METEOROID STREAMS

DUNCAN STEEL

Anglo-Australian Observatory, Private Bag, Coonabarabran, NSW 2357; and Department of Physics and Mathematical Physics, University of Adelaide, G.P.O. Box 498, Adelaide, SA 5001, Australia

E–mail : DIS@AAOCBN3.AAO.GOV.AU

Abstract. Meteoroid streams, producing meteor showers if some part of the stream has a node near 1 AU, have complex structures which are only just beginning to be understood. The old simplistic idea of a narrow loop being formed about the orbit of a parent comet with one, or possibly two, terrestrial intersection(s) is now being replaced by the recognition that their dynamical evolution may render convoluted and distorted ribbon shapes with eight or more distinct showers being generated. As such the streams are excellent tracers of the sorts of orbital evolution which may be undergone by larger objects (asteroids and comets) in the inner solar system; indeed it is now known that objects presently observed as Apollo-type asteroids may also be the progenitors of streams.

Searches for showers associated with newly-discovered possible parent objects may be carried out either via the calculation of theoretical meteor radiants (which have hitherto been derived using an untenable method), or through searches of catalogues of individual meteor orbits. In order to accomplish the latter, about 68,000 radar, photographic and TV meteor orbits from various programmes in the U.S.A., the former Soviet Union, Canada and Australia are available from the IAU Meteor Data Center, and more than 350,000 orbits of very faint meteors have been determined over the past three years using a new facility in New Zealand.

The discovery amongst IRAS data of dust trails lagging behind comets has opened up a new way in which meteoroid streams may be investigated, although the relationship between these trails and the streams observed as meteor showers at the Earth is by no means clear at this stage. Similarly radar, radio and spacecraft impact observations of meteoroids near cometary nuclei have added to our knowledge.

In spite of the improvement in our understanding of meteoroid streams over the past few years it is clear that there is much still to be done. The words of W.F. Denning in 1923 are still pertinent : "Few astronomers occupy themselves with the observation and investigation of meteors, and yet it is an attractive field of work offering inviting prospects of new discoveries".

1. Historical Introduction

Although meteor showers have been observed since time immemorial, it was only with the great Leonid storms of 1799 and 1833 that meteor studies started to attain any proper scientific understanding. The wonder (and alarm, in some people) provoked by these spectacular events eventually led to the recognition that these great meteor storms occur periodically, and might be linked to a certain comet (P/Tempel-Tuttle in the case of the Leonids), and also that the various seasonal showers with broadly-constant annual activities might similarly have a cometary origin. Thus by 1861 Daniel Kirkwood was able to ask "May not our periodic meteors be the debris of ancient but now disintegrated comets, whose matter has become distributed around their orbits?". The reader is referred to Porter (1952) for a thumbnail sketch of the history of meteor shower studies, and their relation to comets; but it should be noted that the title of his book is semantically incorrect

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(and indeed contrary to later IAU nomenclature recommendations) since strictly-speaking one should refer to 'meteor showers', and 'meteoroid streams'. A more recent discussion of the history of meteor studies has been presented by Beech (1988).

A number of compilations of records of ancient meteor showers have been published; see for example Hasegawa (1992) and references therein for Chinese and Japanese records, and for Arab chronicles see Rada and Stephenson (1992; but see also Kidger, 1993). In the last of those references, historical work on meteor showers observed and recorded by a variety of human cultures is mentioned. Such records are invaluable with regard to providing a check upon theoretical analyses of the dynamical and physical evolution of meteoroid streams : a number of researchers have made use of such tabulations of meteors and fireballs, for example Fox and Williams (1985) and Bailey *et al.* (1990). Records of the activities of well-known streams over the past few centuries are also of great use in aiding an understanding of stream evolution, for example how the rotation of the line of apsides under planetary perturbations brings the node to a heliocentric distance of 1 AU so that a shower is observable for a period of time (*e.g.* in the case of the Geminids, this shower having been observed only since about the middle of the last century : Fox *et al.*, 1982; Hunt *et al.*, 1985). Also noteworthy, regarding the genesis of particular showers/streams, has been work aimed at correlating ancient comets and meteor showers, for example by Kresáková (1987).

