THE TRANSITION BETWEEN LONG PERIOD COMETS, SHORT PERIOD COMETS AND METEOROID STREAMS

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1. INTRODUCTION

It has long been realised that Jovian perturbation is the dominant cause of the transition of long period comets (Period > 200 yr) into short period ones (P < 200 yr). When the differences in the detectability of comets in the two groups are taken into account it is clear that the present day flux of long period comets is sufficient to provide the present collection of short period comets in the inner solar system.

The fact that meteoroid streams are produced by decaying short period comets was first recognised around 1866 (see Hughes 1982a). The magnificent display of Leonids in that year enabled the radiant position and time of maximum rate to be easily calculated. Assuming the orbital period to be 33.25 yr Le Verrier (1867) and Schiaparelli (1867) published orbits for the meteoroid stream. The orbit of comet 1866 I, which had been discovered by Guillaume Tempel, from Marseilles on December 19, 1865 and independently by Horace P. Tuttle from Harvard, Massachusetts on January 5, 1866, has been calculated and published by Oppolzer (1867a). Almost to a man Peters (1867), Schiaparelli (1867) and Oppolzer (1867b) realised that the comet and the stream had similar orbits. Since that time many more examples have been put forward, two famous ones being the Perseids and comet Swift-Tuttle (1862 III) and the Eta Aquarids and Orionids both of which have comet Halley (1910 II) as their parent. For more details see Cook (1973).

Olivier (1925) was also convinced that the connection between comet orbits and meteoroid stream orbits was too close to be fortuitous, but he was still slightly worried, "The contrary fact has not yet been stated, however, that some comets whose orbits come quite near the earth's seem to furnish us with no attendant meteor streams". (In passing, Olivier also warned against putting the comet first and questioned "is it possible for a meteor stream to be condensed by the perturbations of planets until, in extreme cases, the densest part appears to be the head of a comet?" Sixty years later the overwhelming opinion is that it is not).

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2. THE TRANSITION BETWEEN LONG AND SHORT PERIOD COMETS

Capture by Jupiter is the dominant mechanism. This is obvious from the peak in the aphelion distribution of short period comets around 5.0 AU. This capture process is rather selective and Everhart (1972) concluded that only a small set of long period comets, those with perihelia between 4 and 6 AU and inclinations between 0° and 9° were responsible for the large majority (~ 90%) of the short period comets. It was shown, however, that after this perturbation all values of perihelion distance (in the inner solar system) were equally as likely. The obvious lack of small perihelia short period comets is due to the rapid decay of this class of object. The quicker a comet decays, the quicker is formed the associated meteor stream, so this could have a converse effect on stream statistics.

The capture calculation runs as follows. Let $\dot{n}_{LP}$ be the flux of long period comets entering the $4 < q < 6$ AU capture area each year. The comets have random inclination. If only those with inclinations between 0 and $\theta°$ can be captured this represents a fraction $f = 0.5(1 - \cos\theta)$ of the flux. Everhart stipulated that θ was 9°. Fernandez and Ip (1983) relaxed this to $\theta = 30°$, which leads to $f = 0.067$. These comets lose, on average, an energy, ΔE, of 3×10^{-4} AU^{-1} per perihelion passage (see Fernandez 1981). So to go from a near parabolic orbit, $E \sim 0$, to a short period orbit (say $P \sim 13$ yr, $E_{SP} \sim - 0.18$ AU^{-1}) requires $(E_{SP}/\Delta E)^2 \simeq 4 \times 10^3$ passages. Unfortunately many of the comets in this group would be ejected by planetary perturbation long before this number of passages is reached. Everhart (1976) calculated that only about one in a hundred would be captured. Let this capture probability be f_c and introduce a coefficient α that takes into account the possibility of the comet being broken up and destroyed during its transition from a long to a short period orbit. The capture rate, $\dot{n}_{SP}$, of short period comets is then given by

$$\dot{n}_{SP} = \dot{n}_{LP} \times \alpha \times f_c \times f \qquad (1)$$

Fernandez and Ip took the number of new long period comets straddling Jupiter's orbit per year, $\dot{n}_{LP}$, to be 1.5. With $\alpha = 1$ (i.e. assuming no losses) $f_c = 10^{-2}$ and $f(\theta = 30°) = 0.067$ one gets $\dot{n}_{SP} = 10^{-3}$. [Using Hughes (1982b) we note that about 26 ± 3 long period comets are being discovered per decade, these having $0 < q < 1.5$ AU. Using this crude number would lead to an $\dot{n}_{LP}$ of about 3.5.]

