time meteor showers best known from visual observations (the Quadrantids, Lyrids, η- and δ-Aquarids, Perseids, Orionids, Taurids, Leonids, Geminids, and Ursids) are shown in Figure 1A; 23 minor streams, identified by Southworth and Hawkins (1963) in the photographic Super-Schmidt data, in Figure 1B; 54 minor streams, identified by Nilsson (1964) in a Southern hemisphere radio survey, in Figure 1C; and 188 minor streams, identified by Kaščeev *et al.* (1967) in a Northern hemisphere radio survey, in Figure 1D. The major streams are widely dispersed over the diagram, with a slight preponderance of high-inclination orbits ($i > 60°$) and orbits of longer period ($a > 5$). Orbits of this type are avoided by the minor streams where $a < 5$ for more than 90% and $a < 3$ for more than 80% of the orbits. The orbits of the minor streams delineated in different surveys agree fairly

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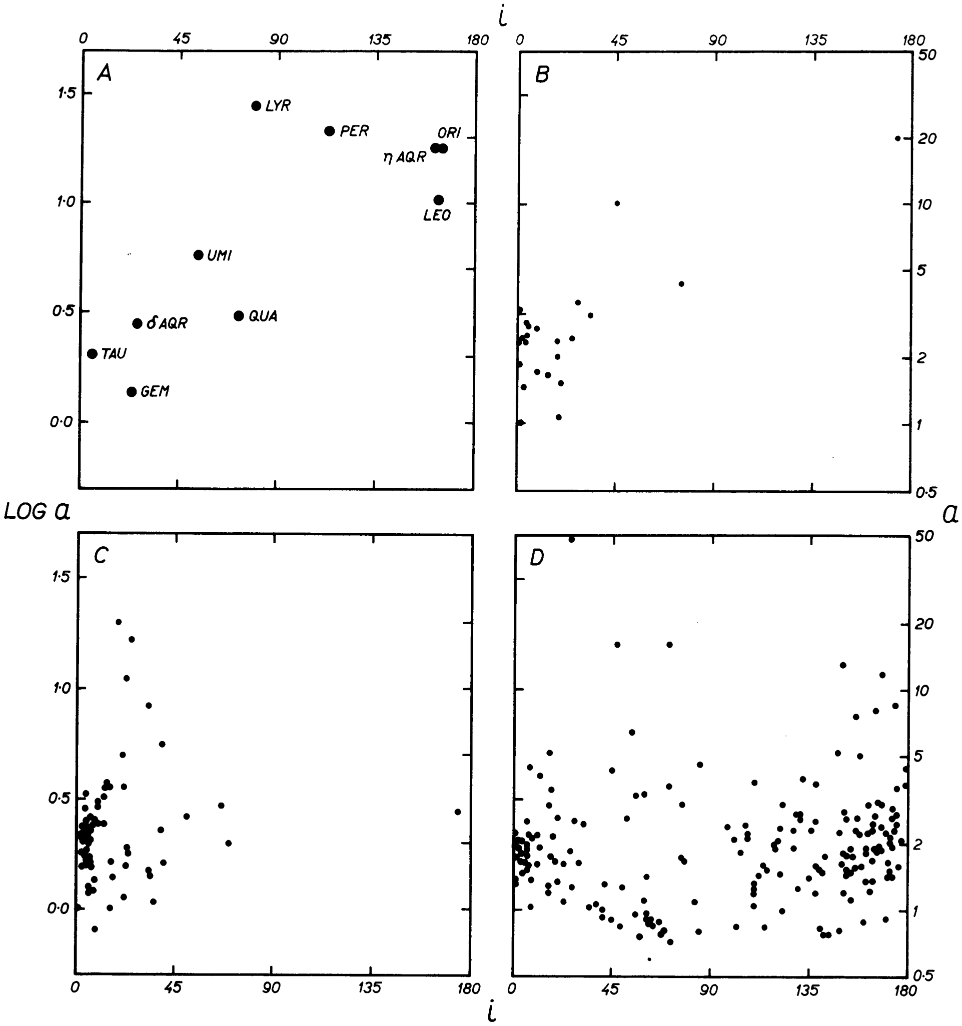

FIG. 1. *The distribution of meteor streams in semi-major axis (logarithmic scale) and inclination. A, major night-time showers; B, minor showers from the Super-Schmidt photographic survey (Southworth and Hawkins, 1963); C, minor showers from the Southern hemisphere radio survey (Nilsson, 1964); D, minor showers from the Northern hemisphere radio survey (Kaščeev et al., 1967).*

well as to the size and shape but differ considerably in inclination. The inclination is less than 50° for 90% of the photographic minor showers of Southworth and Hawkins and for Nilsson's Southern radio data, whereas retrograde orbits prevail over direct ones among the radio data of Kaščeev *et al.* The median values of the semi-major axis, eccentricity and inclination are given in Table 1.