2. Modern Studies

Over the past century the dictates of astronomical fashion have led to periods in which interest in meteors and meteoroids has waxed and waned. For example, throughout the 1960's the Harvard Radar Meteor Project in the U.S.A. (Cook *et al.*, 1972) made that nation pre-eminent in the field, but since the demise of that programme there has been comparatively little meteor research done there. This contrasts with the situation in the old eastern European countries, of which the former Soviet Union and Czecho-Slovakia in particular might be mentioned, where very active groups have continued to produce results of import for several decades; indeed, one of the problems faced by this author in preparing this review is that much of the most significant work, judging from the English translations of publication abstracts, has been published only in Russian (and the consequent inaccessibility of the work is the responsibility of this author).

Research groups elsewhere, however, are also making very important contributions to meteor science so that the subject may be characterized as being one full of vigour and rigour (as opposed to *rigor mortis*). Beech (1988) has expressed the view that the study of meteors may be classified as a mature science, but despite that it is by no means true that we have done more than scratch the surface in our quest for an understanding of meteoroid stream behaviour. For example, an unresolved problem remains the mechanism by which streams are dispersed so as to give showers of the observed durations, and this must be tied up with the ejection speeds of the meteoroids from their parent bodies, and the physical mechanisms whereby those speeds are attained. This is the case for the Geminids, which appear to be 'too dispersed' for current models of stream formation and subsequent orbital evolution to accommodate (Fox *et al.*, 1983; Jones, 1985; Jones and Hawkes, 1986; Ryabova, 1989). The nodal motion (or lack of it) in the case of the Geminids has also been an outstanding problem (Fox *et al.*, 1982), with similar questions (with the inclusion of notable mass segregation) being posed by the Quadrantids (Hughes *et al.*, 1981; Froeschlé and Scholl, 1986).

One fundamental benchmark in meteor studies is how the observations of meteors agree with the theory : for example whether meteor storms recur at their predicted times. In many instances the comment of Padevět (1973) is still pertinent : "Even if we use the classical physical theory of meteors, there may still be some possibility for agreement between observations and theory". That comment was made in regard to meteor physics, as opposed to the meteor astronomy which is of interest here, but still it rings true : theory and observations are still a long way apart in many of the outstanding problems of meteoroid streams. The provision of observations of high quality is essential to the testing of any hypothesis, and professionals often do not have the time or the funds to carry out the sorts of observational programmes that are required. Thus the foundation of the International Meteor Organization (Gyssens *et al.*, 1991), with amateur enthusiasts collecting data under controlled conditions, bodes well for the future of this subject.

The scientific study of meteoroid streams, then, remains an area of research with many tantalizing problems yet to be solved. Modern techniques have made many of these amenable to attack, for example the availability of computing power putting large numbers of statistical numerical integrations within the grasp of research groups with quite modest budgets. Over the next few years, with increasing interest in small bodies (asteroids and comets) as potential space mission candidates, there is certain to be added emphasis on the relationship between such objects and the streams that they spawn. The study of meteoroid streams is an exciting field which, after a period of relative quiescence, is now re-awakening to meet the challenges of the spacefaring age.

In this review my intention is only to give an introduction to the field for those who may be newcomers to it, and to point to published work which may be accessed in order to discover the state of the art in various areas of research on meteoroid streams. Due to the lack of space even this intention cannot be fully carried out, and to a large extent only the most recent papers by various researchers on various topics are referenced, or at least those publications which are most easily accessible. This is meant as a review for an ingenue, not an old-hand, although it is hoped that all will find it a suitable compendium for many enquiries.

3. How are meteoroid streams investigated?

In this section I will attempt to give a very simple background sketch about how meteoroid streams are investigated. I will concentrate here on observational/ experimental methods, along with very simple theory, and in section 4 discuss the more intricate theoretical modelling that has been attempted.