To estimate the steady state numbers n_{SP} of short period comets in the inner solar system we need to have some idea as to their average lifetime, L_{SP}. (This is not the time since the origin of the comet, but the time since it was captured into the inner solar system). Kresak (1981), considering the decay of known short period comets, estimated that short period comets have a mean lifetime L_{SP} of 400 orbits. Taking the mean period to be 7 years this gave an L_{SP} of 2800 yr. So the steady state number of short period comets was given by

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$$n_{SP} = \dot{n}_{SP} \times L_{SP} \simeq 2.8 \qquad (2)$$

Fernandez and Ip (1983) stressed that, as this was two orders of magnitude below the observed number of short period comets, something was drastically amiss. They overcame this problem by proposing a second source of comets in addition to the Oort cloud, this second source being a belt of low inclination comets with semi-major axes of about 50 AU.

Maybe we don't need to be so inovatory. Firstly Kresak could have underestimated the cometary lifetime. Hughes and Daniels (1982) calculated that the members of the short period comet family have on average been past perihelion 800 times since capture. As the mean period is 7 years this corresponds to an average age, A_{SP}, of 6000 yr. The mean lifetime between capture and complete decay is, however, another matter. Unfortunately comets are not like people. If we measure the mean age of a cross section of people we would arrive at a value near 38 yrs, and we would be justified in doubling this to get a typical life duration of 76 yr. Comets, however, don't have a typical life duration. Short period comets can suffer from close approaches to Jupiter and the concomitant possibility of ejection from the inner solar system. Also as 'well behaved' comets seem to lose a fixed percentage of their mass each time they pass the Sun the more massive comets last longer than their slimmer brethren. Assume that the lifetime is β times the average age. Equation 2 thus becomes

$$n_{SP} = \dot{n}_{SP} \times \beta \times 6000 \simeq 6\beta \qquad (3)$$

Astronomers since the dawn of scientific sophistication have seen about one hundred short period comets so if equation 3 is producing the correct answer β still seems to be uncomfortably large.

The problem really lies with the estimation of $\dot{n}_{LP}$ and this stems from the comparisons between the number of short period and long period comets that we have seen. Figure 1 shows the cumulative number of comets that are brighter than a specific absolute magnitude. Simply relying on the observations of astronomers during the period of scientific sophistication has produced detailed magnitude records of 104 short period and 522 long period comets. These two numbers must, however, be corrected before intercomparisons can be made. It can be seen from Figure 1 that the short period comet data breaks away from linearity when the absolute magnitude is greater than (i.e. the comets are fainter than) $H_{10} = 10.6$. This is equivalent to saying that during the historical period of scientific investigation we have recorded all the short period comets (SPC's) brighter than 10.6 absolute magnitude. As one progressively considers fainter and fainter comets more and more have slipped by unnoticed. Turning to the long period comets (LPC's) the knee of the curve occurs at $H_{10} = 5.8$.

One way of comparing the two comet groups is to extrapolate the LPC curve and slide the data set up until it breaks away from linearity at the same H_{10} value as the SPC curve does (this extrapolation is shown as a dashed line in figure 1). This is equivalent to saying that the Earth based astronomers have an equal probability of detecting and observing long period and short period comets. [There are obviously some minor problems with this bland

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statement. Short period comets return every seven years (on average) so we have more chances to discover an individual comet. Also the orbital characteristics of the two groups, especially the inclination, differ considerably and this could effect the detectability. The above statement must be taken as a first approximation.]