Table 1

	a_M	e_M	i_M
10 major visual showers	8·0	0·93	76°
minor showers:			
Southworth and Hawkins (1963)	2·4	0·64	9°
Nilsson (1964)	2·1	0·86	9°
Kaščeev *et al.* (1967)	1·9	0·71	113°

These significant discrepancies are to some extent due to different selection effects involved in individual techniques of observation and reduction. No doubt some of the minor streams shown in the figure do not exist at all, their identification being based only on a fortuitous resemblance of several sporadic orbits. The frequency of such misinterpretations primarily depends on the distribution of orbits within the sporadic background. This circumstance affects all identification criteria, whether they are based on the concept of planetary perturbations (Southworth and Hawkins, 1963; Terenteva, 1965), or on the dispersion due to measuring errors (Nilsson, 1964; Kaščeev *et al.*, 1967), and cannot be fully eliminated. Nevertheless it appears obvious that the minor streams differ substantially from the major ones. Among them are found far more orbits of the type of the Taurids, Geminids or δ-Aquarids than of the type of the Perseids, Orionids, Leonids or Lyrids, and even orbits essentially different from any major streams.

In order to get a correct idea about the complex of meteor streams in the solar system, a number of selection effects must be considered. In the first place there is the requirement of crossing the Earth's orbit for a stream to be observable as a shower. This is impossible for all streams with $q>1$; if $q<1$ the probability of encounter increases with inclinations approaching 0° or 180°, and with increasing cross-section of the stream. The width of the Perseid or Taurid shower at $r=1$ exceeds 0·3 AU and there can exist only few similar streams with $q<1$ which are unknown because the Earth does not meet them. On the other hand, the cross-section of the Quadrantid shower is about 0·03 AU, and that of the Draconid shower less than 0·003 AU. No doubt a great majority of streams of that type remain unobserved from the Earth even with $q<1$ and low inclination.

Another selection effect is connected with the geocentric radiant position of the shower. This is most serious in optical observations where it eliminates all meteor showers coming approximately from the direction of the Sun, like the complex of summer day-time streams. Radio surveys are free from this bias, nevertheless the directional selectivity introduces other, and often very serious, complications. Important also is the effect of geographic position of the observing place. A shower exhibits its full activity only when the radiant passes near to the zenith. As a matter of fact, most of the observational evidence of meteor streams now available is based on the observations from a narrow latitude zone, between about 35° and 55° North. The recent progress of meteor astronomy in Australia is invaluable in this respect, since, in spite of known ways of reducing observations from different locations to uniform conditions (Keay and Ellyett, 1961; Kresák, 1964), there always remain a number of important streams for which relevant data cannot be obtained from a given location. For instance, the Southern Puppid-Velaid complex (Ellyett and Roth, 1963; Nilsson, 1964) represents an important addition to our information of meteor streams, comparable to the discovery of the summer day-time streams in 1945. The effect of geographic longitude is of secondary importance as far as broad annual streams are concerned. Its significance, however, becomes quite fundamental in the case of temporary showers of short duration. This was best illustrated by the brilliant Leonid display of November 1966, which was well observable from a part of the American continent only.

The position of the true radiant of a meteor shower with respect to the Earth's apex gives rise to another selection effect of primary importance. The vectorial combination of the stream's motion with the motion of the Earth disperses the encounter velocities of different showers over a range of 1:6, i.e. over a range of 1:40 in the kinetic energy per mass unit. Both the optical and radio observations, recording the effects of meteor penetration into the atmosphere, are rather sensitive to the velocity. High-velocity streams, with radiants situated close to the apex (like the Leonids, Orionids, or Perseids) appear relatively much denser because we can observe, with the same equipment, smaller members of these showers than of the low-velocity ones. For instance, the actual spatial density of the well-known Perseid stream is much smaller than that of many minor streams moving in direct orbits, and the Perseids do not represent any appreciable contribution to the density of the sporadic background they are moving through. This effect, together with the lack of long-periodic retrograde orbits among the minor streams, implies that the Perseids, Leonids, Orionids, Lyrids, and η-Aquarids, known long ago as most outstanding showers to visual meteor observers and contributing very efficiently to the present data on photographic meteor orbits, are certainly not characteristic examples of stream meteors whatsoever.