3. 1. OTHER OBSERVATION TECHNIQUES

Before discussing the standard techniques whereby streams are observed through the showers that they produce, it is worthwhile to mention other techniques that have been applied, and may well be expanded in the future. Impact detectors on spacecraft either in the vicinity of the Earth (Singer and Stanley, 1980) or in deep space (Grün *et al.*, 1993; Grün, this volume) provide stream detection for very small dust particles. Moving to the other end of the mass spectrum, meteoroids with masses to order 1 tonne have been detected hitting the Moon with the Apollo seismometers, and many of these appear to be in streams (Oberst and Nakamura, 1991); and even larger bodies (to 5–10 m) have been telescopically-detected in near-Earth space (Rabinowitz, 1993) and the two nearest-misses to date have been by objects with orbits similar to the Taurid stream, which may extend to kilometre-plus asteroids (Asher *et al.*, 1993). There is also evidence for some meteorites being in streams (Halliday *et al.*, 1990; Terentjeva, 1990; Dodd *et al.*, 1993). Another technique whereby streams might be observed is from the scattering of sunlight by the particles in space, as suggested by Baggaley (1977). At longer wavelengths the IRAS dust trails associated with short-period comets appear to be due to millimetre-sized particles (Sykes and Walker, 1992), although the relationship between these structures and the streams observed impacting the atmosphere is not yet clear; Kresák (1993) discusses the possibility that meteor storms occur when the Earth passes through such trails. At even longer wavelengths, in the millimetre range, meteoroids have been detected near comets through their thermal emission (Crovisier and Schloerb, 1991), and through centimetre-wave radar scattering (Harmon *et al.*, 1989; Campbell *et al.*, 1989).

3. 2. METEOR SHOWERS

Our predominant method for sampling any meteoroid stream is by the study of the meteor shower produced when the Earth passes through the stream. Clearly this requires at least part of the stream to have a node near 1 AU. The phenomena produced in the atmosphere may then be studied by ground-based observers, either using optical (visual, photographic, TV) or radar techniques.

The duration of such showers provide information on the transverse stream profile, from the variation in the meteor count rate from day-to-day, and also such factors as the varying mass distribution across the stream. For example, the Geminid shower has a long build-up over about 10 days for the smaller ($\sim$1 mm) particles detected using meteor radars, but a rather shorter climb, over just a few days, for the larger ($\sim$1 cm) optically-detected particles; both then show a rapid fall off in count rates (see *e.g.* the papers cited in section 2 with regard to the Geminids, and Babadzhanov *et al.*, 1992). Other showers have also been studied in this regard; for example the Quadrantids (Porubčan and Cevolani, 1990; Šimek and McIntosh, 1991) and the Perseids (Šimek and Lindblad, 1990).

Whilst day-to-day variations in shower strength render information about the transverse profile through a stream, year-to-year variations can provide information about the lengthways stream profile; these can delineate also the transverse profile since observations on the same day each year will be at slightly different solar longitudes. A good example of how a stream spatial structure may be investigated in this way is given by Bel'kovich (1986).

One confusing factor is the effect of the state of the atmosphere upon meteor count rates, in particular for radar observations. A substantial change in the number

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of radar-detected meteors will occur if the scale-height at ~100 km alters by only ~10% (*e.g.* see Ellyett and Kennewell, 1980).

Many showers demonstrate consistent count rates from one year to the next, showing that the meteoroids are equably distributed about the stream, and indicating it to be a mature structure : for example see the discussion of the Geminids by Jones (1982). Conversely, some streams are relatively young, or are being dynamically replenished by the parent object, as is the case for the Leonids, spawned by P/Tempel-Tuttle (1866 I). That shower exhibits a 33 year periodicity in its activity, with strong storms occurring when the Earth passes through the stream in the vicinity of the comet (Yeomans, 1981; Williams *et al.*, 1986; Wu and Williams, 1992a). However, the Leonid storms sometimes precede the cometary perihelion passage (*e.g.* in 1799 : Yeomans, 1981) or can occur some years later (an outburst was observed in 1969, three years after the main storm in 1966 : Porubčan and Štohl, 1992)