The initial data set contained 522 LPC's and 104 SPC's, a

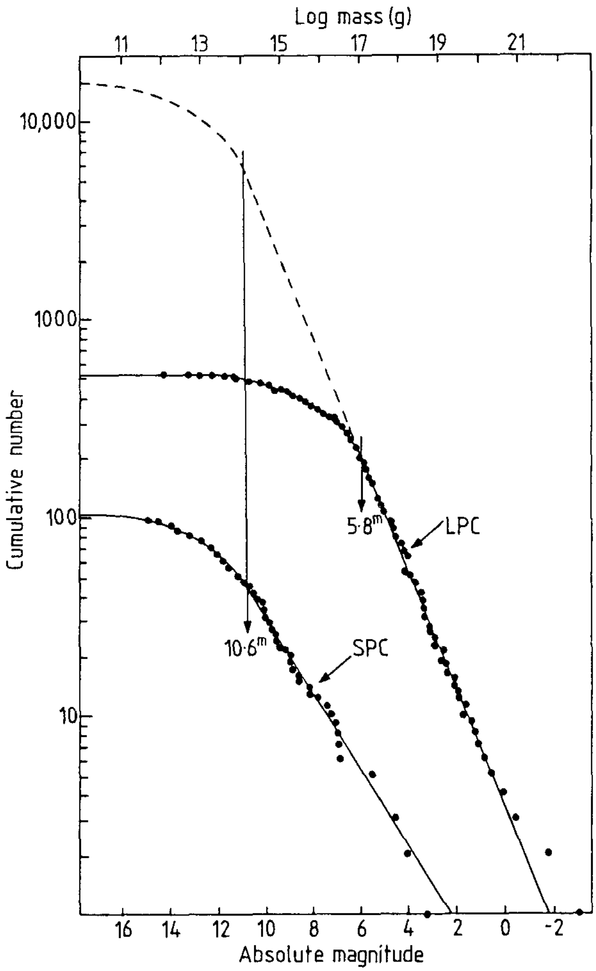

Figure 1 The cumulative number of short period (SPC) and long period (LPC) comets plotted as a function of their absolute magnitude, H_{10}. This is defined as being the apparent magnitude a comet would have if it was 1 AU from the Sun and 1 AU from Earth as well. It is obtained by substituting apparent magnitude values into the formula $m = H_{10} + 10 \log r + 5 \log \Delta$. The upper abscissa is obtained by using the relationship $\log M = 20.58 - 0.6\ H_{10}$ where M is the mass of the comet in grams.

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ratio of 5.0. Using the intersection points on the ordinate of the extrapolated LPC data and the original SPC curve gives a ratio of 150. Due to the differing gradients (see Hughes et al 1982) of the two linear portions of the data sets in figure 1 this ratio will depend to an extent on the knee value used. In this rough analysis it is sufficient to note that the ratio between the numbers of long and short period comets is probably much closer to 150 ± 50 than to the value of 5 previously used. This change will be echoed in the $\dot{n}_{LP}$ value to be used in equation 1. The value of 1.5 yr^{-1} used by Fernandez and Ip must be replaced by a value of about 45. Using Kresak's value for the mean lifetime, and equation 2 gives n_{SP} = 84. Obviously the discrepancy between the predicted number of short period comets and the observed number has vanished.

The veracity of the above approach can be illustrated in another way. If we return to the original data set of 522 LPC's and 104 SPC's it is clear from figure 1 that the median LPC has an absolute magnitude of 6.4 and a mass of 5.5×10^{16} g. The median SPC has an H_{10} of 11.0 and a mass of 9.6×10^{13} g. No matter what feed system between the two groups is envisaged a mass difference between median members of a factor of 580 is surely untenable. Crudely assuming that a comet loses 1% of its mass at each close solar pass, a decay from mass m_i to mass m_f would take n passes where n is given by

$$\log \frac{m_f}{m_i} = n \log 0.99 \qquad (4)$$

The figures quoted above result in n being 630!

Using the extrapolated LPC data as shown in figure 1 results in the median mass of an LPC comet being only slightly larger than that of a SPC. The value of n obtained by using equation 4 turns out to be a single figure number - a result which is surely much more reasonable.

Returning to meteor streams it thus seems that the 'typical' short period comet in the inner solar system was captured by Jupiter in the not too distant past, has decayed somewhat but has by no means transferred all its dust mass to an infant meteor stream.

Unfortunately the mass of a comet is not an easy quantity to estimate. Hughes and Daniels (1980) briefly reviewed the problem and quoted four relationships that had been proposed between mass (M, in grams) and absolute magnitude H_{10}

$\log M = 21 - 0.4\ H_{10}$ (Allen, 1973)

$\log M = 19 - 0.4\ H_{10}$ (R. Newburn Jr, private communication)

$\log M = 19.39 - 0.6\ H_{10}$ (Whipple, 1975)

and $\log M = 20.30 - 0.6\ H_{10}$ (Öpik, 1973)

Hughes (1984) has reinvestigated the problem and concludes tentitatively that

$$\log M = 20.58 - 0.6H_{10} \qquad (5)$$

This relationship has been used to mark out the upper ordinate of figure 1. Use of the other relationships can change the median mass of the short period comets by up to two orders of magnitude!