The vectorial combination of the motion of the stream and the Earth introduces still another selection effect which seems not yet to have been adequately accounted for. The internal dispersion of velocity vectors within a stream produces a dispersion of individual radiants which can be measured by techniques of sufficient precision, in particular by double station photography. However, the radiant dispersion which can be observed, i.e. the dispersion of apparent radiants, is distorted by the motion of the Earth. The operation of this effect is schematically represented in Figure 2, where a standard circular area of the true radiant (middle row) is shown displaced toward the apex and deformed into the corresponding area of the apparent radiant (above for $a = \infty$, below for $a = 2$). Only the dispersion of directions within a cone is considered; the dispersion of heliocentric velocities (or semi-major axes) would produce an additional extension of the areas in the horizontal direction. It is evident that the motion of the Earth considerably reduces the size of the apparent radiant areas of

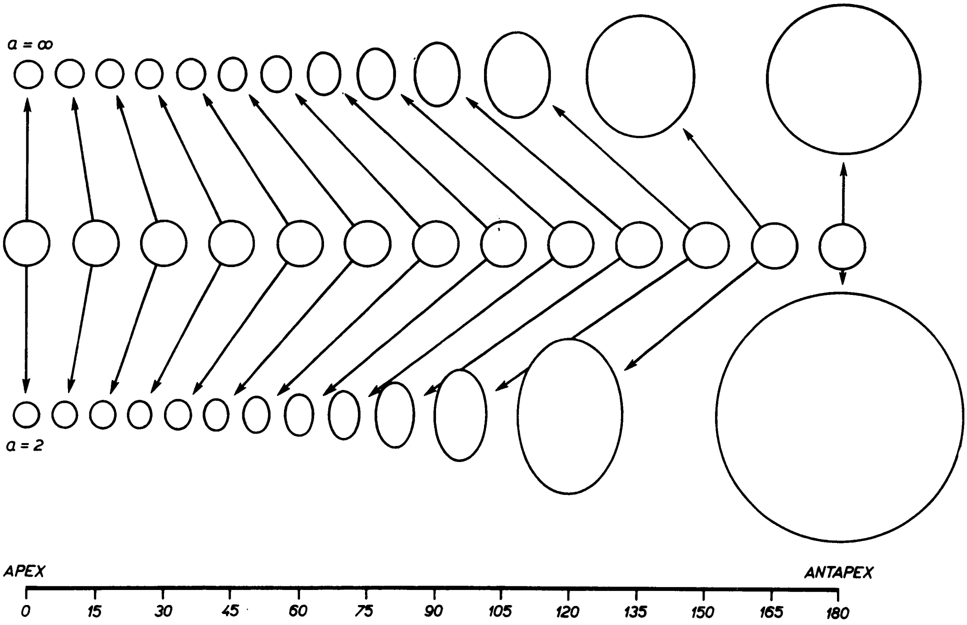

FIG. 2. *Transformation of the true radiant area (middle row) into the apparent radiant area (above for $a = \infty$, below for $a = 2$) at different elongations from the apex.*

long-period retrograde showers (to 34 % of the true radiant area for the Leonids, 38 % for the Orionids and η-Aquarids, 43 % for the Perseids), while it can increase this greatly for some of the short-period direct showers (to 240 % for the Draconids, 410 % for the Andromedids, and as much as 1700 % for the Corvids). The dispersion of velocities, which is generally larger in short-period streams, would tend to increase this difference still more. In meteor streams overtaking the Earth from the direction of the antapex, even splitting into two diffuse radiant areas on both sides of the antapex may result. Consequently, if radiant coordinates are applied to separate minor meteor showers from the sporadic background, retrograde streams are greatly favoured against the direct ones. This is one of the reasons why an identification of minor streams based on the orbital elements, and not on the radiant coordinates, enhances just the number of diffuse direct short-period streams.

