SECTION III

METEOR STREAMS AND INTERRELATIONS WITH MINOR PLANETS

THE FORMATION AND EVOLUTION OF METEOR STREAMS

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ABSTRACT. The physical processes which may affect the evolution of meteor streams are discussed and a review is then given of the work carried out to date on the evolution of meteor streams. It is clear that they evolve principally due to the effect of planetary perturbations and radiation pressure. The formation of streams from the breakup of a comet is also discussed. All the evidence, including the recent discovery of 1983TB points to the correctness of this hypothesis.

1. INTRODUCTION

The existence of meteor streams is inferred from the observations of meteor showers, where a number of meteors, significantly in excess of the sporadic (or random) is observed, the radiant (or apparent point of origin) of these meteors being situated within a small area of the sky. This observation indicates that the original orbits of all the meteors were parallel to each other. Since most showers are annual, that is they are seen regularly at approximately the same time each year, the meteor shower phenomenon is simply explained in terms of a stream of meteoroids, all moving on similar orbits about the Sun, with these orbits intersecting the orbit of the Earth close to a fixed point in space. This point will, by definition, be either the ascending node or the descending node of the meteoroid orbit.

As well as being detectable as a visible trail of light in the sky, some smaller meteoroids can be detected by radio when they enter the atmosphere of the Earth.

The overwhelming majority of meteors detected in the atmosphere lie in the size range 0.02 to 0.5cm, with corresponding masses in the range 3×10^{-5} to 1.5×10^{-1}g, (Hughes,1978). The number of meteors seen per hour can also be recorded and from this can be inferred the rate which would have been observed had the atmospheric conditions been perfect and had the radiant of the stream been at the zenith of the observer. This inferred rate is called the Zenith Hour Rate, Z.H.R.. In many streams the Z.H.R. is less than 20 and so the actual observed rate is comparable to the sporadic rate. For these streams, there is still considerable debate as to whether they are real as opposed to being a fluctuation in the sporadic background. Most of the well known streams have a Z.H.R. in

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the range 20-100 and some of the relevant data on these showers is given in Table 1. The criterion for inclusion in the Table is a Z.H.R. in excess of 20 either visually or by radar, the data being taken from Cook(1973). In a number of showers, while the normal Z.H.R. is minimal, a very spectacular display has been observed on a few occasions, where the Z.H.R. has reached many thousands. Good examples of this phenomenon are the Andromedids with a Z.H.R. of 13000 in 1885 and the Pegasids with 14000 in 1833. The Leonids and Draconids also display this phenomenon and both these streams are mentioned again later.

In discussing the age of a stream, it is important to realize that there are two concepts involved, the time that has elapsed since the formation of the stream, which can correctly be termed the age of the stream, and also the period of time for which the stream has been intersecting the orbit of the Earth and so has been seen on Earth as a meteor shower.This latter time should correctly be termed the age of the shower. The two times are not generally related, though of course, the shower age cannot exceed the stream age. The shower age is principally governed by the rate at which perturbations and radiation forces cause the meteoroid orbits as a family to evolve, while the stream age is governed by destruction and dispersal mechanisms. A non-quantitative guide to the age of a stream may be gained from the homogeneity of the meteoroid distribution around the stream orbit and the stream density. In an old stream, the meteoroids will be distributed fairly uniformly and at a low density, while a young stream will be expected to show high density, probably in clumps. The picture in reality may of course be more complicated, especially if the source of the meteoroids has been active over a long period of time, so that the stream has no unique age. A further complicating factor is the fact that it is the number of orbits completed, rather than the number of years that has elapsed, that is the dominating factor in determining the amount of evolution in a stream. Thus, a stream with a five year period like the Quadrantid may show signs of old age, like uniformity, in a much shorter interval than a stream like the Orionid, with a period in excess of half a century.