The mass of the meteoroids in a meteor stream can be estimated from the influx per year to the Earth and the volume of the stream. Hughes (1974, 1983) found that the mass of dust in the Quadrantids,

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Perseids and Geminids was 5×10^{13} g, 2×10^{15} g and 9×10^{14} g respectively. McIntosh and Hajduk (1983) obtained a value of 5×10^{17} g for the Orionid and Eta Aquarid streams of Comet Halley. The meteor stream dust probably constituted about 20 per cent of the mass of the material that had decayed from the comet so these values are reasonably consistent with the cometary masses given above.

3. A COMPARISON BETWEEN METEOROID STREAM AND SHORT PERIOD COMET ORBITS

Cook (1973) produced a working list of meteoroid streams and from this one can conclude that there are around 48 easily observable independent meteoroid streams intersecting the Earth's orbit at the present time (see also Drummond 1981). The distribution of the orbital parameters of these streams are shown in Figure 2. The dashed lines indicate the median values (the median has half the values smaller and half the values larger and is much less sensitive to odd extreme values than, for example, the mean). As is to be expected the distribution of Ω and ω seems to be random.

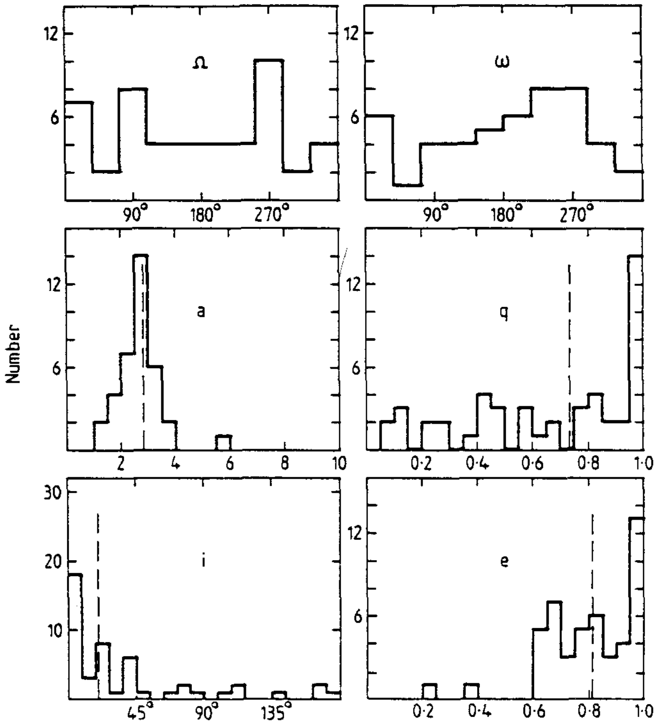

Figure 2 The distribution of the orbital parameters (longitude of ascending node, Ω, argument of perihelion, ω, semi-major axis a, AU, perihelion distance q, AU, inclination, i, and eccentricity, e) of the 48 independent meteoroid streams listed by Cook (1973). The dashed lines indicate the median values of the parameters and these are $a = 2.84$ AU, $q = 0.73$ AU, $i = 19.2°$ and $e = 0.813$.

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It is instructive to compare stream and comet orbits. The orbital parameters of the 123 known short period comets have been taken from Marsden (1979). The inclination of the orbits of the short period comets and meteoroid streams are shown in Figure 3A. The median inclinations are 12.4° and 19.2° respectively and it is interesting to note that there is a higher percentage of meteoroid streams with $i < 2.5°$ than comets.

The distribution of semi-major axes are shown in Figure 3B and the differences between the two groups are now much more striking. the median value for comets is 3.73 AU and for streams is lower at 2.75 AU. It must be stressed, however, that meteoroid stream statistics vary considerably as a function of the strength of the meteor shower. This was clearly pointed out by Kresak (1968) who differentiated between the major meteor showers with high flux rates (the Quadrantids, Lyrids, Eta and Delta Aquarids, Perseids, Orionids, Taurids, Leonids, Geminids and Ursids) and the host of minor showers which are hardly distinguishable from the sporadic background and are usually recognised in photographic and radar surveys simply by comparing individual meteor orbits. The ten major showers mentioned above have median values of inclination, semi-major axis and eccentricity of 76°, 8.0 AU and 0.93 respectively. The transition from major to minor shower seems to be characterised by a considerble decrease in all three parameters to values which are roughly 9°, 2.1 AU and 0.7. This is illustrated graphically in Figure 4.