It has already been mentioned that the general pattern of meteor showers depends upon the magnitude limit of the survey. Visual (Kresáková, 1966), telescopic (Kresák and Kresáková, 1966) and radio echo data (Millman and McIntosh, 1963) conformably betray a progressive overshadowing of the major showers by the sporadic background with decreasing particle size. This effect seems to apply to all annual showers without exception, as illustrated best by the finding of Millman and McIntosh (1966) that the mean mass distribution factor *s* always drops when an annual shower appears. On the other hand, some observations of extremely faint radio meteors (e.g. Gallagher and Eshleman, 1960) indicate that compact meteor showers composed of very small particles should exist. Unfortunately, the evidence is not yet conclusive enough.

Since a special session of this symposium will be devoted to the origin of meteors, I shall discuss here only the evolution of meteor streams, beginning with a cloud of particles separated from the parent body. The orbital association of observed meteors with every short-period comet that passes close to the Earth's orbit, say within 0·1 AU, yields an unambiguous evidence of their origin, and also of the fact that probably every comet produces its own meteor stream. On the other hand, many well-defined meteor showers are not associated with any known comet whatsoever. This refers, in particular, to meteor streams of very short periods, with aphelia situated far inside the orbit of Jupiter. It is obvious that the parent comets of such streams must have disintegrated rather rapidly, and we need not question why we cannot observe them today. On the other hand, it is difficult to explain how orbits of this type could originate from long-period cometary orbits by the process of perturbational capture.

It appears that meteor streams originate by ejection of particles at low velocities, probably of the order of 10 m/sec. Such velocities are predicted by Whipple's icy conglomerate model of cometary nuclei (Whipple, 1951) and are in accord with the behaviour of the dust tail of Comet Arend-Roland (Öpik, 1958). The most straightforward evidence for ejection velocities of the order of 10 m/sec has been presented by the Draconid showers, thanks to the fortunate circumstance that an approach to Jupiter in 1898 made it possible to fix the upper age limit of the meteors (Evdokimov, 1955; Plavec, 1957; Davies and Turski, 1962).

Even at these low ejection velocities the meteors disperse along the whole orbital ellipse in a relatively short time. The computations of Plavec (1954) have shown that an ejection velocity of 10 m/sec is sufficient to form a closed meteor ring in several centuries (160 years for the Geminids, 700 years for the Draconids, 1200 years for the Leonids, 1800 years for the Perseids) even in the absence of perturbing forces. Hence, the widely adopted concept of separate meteor clouds moving in the vicinity of their parent comets is rather doubtful. We can admit this structure only for swarms of very recent origin, i.e. for a small fraction of all streams existing at a given time. Most relatively young streams can be more correctly visualized as narrow tails stretching, as time goes on, along the whole orbit of the parent comet. Planetary perturbations distort these filaments and displace the individual sections to distances much larger than the cross-section. By this process a periodic recurrence, resembling returns of a meteor cloud, may arise; however, the rich returns need not coincide with the returns of the parent comet, as in the case of the Draconids or Leonids. In fact, the long-period Lyrids indicate a 12-year recurrence of unusual activity (Guth, 1947) and their most spectacular display in 1803 (Olivier, 1925) preceded the parent comet by 58 years. The Aurigids (Guth, 1936) followed the parent comet by 24 years. The most spectacular return of the Ursids in 1945 (Bečvář, 1946) occurred when the parent comet Tuttle was just in the opposite part of its orbit.

In the second stage of evolution, after the front part of the stream has overtaken the rear part forming thus a complete ring, its structure tends to become much more complex. Random perturbations by major planets, in particular by Jupiter, represent the main dispersing agent, and a pattern of parallel filaments may give rise to irregular changes of activity of the shower. The growing dispersion of semi-major axes mixes the filaments at an increasing rate and rebuilds them eventually into a broad stream with particle density more or less continuously decreasing to the borders. Finally the secular perturbations, different in different parts of the ring, gain the upper hand over the random perturbations, and make the stream expand and displace it as a whole. A good example of the large changes of orbits by secular perturbations is given by Hamid and Youssef (1963), who show that the inclination of the Quadrantid orbit has grown from 13° to 72° and the perihelion distance from 0·07 to 0·98 during the last 1700 years. One of the characteristics of the advanced age of low-inclination streams is a splitting into two branches, with avoidance of orbits close to the plane of the ecliptic, orbits which are mostly affected by perturbations (the Taurids, δ- and ι-Aquarids). The radiant areas of the Northern and Southern branch are usually situated about 10°–15° apart. Terenteva (1966) suggests that symmetrical pairs of minor shower radiants exist even at much larger distances.