Some indication of the age of a shower may be obtained from the study of historical records. In the mid nineteenth century, when interest in meteors and meteor streams had just started, Biot(1848) produced a catalogue of observed "fireballs" through antiquity, though in reality these were more concentrated in the eleventh century. Astapovic and Terenteva(1968) used this catalogue in an attempt to determine the changes in the present day meteor streams. Unfortunately, they took no account of planetary perturbations, which of course, moves both the time of observation (that is, the position of the node of the orbit) and also the position of the radiant. In cases where no continuous record of a shower exists, identification of a particular shower with a set of fireballs ten centuries earlier can therfore be doubtful. They found a scatter of observations around January 9th with a Right Ascension and Declination roughly comparable with those of the Quadrantid shower. The change in the day of observation between then and the present represents a nodal retrogression rate of 0.7 degrees per century. This value is consistent with, but somewhat higher than, both the current observed rate and the rate calculated by considering the effects of planetary perturbations (Hughes *et al*, 1979). They also found a set of fireballs in the period December 6 to 18 with the radiant being some 10 degrees away from that of the current Geminid shower. If the identification is correct, it would imply that the node of the Geminid stream had not changed over ten centuries while the inclination has changed considerably. This behaviour is in contradiction with the predictions of most computer models of the Geminid stream. There are strong suggestions that a secondary radiant exists in the neighbourhood of that of the main Geminid shower (Webster *et al*,1966, Hindley,1969). Kresakova(1974) also suggested that there may be two streams crossing the ecliptic close to the same point and that the more minor of the two may be associated with comet Mellish. It may be that the eleventh century observations refer to the minor stream rather than to the main Geminid stream. The real problem with both the Geminid and Quadrantid observation from the eleventh century is that no other mention seems to have been made of either of them until the 1830's when recorded observations become prolific. Other showers notably the Eta Aquarids, Orionids and Perseids have more continuous records stretching back over 1500 years and so a far more reliable guide to their evolution is obtainable from a study of historical records.

In this review, we discuss the formation and subsequent evolution of a family of small particles, concentrating on the stream aspects though some attention will also be given to the observed characteristics of a shower. We will discuss the evolution first and proceed to draw conclusions about the formation process. We proceed in this order because the evolution of a stream is governed only by the forces which act upon it and since these are well-determined then, in principle, following the evolution is straightforward.

In two recent reviews (Babadzhanov and Obrubov,1983, Williams and Fox,1983) references are given to many works on the subject and to its chronological development. For this reason we shall attempt to follow the development of ideas which lead to our current understanding of meteor stream and we shall make no attempt to give an exhaustive coverage of the literature.

2. THE PHYSICS APPLICABLE TO METEOR STREAM EVOLUTION

To a good approximation, each meteoroid in a meteor stream is moving on an ellipse with the Sun at one focus at any given instant. One process of spreading the meteoroids uniformly around the path of the stream follows from the formation process, whatever that formation process is. In no process will every meteoroid be given exactly the same initial velocity and neither will they all be ejected at exactly the same point. Consequently, all the meteoroids will be moving on slightly different ellipses, each with a slightly different period. The meteoroids will not therefore return to the ejection point at the same instant and a stream is formed with particles distributed throughout the volume enclosed by the stream envelope.

Each meteoroid is also subject to gravitational forces arising from the presence of the planets in the Solar System and these forces cause perturbations to the main orbit. As Jupiter is the most massive planet,

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perturbations due to it are always important. Also important are those due to the Earth, as the stream, by the very virtue of being detected, must pass very close to the Earth. The importance of the perturbations due to the other planets must be assessed individually before reaching a decision on inclusion or exclusion in a particular model. The inclusion of each additional planet increases very considerably the amount of calculation which needs to be carried out. Analytical expressions for the mean perturbation to an orbit are of course available and have been developed by Brouwer(1947) or Hagihara(1972) for example. These can give good results for the mean behaviour of a stream (that is the mean behaviour of a set of particles placed on an orbit which is the mean of all the known stream orbits). However much of the interest in meteor streams comes from the variation from the mean behaviour which individual meteoroids exhibit. For example, if a meteor stream has its period close to a resonance with Jupiter, then it is the same set of meteoroids that always experience a close encounter with Jupiter and hence experience large perturbations, while another set never get close to Jupiter and so suffers no appreciable perturbations. The mean behaviour predicted by the analytical theory may well be the average of the above two types of behaviour, but in reality, it misses all the interesting points in the evolution of the stream.