Perihelion distribution is shown in Figure 5. Notice that

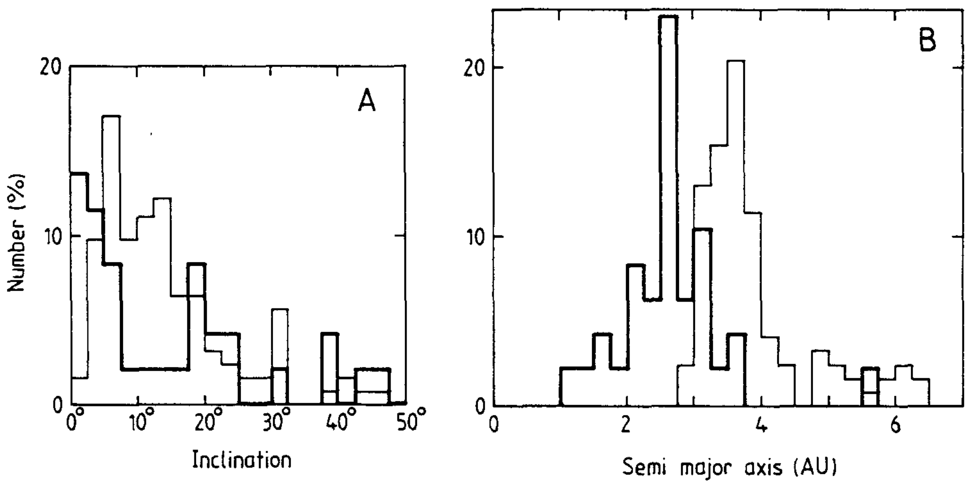

Figure 3(A) The distribution of the orbital inclinations of meteoroid streams (thick lines) and short period comets (thin lines). Seven percent of the comets lie off the diagram and 29 percent of the streams do likewise. (B) The distribution of the semi-major axes of meteoroid streams (thick lines) and short period comets (thin lines). Seventeen percent of the comets and 27 percent of the meteoroid streams lie off the diagram.

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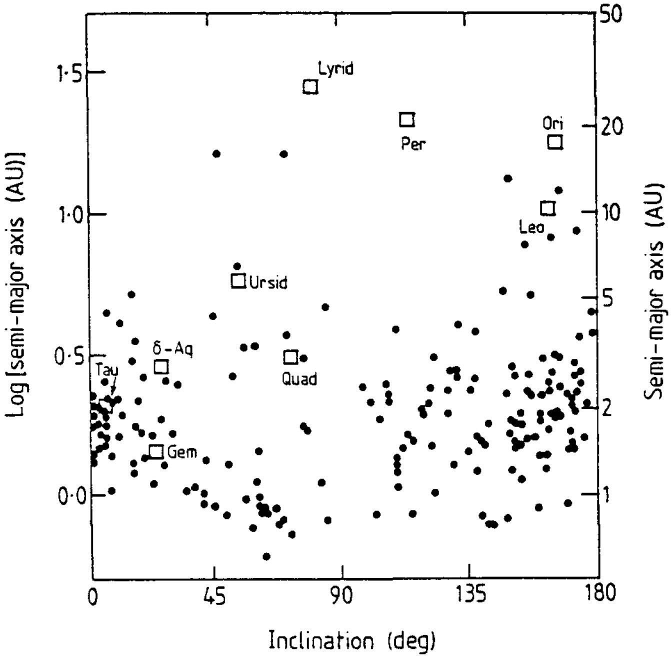

Figure 4 The distribution of the semi-major axes (shown on a logarithmic scale) and the inclinations of meteoroid streams, □ the nine major showers, ● the minor showers (taken from the Northern Hemisphere radio survey, Kasceev, Lebedinec and Lagutin, 1967).

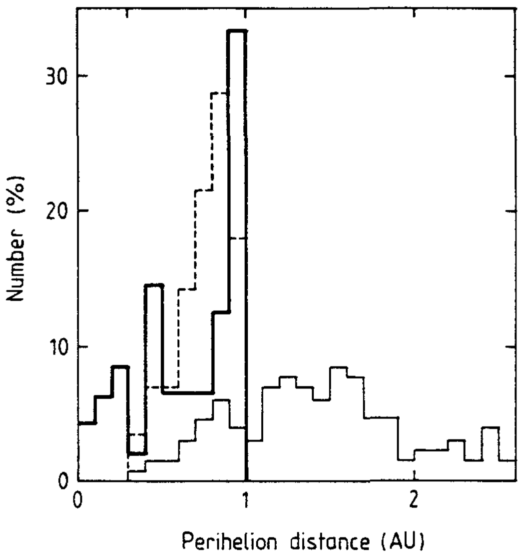

Figure 5 The distribution of the perihelion distances of meteoroid streams (thick lines) and short period comets (thin lines). The dashed line represent the distribution of the short period comets that have q < 1.0 AU.