Recent calculations of the perturbations experienced by short-period comets over intervals of several centuries, in particular the work of Marsden (1967), Kazimirčak-Polonskaja (1967) and Beljaev (1967), allow us to estimate the displacements of meteor streams near a crossing with the Earth's orbit. We have carried out some rough computations which show that at the distance of 1 AU from the Sun the median displacement of the trajectory of a comet of Jupiter's family is about 0·12 AU per century (it reaches a maximum of 0·5 AU at $r=3$). The mean displacement per one revolution can be estimated at about 0·015 AU, the probability of a displacement larger than 0·1 and 0·5 at 1:10 and 1:100, respectively. With an average crossing angle of the Earth and the stream the standard displacement of 0·015 AU corresponds to a distance covered by the Earth in a little more than 1 day. The perturbations are obviously less effective in high-inclination and long-period orbits, and also for the short-period orbits with aphelia situated far inside the orbit of Jupiter. For example, the integration of 11 Leonid orbits 1866–2001 by Kazimirčak-Polonskaja *et al.* (1967) yields a median of 0·006 AU. Nevertheless it can be inferred that showers of duration shorter than 1 day should not recur annually with the same strength even if their matter is uniformly dispersed in mean anomaly. And inversely, temporary encounters with unexpected streams should not last more than a few hours. The relative stability of annual showers with several weeks' activity (like the Perseids or Taurids), the variability of annual showers of shorter duration (like the Quadrantids or the core of Lyrids), and scarce apparitions of sharp showers like the Draconids, Monocerotids or Aurigids, is in full agreement with expectation. The persistence of a shower through centuries is probable only if its duration is at least 2 or 3 weeks.

Some of the broad meteor streams can be observed at both nodes. The fact that the Earth can only in exceptional cases pass through the centre of a stream is the main reason why the mean orbital elements of shower meteors may differ appreciably from those of the parent comet. The association of the η-Aquarids and, in particular, the Orionids with Comet Halley is rejected by some authors (e.g. Southworth, 1963) just because of the considerable difference in angular elements. The association, however, appears highly probable if we consider the potential conditions of encounter with the Earth. Figure 3 shows the Earth's path referred to the orbit of Comet Halley (projected on the plane perpendicular to the comet's motion) during the two annual appulses. The times of maxima and the shower limits are indicated according to Millman and McIntosh (1963); the dots continuing outside indicate 1-day intervals. The agreement is good indeed, especially if we consider that the end of the Aquarid activity may be shifted back due to blending with the summer day-time showers. A moderate displacement toward the Sun, as expected, is indicated; contrary to expectation, the dispersion seems to be smaller within the plane of the comet's orbit than perpendicularly to it; the total stream width of 0·35 AU appears 1·5 times greater than determined from the Aquarids alone, and 3 times greater than determined from the Orionids alone. For the sake of comparison, the passage of the Earth through the

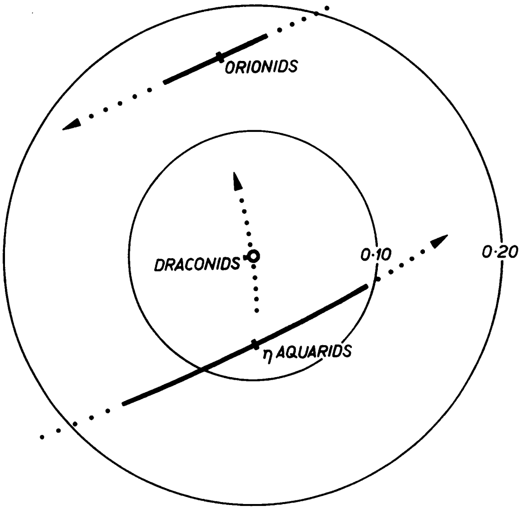

FIG. 3. *The passage of the Earth through the meteor streams of Comet Halley (Orionids and η-Aquarids) and Giacobini-Zinner (Draconids), projected on the plane perpendicular to the comet's motion. Sun to the left, distances in AU.*

extremely thin shower of Draconids is plotted on the same scale. The minimum distance of the Earth from the orbit of Comet Halley is 0·154 AU at the time of the Orionids and 0·065 AU at the time of the η-Aquarids, while the minimum distance from the orbit of Comet Giacobini-Zinner in 1946 was only 0·00135 AU. It appears that the cross-sectional area of the Draconid shower was about 10000 times smaller than that of the stream associated with Comet Halley. Should the Draconids disperse into a stream as broad as this, we would hardly observe any appreciable activity.