To deal with gravitational perturbations numerically requires a reasonable amount of time on a large computer. There is a requirement to know the position of each important planet at any given time so that the gravitational force due to it can be evaluated at any field point. This can be done, either by integrating the relevant n-body problem (Sun plus all the required planets), or by making use of a pre-existing Ephemeris tape such as the JPL tape. The former approach may be more efficient if only perturbations from a few planets are important, since searching through a large tape for the relevant data can be very time consuming. Having obtained the gravitational field, the equations of motion for each test particle representing the stream is then numerically integrated, preferably using a high order method. The methods in common use are Taylor, Runge-Kutta, Gauss-Jackson and Gauss-Radau. The efficiency of the various methods have been discussed by Fox(1984), who concluded that the choice between the above methods depended on the precise nature of the problem.

The individual meteoroids are small and so forces due to the existence of radiation from the Sun are also important. There are two effects which need to be considered. First, the radial component of the radiation field has the effect of weakening gravity. In consequence, any small meteoroid, released from a larger parent body will immediately move on a larger orbit. This effect was first discussed by Kresak(1974). Fox(1982) gives the following relations for the change in the semi major axis a and period P of the large parent to the corresponding elements a^* and P^* for a small meteoroid.

$$a^* = (ar(1-\beta))/(r-2a\beta)$$

$$P^* = P(1-\beta)(r/(r-2a\beta))^{3/2}.$$

Here r is the heliocentric distance of the meteoroid at the instant of ejection and β is the ratio of the magnitude of the forces due to radiation and gravity on the meteoroid. Numerically, for motion in the Solar System, β has a value $5.74\times10^{-5}/s\rho$, when all units are cgs, s being the radius and ρ the density of the meteoroid . It must be remembered that this effect is a one-off effect, that is the meteoroid has instantaneously a different orbit from the parent, even if the ejection velocity is zero, but this effect has no influence on subsequent orbits. They will all have a period P^* in the absence of other perturbations.

The second effect associated with the radiation field is the Poynting-Robertson drag (Robertson,1937). Here, angular momentum is lost from the meteoroid because it absorbs photons travelling in the rest frame of the Sun while it re-emitts photons isotropically in its own rest frame. These re-emitted photons therefore have some forward momentum associated with them in the rest frame of the Sun, and this momentum can only have come from the meteoroid. The resulting rate of loss of specific angular momentum is given by

$$GM_{\odot}\beta\theta/c,$$

where c is the velocity of light and G the gravitational constant.

The corresponding rate of decay of aphelion is approximately given by

$$1.5\times10^{-7}/s\rho,$$

assuming the value previously given for β.

The effect of radiation pressure on small particles, which leads to the two expressions above have been discussed in detail by Wyatt and Whipple(1950), Burns *et al* (1979), Williams(1983).

Taking s=0.5cm, which corresponds to the largest of the detected meteoroid sizes, and ρ=1gcm^{-3}, being about the highest density considered, a change in the aphelion distance of 0.1A.U., which is roughly the minimum dimension of a stream cross-section, will take place in about 3×10^5years. For the smallest detected meteoroid, s=0.02cm and a typical density is 0.8gcm^{-1}, so that the same change in the aphelion occurs in 10^4 years. Thus for a time interval considerably less than 10^4 years, the Poynting-Robertson effect may be ignored, while it becomes important for all meteoroid sizes after 3×10^5years. Of equal interest is the intermediate size range, where the Poynting-Robertson effect may cause a differentiation between the small and the large meteoroids to become apparent.