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there are no observed short period comets with $q < 0.3$ AU whereas about 19 percent of the streams fall into this catagory. These $q < 0.3$ AU comets decay so quickly that our chances of detecting them are much reduced.

Obviously only $q < 1.0$ AU must be considered because meteor streams outside this ramge cannot be detected from Earth orbit. Concentrating on $q < 1.0$ AU the median q for comets is 0.73 AU which fortuitously turns out to be the same as the value obtained for streams.

4. DISCUSSION

Kresak (1973) divided the evolution of a meteoroid stream into three principle phases. (I) - that influenced by the orbital evolution of the parent comet, (II) - differential accelerations, experienced at the time of separation from the cometary nucleus and III subsequent stream evolution. Phase I is governed by major planetary perturbations and also the non-gravitational effects. Now planetary perturbations tend to produce a random walk in orbital parameters whereas non- gravitational forces are much more effective in producing a long term change in one specific sense. Assuming that the spin axis direction of the cometary nucleus does not vary, the value of the reciprocal of the semi-major axis undergoes regular, unidirectional steps and the total change produced in this quantity is simply a function of the number of times the comet passes close to the Sun.

Non-gravitational forces are responsible for changing the orbits of many of the short-period comets. Weissman (1979) suggests for example that they have decreased the semi-major axis of the periodic comet Encke and have pulled it away from the influence of Jupiter. This effect can thus greatly increase the inner Solar system lifetime of these short-period comets and there is the possibility that they could lose all their ices without violent disruption and so evolve into Apollo or Amor-type asteroids. In stage III the meteoroids are small and are influenced by planetary perturbation and also by the dynamical effects of solar radiation and interplanetary magnetic fields.

Why do some streams have extant parent comets whereas others do not? If streams last longer, as observable entities, than comets, it is to be expected that the majority of streams would be comet-less. also the closer a comet gets to the Sun the faster it decays. So, as Kresak (1968) pointed out, streams with small perihelion distances are less likely to have extant parents than the others. A division of the streams into two groups, those without extant comets (NC) and those with extant comets (C) (see figure 6) shows that about 56% of the C group have perihelia in the $0.9 < q < 1.0$ AU range whereas only 22% of the NC group lie in this range. And this isn't the only difference between these two groups. The NC group tend to have lower inclinations with 62% in the range $0 < i < 20°$ as opposed to 31% in the C group. This trend is obviously following the one between major and minor streams. The semi major axes also differ slightly. The NC group has about 87% of the semi-major axes in the $1 < a < 4$ AU range whereas the C group only has

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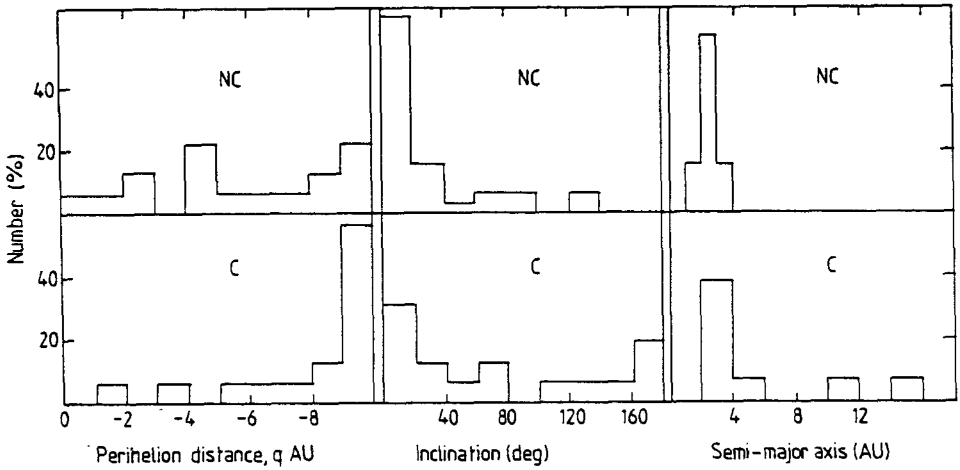

Figure 6 The orbital parameters of meteor streams, the streams having been divided into two groups, those with no extant parent comets (NC) and those with extant parent comets (C).