Obviously, where the parent comet is still disintegrating within the stream, young filaments imbedded in the old stream may appear as temporary showers. The two components of the Leonid stream yield a nice example of this. It would be unjustified to associate the 1966 Leonid display with a 'meteor cloud' that produced the famous Leonid showers of the preceding centuries; the dispersion velocities would have been much too small to keep the cloud compact enough for such a long time span. A comparison of the physical properties of meteors constituting the dense temporary component with those of the broad annual showers would be of great importance, in view of the obvious difference in age. A component of lower age may also show itself as a sharp annual radiant within a diffuse radiant area; such a structure was found by Kaiser *et al.* (1966) for the Perseid stream.

The pattern of 'permanent' meteor showers meeting the Earth varies slowly as time goes on. Most of the present annual major showers have been traced in ancient Chinese, Japanese and Korean records by Imoto and Hasegawa (1958) and by Astapovič (1960). Although some identifications are only tentative, it appears that the Lyrid records date back by more than 2000 years, those of the Orionids and η-Aquarids by at least 1500 years, and those of the Perseids, Leonids, Taurids, Geminids and Andromedids by at least 1000 years. The Lyrids seem to have been earlier much stronger than at present, and several additional recurrent showers, no longer active, are indicated. These slow changes permit us to estimate the lower limit of the lifetime of meteor streams at more than 1000 years, but we must remember that in seven of the eight cases quoted the parent comet is still under observation, and can feed the stream by fresh meteoric matter. The upper limit cannot be appreciably higher because the potential lifetime of periodic comets is also limited, and planetary perturbations would disperse a stream entirely within 10^4 to 10^5 years.

This fact is of utmost importance regarding the age of individual meteor particles. There is clear observational evidence that an appreciable fraction of all meteors observed is concentrated in meteor streams. The proportion of shower meteors is about 20% according to Öpik (1955), 36% according to Southworth and Hawkins (1963), 25% according to Nilsson (1964), 25% according to Kresák and Kresáková (1965) and 28% according to Kaščeev *et al.* (1967). These are obviously the minimum values since the minor showers unresolved by individual methods are not included. Should the meteor streams eventually disperse within the sporadic background and add to the sporadic component, a striking prevalence of sporadic meteors would appear in the course of 10^3–10^4 years. The fact that this is not the case leads us to conclude that most individual shower meteors must either terminate their existence while within the stream, before diffusing into the sporadic background, or must be removed from the solar system. In other words, the potential lifetime of individual meteoroids cannot be much longer than the lifetime of meteor streams; probably even shorter, owing to the gradual formation of meteor streams from comets.

There are different ways that individual meteoroids can be destroyed or removed: destructive collisions, acceleration into an hyperbolic orbit, evaporation near the Sun (in particular as a result of the Poynting-Robertson effect), and gradual etching by corpuscular sputtering and dust erosion.

Collision probabilities with the planets were extensively investigated by Öpik (1963), who found that this process is inadequate for removing an appreciable fraction of the meteors earlier than in 10^7–10^8 years. The transformation of elliptical orbits into hyperbolical ones by close approaches to the planets is also not effective enough, and in the case of streams of shorter period it is even unattainable by a one-stage process. Moreover, the passage of a planet through a stream decelerates one part of the meteors at the same time as it accelerates the other part. For the appulse of two meteors passing symmetricaly before and behind the planet, the perturbation in the reciprocal semi-major axis, $\Delta(1/a)$, differs only by sign. Let us suppose that the two meteors were perturbed by Jupiter and can be observed in collision with the Earth. Since the probability of encounter is inversely proportional to the period of revolution, the compound encounter probability for this pair of particles after the perturbation will increase by a factor of F,

$$F = \frac{1}{2} a^{3/2} \left(\left[\frac{1}{a} + \Delta\left(\frac{1}{a}\right) \right]^{3/2} + \left[\frac{1}{a} - \Delta\left(\frac{1}{a}\right) \right]^{3/2} \right) =$$
$$= 1 + \frac{3}{8} a^2 \left[\Delta\left(\frac{1}{a}\right) \right]^2 + \frac{3}{128} a^4 \left[\Delta\left(\frac{1}{a}\right) \right]^4 + \cdots > 1 .$$