The remaining physical effect which needs to be considered is collisions. There are different types of collisions, with different consequences for the meteoroids concerned.

(1) Collisions between a meteoroid and the Earth, or any other planet, clearly occur since it is the consequence of such collisions that is the only observational evidence for the existence of meteor streams. As far as the individual meteoroid is concerned, such a collision is clearly catastrophic and the meteoroid ceases to exist. As far as the stream as a whole is concerned, one meteoroid is lost from its population, and whether or not this mechanism of meteoroid loss is important for the evolution of a stream depends on the ratio of the number of meteoroids lost to the number remaining in the stream. It is difficult to accurately determine either number, but reasonable bounds can be established for both. The total number of meteoroids is given by the

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mass of a stream divided by the mean mass of a meteoroid and so the number must lie in the range 10^{16} to 10^{20}. On the other hand, in an average stream one observer sees the loss of up to 100 per hour for a period of up to 10 days. Scaling up to take account of the number vissible over the whole surface of the Earth, rather than the number vissible within the horizon of a single observer, gives a value for the total number lost per encounter with the Earth which is less than 10^{10}. This mechanism for the loss of meteoroids is not therfore important over time periods of only a few thousand years.

(2) Meteoroid-meteoroid collisions will occur, resulting in the possible loss of both meteoroids from the stream as their orbits may be drastically altered in the collision. Let the mean value of the meteoroid radius be s and let us also assume that the mean relative velocity in a collision, v, is equal to the mean orbital velocity. (This latter assumption clearly overestimates the relative velocity, since, meteoroids in a stream will be moving on nearly parallel orbits, and in consequence will also overestimate the number of collisions). Denote also the number of meteoroids per unit volume by n, the total mass of the stream by M, its average cross-section by A and its average period by P, then $M=mnAPv$, where m is the average mass of a meteoroid and is given by $3m=4\pi\rho s^3$. The mean free path, L, of a meteoroid is given by $4\pi ns^2L=1$, and on average each meteoroid will experience a collision after travelling this distance, which takes a time L/v. Hence, the number of collisions per unit volume per unit time is nv/L. Each collision, by hypothesis, removes two meteoroids and so the fraction of meteoroids lost per orbit is 2vP/L. Substitution from the above expressions gives the fraction lost as $6M/(As\rho)$. For the detectable meteoroids, $s=0.02$cm is the minimum radius which corresponds to the maximum loss and with $M=10^{15}$g and $A=10^{-2}(\mathrm{A.U.})^2$, the fraction lost per orbit is under 10^{-9}. Even if considerably smaller meteoroids are considered, this fraction cannot become significant over a few thousand orbits.

(3) Meteoroid-meteoroid collisions can occur which do not cause a loss of meteoroids but rather cause fragmentation which leads to a change in the size distribution of the meteoroids present in a stream. The expression for the collision rate is the same as found in (2) above except that we need to consider a smaller value of s. The minimum possible value of s is about 5×10^{-5}cm, since for smaller values, β exceeds unity and radiation pressure is stronger than gravity. Such meteoroids are driven directly out of the Solar System. Thus, the fraction involved in collision per orbit is increased by about 400. As the fraction of large meteoroids within a stream is small, then it is possible that this mechanism could lead to an errosion of the larger meteoroids on a realistic time scale but until more information is available on the mass distribution within streams, it is very difficult to quantify this effect. It may be that with the EURECA space experiment more data will become available in the near future.

At the current time, no quantitative account of any of the three types of collisions has been taken in any of the computer models that have been investigated.

3 METEOR STREAM EVOLUTION

From the earliest investigations, the aim of generating models for meteor stream evolution has been to match the predictions of the model to the observed data on meteor showers. The observational data consists of the following pieces of information: (i) the time of the year at which the stream is observed, (ii) the number of meteors per hour observed and the variation in this rate throughout the duration of the shower, (iii) the position of the radiant of the shower, and (iv) the date of the first recorded detection of the stream. The data given from (i) is an indication of the position of one of the nodes of the orbit, (ii) gives information about the stream density and the variation in this density along the path of the Earth through the stream, (iii) allows a determination of the orbital elements to be made and (iv) gives information regarding the motion of the mean stream relative to the Earth as a consequence of the perturbations acting on it.