37.5% of its members in that range. So the C group has in the main, larger semi-major axes.

5. SELECTION

The effect of observational selection is severe. Let us take meteor streams first. To be seen at all they must intersect the Earth's orbit, so q must be less than 1 AU. We also have a better chance of seeing wide streams, such as the Perseids, Taurid, Geminid and Halley streams, than narrow ones, like the Quadrantids and Draconids. The probability of encounter also increases for streams close to the ecliptic, that is with inclination near 0° and 180°. Radiant position is important too, the summer day-time streams being difficult to observe visually because the radiant is approximately in the solar direction.

The size of the orbit is significant. For streams of similar dust masses the flux per unit time at any intersection will be inversely proportional to the orbital period. This favours the streams that lie well within Jupiter's orbit, added to which, they have a special advantage in as much as Jovian perturbation does not change the orbital parameters significantly, a change which can quickly sweep a stream node away from the Earth's orbit. Streams which have aphelia way beyond Jupiter suffer due to the decrease in the spatial density of the meteoroids.

The activity of a shower, as observed from a given location, decreases with the increasing zenith distance of the radiant and becomes very low when the radiant passes below the horizon.

Even today the majority of our information about meteoroid streams comes from observations in the latitude zone between 35°N and 55°N. This effect is clearly shown in figure 7A. Notice that the

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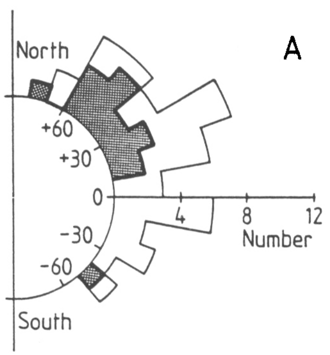
'cometary' streams seem to be predominantly northern hemisphere.The observations that have been made from the southern hemisphere indicate that this is not entirely due to observational selection, no major southern streams having been found.

The geometry of the intersection between the meteoroid stream and the Earth is of paramount importance. It is well known that the geocentric velocities of meteoroids lie in the range 11 to 74 km sec^{-1}, the lower limit being set by particles which just manage to catch up with the Earth and the upper ocurring when the particle and our planet have a head-on collision. Thus shower meteoroids have encountered velocities dispersed over a range of over 1 to 6. More significant is the fact that the kinetic energy per unit mass of the incident meteoroid varies over a range of 1 to 44. Both the meteor luminosity and the electron line density are direct functions of the kinetic energy of the meteoroid. So streams with high geocentric velocities, such as the Leonids, Orionids and Perseids are over impressive because, with a specific piece of equipment such as the eye, we can detect much lower mass meteoroids than we could in the low geocentric velocity minor streams (see Figure 7B). In sharp contrast to the above, our ability to detect comets does not depend drastically on their geocentric velocity.

Kresák (1968) points out a further problem. The internal dispersion of stream meteoroid heliocentric velocities leads to the radiants being distributed over a finite area of the sky. This area increases considerably for radiants elongated at between 100 and 180 degrees of the apex, thus making visual meteors from these streams much



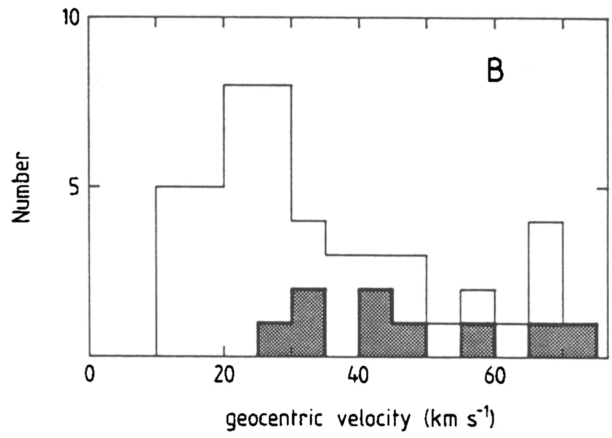


Figure 7(A) The distribution of declinations of observed meteor streams. Hatched region - the C set, bold histogram, the total group.
(B) The distributions of meteoroid geocentric velocities for the 48 meteor streams. The bold histogram represents the nine most active streams: Quadrantid, April Lyrid, Delta Aquarid, Perseid, Orionid (plus Eta Aquarid), Taurid, Leonid, Geminid and Ursid.