This is an interesting paradox expressing that, in the probability of future collisions, the reduction of semi-major axes of some meteors always overbalances the increase of semi-major axes of the others, inclusive of the losses into hyperbolic orbits. It is obvious that the region of collisions at the same time approaches nearer to the Sun, the median semi-major axis of the shower decreases, and the collision velocities generally tend to diminish. So this effect cannot explain the disappearance of meteor streams, and the shorter semi-major axes of shower meteors compared with that of the parent comet need not be interpreted as an effect of solar radiation or of a resisting medium.

After the recognition of the importance of the Poynting-Robertson effect in the evolution of meteors (Wyatt and Whipple, 1950) it was assumed that this is the reason for the final destruction of most meteor streams. The relative lack of faint meteors in meteor showers could also be accounted for by this hypothesis (Plavec, 1950). However, when this concept was applied to the computation of the ages of meteor streams (Plavec, 1950; Lindblad, 1952; De Jager, 1953; Kresáková and Kresák, 1953), ages of the order of 10^5–10^7 years resulted. No doubt these figures are much too high, because planetary perturbations would disperse the streams in much shorter time intervals. The computed ages could be reduced by assuming a prevailing contribution of the corpuscular radiation (Whipple, 1955) but direct observational evidence does not admit the intensity of the solar wind required for this explanation. According to Whipple (1967) the solar wind increases the normal Poynting-Robertson effect by 22% only. It appears inevitable to conclude that most of the meteoroids capable of producing visual meteors do not accomplish the whole cycle of spiralling but are destroyed at larger distances from the Sun.

Three destructive processes come into consideration:

(a) Erosion by interplanetary dust and sputtering by solar protons, gradually reducing the size of the meteoroid until it vanishes completely (Whipple, 1963). This explanation is compatible with the lack of faint shower meteors, as the relative mass loss accelerates with the decreasing size of particles; even the abrupt changes of the magnitude function can be explained this way (Kresák, 1960).

(b) Destructive collision with a particle of comparable size eliminating the meteoroid by one impact. Since the destructive collision lifetime increases significantly with particle mass for masses exceeding 10^{-2} g (Whipple, 1967), this process would require a decreasing proportion of shower meteors in the range of bright fireballs, where the lifetime becomes much longer than the dispersion time.

(c) Intermediate cases of hypervelocity-impact breakage combined with mass losses due to evaporation.

The role of non-gravitational processes other than the Poynting-Robertson effect in the dispersal of meteor streams is still rather uncertain. At any rate, the clue to the problems of evolution of meteor streams may be looked for in the determination of accurate orbits of smaller particles. Of the two principal groups of evolutionary agents, perturbations by the planets and non-gravitational effects, only the latter is selective in regard to particle size and can be separated by using a wide range of meteor magnitudes. The present development of radar techniques gives good promise in this direction.

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DISCUSSION

Whipple: Long ago it became apparent that the Poynting-Robertson effect cannot eliminate the larger shower meteors. Erosion appears now to be qualitatively and quantitatively effective. Small bodies at high-relative velocities as in the 10 major streams should be eliminated relatively rapidly, as the stream itself disappears. Larger bodies in low-inclination, small-eccentricity orbits such as the Taurids can probably contribute by perturbations to the sporadic background.

Lancaster Brown: I should like to ask Dr. Hemenway whether or not the corpuscular sputtering effects, and the effects of dust erosion have been found in micrometeorites recovered by him.

Hemenway: The surfaces of the particles which we collect at high altitudes are very rough and irregular and it is possible that they show bombardment effects of smaller particles.

Elford: Could you indicate the limiting magnitudes for the three sets of observations of minor streams given in Figure 1?

Kresák: The elements of the major showers and of the Southworth-Hawkins sample of minor showers are taken from the Super-Schmidt photographic survey, with a limiting magnitude of about $+3^m$. The limiting magnitudes for the radio surveys by Nilsson and Kaščeev *et al.* are about $+6^m$ and $+7^m$, respectively. Thus some difference is involved, but the differences in the selection effects seem to be more significant.