One of the first streams on which any calculations were carried out was the Leonid. This stream is generally assumed to be associated with comet Tempel-Tuttle because of the similarity in their orbits. Magnificent displays of meteors had been seen in 1799, 1833 and 1866. It was postulated that the group of meteoroids causing these spectacular displays were close to the comet itself and so had the same orbital period as the comet. Hence, displays were seen when the comet passed close to the Earth. Calculation by Adams, Storey and Downey (see Lovell,1954) showed that no close encounter would ocurr in 1899, and so no display of meteors was to be expected. As predicted, no display was seen. No disply was seen in 1933 either, but in 1966 a very spectacular disply was observed. A second stream which gives occasional spectacular displays is the Draconid, which is associated with comet Giacobini-Zinner, and again these displays are seen only when the Earth and comet are close. Information on the relative positions of Earth and comet at each display can be found in Yeomans,(1981). In these two streams, which are presumably very young, and the meteoroids are still very close to the parent, simple models, where perturbations on only the single parent body are considered, were able to produce good agreement between theory and observations. However, as the stream evolves and the meteors spread around the orbit, more complex models, considering each meteoroid sepparatly are called for.

The first obvious development of a model is to include the perturbations from the planets on a set of slightly different orbits which represent the stream. By using such methods, Whipple and Hamid(1952) showed that the Taurid meteor stream and Encke's comet had very similar orbits 4700 years ago, while Zausaev (1972) showed that at no time in the past did the Quadrantid and the Delta Aquarid streams have similar orbits. Babadzhanov and Obrubov(1980) developed this model further by including the effects of radiation pressure. Their model was able reproduce the mean evolution of both the Quadrantid and the Geminid streams and predicted a behaviour in agreement with the observations of the corresponding showers. A further development was to produce models consisting of test particles rather than considering perturbations of orbits. Direct integration of test particles in model streams consisting

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of tens of particles were carried out by Levin *et al* (1972), Kazimirchak-Polonskaya *et al* (1972), Hughes *et al* (1979), Murray *et al* (1980). Hughes *et al*(1981) increased the number of test particles to a few hundred and by now, Fox *et al* (1983) can include many hundreds of thousands of test particles for some models of stream evolution. As a consequence of these models, a picture has emerged whereby it is clear that the general evolution of a meteor stream is governed by the physical processes already described, principally planetary perturbations and Poynting-Robertson drag.

A number of minor variations from the predicted mean behaviour has however maintained interestin the topic. For example, one anomaly in the Quadrantid stream is that the small radio meteors appear to show a different evolutionary behaviour from the visible meteors as far as the variation in the date of appearance is concerned (Hughes and Taylor, 1971). This was explained by Hughes *et al* (1981) in the following way. Radiation effects can cause a difference in the orbital parameters of meteoroids of different sizes, and in the case of the Quadrantids, this results in the small meteoroids having aphelia very close to Jupiter. By coincidence, this is also very close to a 2:1 resonance with Jupiter. Thus some of the small meteoroids suffer large perturbations, while others do not. The orbital parameter in which small changes are easiest to detect is the position of the node. Such changes results in a change in the annual time of appearance of the shower and explains the observed unpredictability of the small meteors.

There is therefore every reason to believe that the main mechanics of meteor stream evolution is understood and the interesting remaining question is whether we can use this understanding to gain an insight into the formation of meteor streams.