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less easy to differentiate from the visual sporadic background. Retrograde streams are thus greatly favoured over the stream meteoroids which are trying to overtake the Earth from the direction of the antapex. To quote Kresak "This is one of the reasons why an identification of minor streams based on the orbital elements and not on the radiant co- ordinates enhances the number of diffuse direct short period streams".

6. CONCLUSIONS

One important point must be stressed. Both meteoroid streams and comets are notorious for moving around the solar system. The Quadrantids (see Williams et al 1979) and Geminids (see Fox et al 1982) are both sweeping past the Earth's orbit and have only been seen, as meteor showers from Earth, since the early nineteenth century. Their orbital parameters, with the exception of the semi-major axes, are changing quickly. There is no reason why the parent comet should undergo perturbations of a similar magnitude so even though they started in the same place the stream and comet can quickly separate as time passes. This is probably the only satisfactory explanation as to why two out of three of the streams in Cook's list do not have recognisable parents. Figure 7 illustrates that the smaller the perihelion distance and inclination of the stream the greater is the chance of the comet being lost. [It is worth noting that the sporadic background is much denser at low inclinations, so that more spurious streams may be mistakenly recognised here due to chance coincidences between sporadic meteor orbits].

The ages of the stream and the comet are also important. Meteor streams are in the main not produced instantaneously (the term 'in the main' is used because there is the possibility of a comet suffering a catastrophic break up, disappearing, and transferring a large percentage of its mass to its offspring the stream). Usually stream formation is gentle, typically one percent of the comet mass being lost at each perihelion passage. Drummond (1981b) noted that a comet loosing a constant thickness of nucleus material at each perihelion passage will inject 270 times as much material into its stream during the first tenth of its life as it will during the last tenth. [If the cometary nucleus started out with a radius R this fraction is simply $\frac{R^3 - (0.9R)^3}{(0.1R)^3}$]. This means that masive and thus bright comets should be associated with dense meteor streams, the decay of the comet and the stream going hand in hand. The corollary to this is that streams such as the Quadrantids and Geminids must have parent comets somewhere. It is simply a matter of recognising them. A rough illustration of this decay process is given in Table I. It is obvious from this table that the stream has reached about 75 percent of its final mass by the time the decaying comet has increased in magnitude by only unity.

We obviously have streams without comets, do we have comets without streams? Drummond (1981b) disagreed with Olivier (1925) and answers this question with a qualified negative. To quote his paper

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"every short period comet that has approached the Earth's orbit to within 0.08 AU has produced recognisable meteor showers except P/Lexell, P/Finlay, P/Grigg-Skjellerup and P/Denning - Fujikawa". The first two are in unstable orbits, the third is marginal and Drummond (1981b) drew attention to the favourable observing conditions for detecting meteors from it in April 1982. The fourth has a radiant less than 30° from the Sun and of negative declination. P/Lexell was so violently perturbed by Jupiter in 1767 and 1779 that its radiant is now probably rather inactive.

Many long period comets have come close to the Earth's orbit but very few (five according to Drummond 1981b) have produced meteor streams.

Table I

This table illustrates the decay of a comet which loses a constant thickness of nucleus material at each perihelion passage. The comet starts out with a mass of M, a radius of R and an absolute magnitude of H. A fraction 'a' of its mass goes into the meteoroid stream (a ~ 0.3). It has been assumed that the brightness of the comet is proportional to its surface area [following equation 5].

Percentage of cometary life that has passed	Radius of nucleus	Mass of comet	Mass of stream	Magnitude of comet
0	R	M	0	H
10	0.9R	0.729M	0.271Ma	H+0.23
20	0.8R	0.512M	0.488Ma	H+0.48
30	0.7R	0.343M	0.657Ma	H+0.77
40	0.6R	0.216M	0.784Ma	H+1.1
50	0.5R	0.125M	0.876Ma	H+1.5
60	0.4R	0.064M	0.936Ma	H+2.0
70	0.3R	0.027M	0.973Ma	H+2.6
80	0.2R	0.008M	0.992Ma	H+3.5
90	0.1R	0.001M	0.999Ma	H+5.0
100	0	Q	Ma	∞

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