4 THE FORMATION OF METEOR STREAMS

The suggestion that meteor streams are associated with comets has been in circulation form some time and it is this association that is developed further here. The suggestion for such an association has arrisen because of the similarity between meteor stream orbits and cometary orbits, and some well known pairings, such as the Leonids with comet Tempel-Tuttle or the Orionids with comet Halley, are well documented. We will not discuss the evidence for specific pairings further here, it can easily be found in the litterátrure. One of the major problems with this hypothesis of an association betweeen meteor streams and comets was the absence of comets associated with two of the richest regular meteor streams, namely the Quadrantids and the Geminids. Following the investigations of Hughes *et al*(1981), the reason for the failiure to find a comet associated with the Quadrantid stream became evident. The current Quadrantid stream passes very close to the orbit of Jupiter and so the meteoroids are subject to very large perturbations. Since the parent comet would not be on an identical orbit, it presumably did not pass quite so close to Jupiter and so experienced different perturbations. Consequently at the present time it could be on a very different orbit to the meteoroids we currently observe, and identification of the parent comet is therfore close to impossible.

The Geminid stream presents a very interesting problem. The actual orbit of the stream has a much smaller semi-major axis than any known cometary orbit and so any comet associated with the Geminid stream would have to be highly unusual. A number of standard calculation for the rate of change of node (Plavec,1950, Babadzhanov and Obrubov,1980, Fox *et al*,1982) which included all known physical effects, predicted a value of about -1.6° per century and all the predictions were in excellent agreement with one another. However, the stream obstinately refuses to show any change in its appearance date over the last 150 years since regular observations have been available, and indeed, over 1000 years if the eleventh century identification of fireballs prove to be correct. Fox *et al*(1982) offered a possible solution to this dilemma resulting from the apparent contradiction between observations and theory. A stream with a very elongated projection of its cross-section onto the ecliptic could, if the mean motion of the stream due to perturbations happened to be in the general direction of the elongation, produce no apparent change in the position of the node. The Earth would in reality be passing through different parts of the stream, but would do so at the same time each year. The situation is illustrated with a simple sketch as Figure 1. It should be pointed out that Fox *et al*(1982) investigated all the likely ways, including general relativistic corrections, in which the calculated perturbations could be modified but could find none that were significant. Hence, the elongation of the projection of the cross-section seems to be the only acceptable way to reconcile observation and theory. The next question is obviously to discuss ways in which such an elongation of the stream projected cross-section could come about. Fox *et al*(1982), found an intellectually satisfying answer, which was that this was a consequence of the formation mode, where dust was released in random directions from a cometary nucleus. The ejection velocity is given by an expression derived by Whipple (1951), based on the icy agglomorate model for a cometary nucleus. In an extension of this model, Fox *et al*(1983) used 500 000 test particles to repr𝜈sent the stream. With such a large number of particles, the authors were not only able to confirm the elongated shape, they could also estimate the number density of meteoroids encountered by the Earth during any passage through the stream. From this, it is possible to generate the expected Z.H.R. at all times during a shower. Spalding(1984), has gathered together most of the vissual observational evidence on the Geminid stream for the last decade, and has shown that the Z.H.R. prof,jlg is very skew, building up very slowly but decaying rapidly. It was very satisfying to find that that the theoretical model reproduced this charecteristic as well as the general shape. The important point is that this distribution of particles was generated through having a continuous ejection of material into the stream, with differing velocities at different points on the orbit. It is the particles released close to perihelion which generates the high density core which gives rise to the mapptwɔ in the predicted Z.H.R., while those ejected elswhere give the halo. Ejection of a large amount of dust at a single instant, as, for example, would occur as a consequence of a collision with the surface of an asteroidal parent, would not give rise to the same distribution. Hence, the evidence from the stream itself points to a cometary origin

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for the Geminid stream. The discovery by Green(I.A.U. circular 3878) using IRAS of object 1983TB seemed to be the final answer, in that what may be the elusive Geminid comet had been found. The orbit of 1983TB and that of the Geminids are indeed almost identical and the orbital evolution of both are discussed elswhere in this volume (see Fox, Williams and Hunt) and so we will not dwell further on the association here. However, some mysteries remain. For example, 1983TB is much more similar, judging by the observational evidence available to date, to an Apollo asteroid than to a comet. It is also rather a small object to be the parent of a very prolific stream like the Geminids, and it may be that rethinking the inter-relations between Apollo asteroids and comets is called for. Indeed, we may have to reconsider our ideas concerning cometary nucleii and entertain the possibility that somewhat larger lumps of solid, or semi solid, material than have hitherto been considered may be embedded within the conventional icy agglomerate model. We look forward with interest to observations of 1983TB in December 1984.

5 CONCLUSIONS

The study of the formation and evolution of meteor streams is at a very exiting stage at present. The basic phenomenon and the governing physics are well understood so that their general behaviour and evolution can be succesfully modeled with reasonable accuracy. However, when most streams are looked at in detail, some unexplained phenomenon or unusual behaviour seems to emerge. Most of these are associated with the formation stages rather than with the subsequent evolution and an interesting posibility is that we may obtain a deeper understanding of the structure and evolution of cometary nucleii through the study of meteor streams.

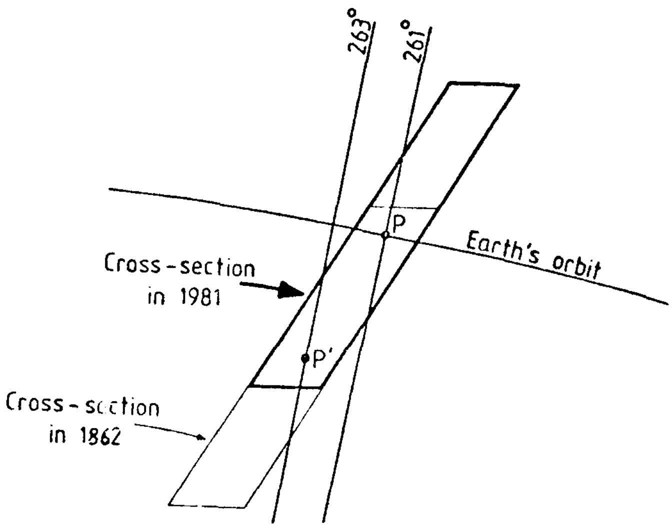

Figure 1. A schematic cross-section for the Geminid stream.

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STREAM NAME	GEOCENTRIC RADIANT			DATE	MAXIMUM ZHR	
	λ_o	R.A.	Dec.		Visual	Radar
Quadrantids	282.7	230.1	+48.5	Jan 1-4	140	
Lyrids	31.7	271.4	+33.6	Apr 20-23	20	
η Aquarids	42.4	335.6	-1.9	Apr 21-May 12	30	
Daytime Arietids	77	44	+23	May 29-Jun 19		60
Daytime ζ Perseids	78	62	+23	Jun 1-17		40
Daytime β Taurids	96	86	+19	Jun 24-Jul 6		30
Phoenicids	109.6	31.1	-47.9	Jul 3-18		30
δ Aquarids	125	333.1	-16.5	Jul 21-Aug 29	30	
α Capricornids	127	307	-10	Jul 15-Aug 10	30	
Perseids	139	46.2	+57.4	Jul 23-Aug 23	70	
Daytime Sextantids	183.6	152	0	Sep 24-Oct 5		30
Orionids	208	94.5	+15.8	Oct 2-Nov 7	30	
Leonids	234.5	152.3	+22	Nov 14-20	10	
Geminids	261.0	112.3	+32.5	Dec 4-16	70	
Ursids	270.7	217.1	+75.9	Dec 17-24	20	

TABLE 1 Data on some important Meteor Streams.

REFERENCES

Astapovic, I.S. and Terentava, A.K.: 1968, in *Physics and Dynamics of Meteors*, Ed. Kresak, L. and Millman, P.M., Dortrecht.

Babadzhanov, P.B. and Obrubov, Y.V.: 1980, in *Solid Particles in the Solar System*, Ed. Halliday, I. and McIntosh, B.A., D. Reidel.

Babadzhanov, P.B. and Obrubov, Y.V.: 1983, in *Highlights in Astronomy*, Ed. West, R.M., D. Reidel.

Biot, E.: 1848, *Mem. pres. par divers savant d l'Ac. des Sci. de L'Inst. Nat. de France*. 10, 129.

Brouwer, D.: 1948, Astr. J., 52, 190.

Burns, J.A., Lamy, P.L. and Soter, S.: 1979, *Icarus*, 40, 1.

Cook, A.F.: 1973, in *Evolutionary and Physical properties of Meteors*, NASA SP-319.

Fox, K.: 1982, *Ph. D. Thesis*, London.

Fox, K.: 1984, *Celestial Mechanics*, 33, 127.

Fox, K., Williams, I.P. and Hughes, D.W.: 1982, *Mon. Not. R. astr. Soc.*, 200, 313.

Fox, K., Williams, I.P. and Hughes, D.W.: 1983, *Mon. Not. R. astr. Soc.*, 205, 1155.

Hagihara, Y.: 1972, *Celestial Mechanics*, M.I.T. London.

Hindley, K.B.: 1969, *J. Brit. astron. Soc.*, 79, 138.

Hughes, D.W.: 1978, in *Cosmic Dust*, Ed. McDonnell, J.A.M., J.Wiley, New York.

Hughes, D.W. and Taylor, I.W.: 1977, *Mon. Not. R. astr. Soc.*, 181, 517.

Hughes, D.W., Williams, I.P. and Murray, C.D.: 1979, *Mon. Not. R. astr. Soc.*, 189, 493.

Hughes, D.W., Williams, I.P. and Fox, K.: 1981, *Mon. Not. R. astr. Soc.*, 195, 625.

Kazimirchak-Polonskaya, E.I., Belyaev, N.A. and Terenteva, A.K.: 1972, in *Motion, Evolution of orbits and Origin of Comets*, Ed. Chebotarev, G.A., D. Reidel.

Kresak, L.: 1976, *Bull. Astr. Inst. Csl.*, 27, 35.

Kresakova, M.: 1974, *Bull. Astron. Inst. Czech.*, **25**, 20.

Levin, B.Y., Simonenko, A.N. and Sherbaum, L.M.: 1972, in *Motion, Evolution of orbits and Origin of Comets*, Ed. Chebotarev, G.A., D. Reidel.

Lovell, A. C. B.: 1954, *Meteor Astronomy*, O.U.P., Oxford.

Murray, C.D., Hughes, D.W. and Williams, I.P.: 1980, *Mon. Not. R. astr. Soc.*, **190**, 733.

Plavec, M.: 1950, *Nature*, **165**, 362.

Robertson, H.R.: 1937, *Mon. Not. R. astr. Soc.*, ***97***, *423*.

Spalding, G.H.: 1984, *J. Brit. Astron. Soc.*, **94**, 109.

Webster, A.R., Kaiser, T.R. and Pool, L.M.C.: 1960, *Mon. Not. R. astr. Soc.*, **133**, 309.

Whipple, F.L.: 1951, *Astroph. J.*, **113**, 464.

Whipple, F.L. and Hamid, S.E.D.: 1952, *Bull. Roy. Obs. Helwan*, 41.

Williams, I.P.: 1983, in *Dynamical Trapping and Evolution in the Solar System*, Ed. Markellos, V.V. and Kozai, D., D. Reidel.

Williams, I.P. and Fox, K.: 1983, in *Asteroids, Comets, Meteors*, Ed. Lagerqvist, C-I. and Rickman, H., Upsala University Press.

Yeomans, D.K.: 1981, *Icarus*, **47**, 492.

Zausaev, A.F.: 1972, in *The Motion, Evolution of orbits and Origin Of Comets*, Ed. Chebotarev, G.A., D. Reidel.