Another comet-related meteor storm is the October Draconids (or Giacobinids), associated with P/Giacobini-Zinner, with a cyclicity of 13 years (Beech, 1986; Kulikova, 1989; Lebedinets *et al.*, 1990), whilst the great Andromedid storm of 1872 is associated with the break-up of P/Biela some decades before (Babadzhanov *et al.*, 1991b). Since 1988 an increase in the activity of the Perseid shower has been noted, with exceptional displays in 1991 and 1992 leading to the prediction that the parent comet, 1862 III Swift-Tuttle, was in the vicinity, and it was duly re-discovered in 1992 September. In 1993 Perseid activity was spectacular but a storm did not occur; for reports see *IAU Circular 5841* and *5843*. This increase in activity (with perhaps a peak yet to come : Wu and Williams, 1993) is again illustrative of how groupings occur close to the parent (*cf.* Kresák, 1993). For the larger meteoroids (above ~1 cm), producing bright visual meteors, the ejection velocities from the parent are expected to be low, with the initial dispersal in periods, due to the effect of radiation pressure, being only 1% or less. Thus it takes many orbits before the meteoroids released on any particular perihelion passage can become fully dispersed around the orbit; indeed the equable meteor count rates well away from the comet's perihelion passage make the minimum stream age estimable.

Another example of a shower which has undergone outbursts, although in this case the parent comet is not in the vicinity of the Earth, is the April Lyrids (associated with Comet Thatcher, 1861 I). This may be due to some form of mass segregation (Lindblad and Porubčan, 1992; Porubčan and Štohl, 1992) although an explanation based upon orbital resonances with Jupiter has been proposed (Emel'yanenko, 1991).

3. 3. EFFECT OF ORBITAL PRECESSION/EVOLUTION UPON SHOWER OCCURRENCE

Whilst certain showers are observed in the present epoch, they were not seen in the past, nor will they be seen at some future time. As the stream orbit precesses under planetary perturbations it may move so as to have both nodes some way away from 1 AU, so that no shower occurs on Earth. For example, as mentioned in section 1, the Geminids have only been observed since the middle of the last century. Historical records, and monitoring of the shower activity now, therefore provide a test of orbital evolution theories. Indeed, in recent years statistical-type integrations of indeterministic cometary or asteroidal orbits have been carried out, with packets of initial orbits with slightly different start elements being used (*e.g.* Hahn and Bailey, 1990). Clearly observations of particles in meteoroid streams represent a real-life portrayal of how slightly different starting elements affect the orbital evolution.

Information on the orbital history of the parent objects can also be gained from a study of their associated streams. For example P/Halley has been observed for almost 2.5 millennia, but this is much shorter than the time for which it has occupied its present general orbit, and any backwards integration becomes indeterminate prior to 1404 B.C. due to a close approach to the Earth in that year (Yeomans and Kiang, 1981). However, the age of the Halleyid stream, producing the Eta Aquarid and Orionid showers, appears to be at least 20,000 years (Jones *et al.*, 1989) so that studies of the orbital evolution of the Halleyids (McIntosh and Jones, 1988; Babadzhanov *et al.*, 1991a; Hajduková and Hajduk, 1991) can provide useful information regarding the comet's history. Stream orbital evolution is more extensively discussed in section 4.

3. 4. SHOWER RADIANTS

Apart from the activity (hourly rates) detected during a shower, information on a stream's structure may be derived from measurements of individual meteor radiants, and orbits. In this section I discuss radiants, and in section 3.5, orbits.

3.4.1. Observed Radiants

The simplest definition of a meteor shower is a concentration of meteors observed to emanate from a particular direction (radiant) at a particular time of year, and with a particular velocity. These specific values then define an orbit for the stream which is producing the shower. Having written that, for many years there has been debate about how a shower may be recognized; whilst there is no argument about the major showers (Perseids, Geminids, Quadrantids, Eta Aquarids, Orionids, Delta Aquarids, Lyrids, Daytime Arietids, Beta Taurids, Zeta Perseids, *etc.*), as soon as the count rates drop to 5 or 10 per hour it is not clear whether a definite shower is being observed, or whether it is a chance alignment, especially for near-ecliptic radiants. The commonly-used list of streams is that presented by Cook (1973), although it is clear that many of those that he tabulates are fictitious, being chance alignments of just five meteors from the Harvard photographic surveys (his major source).

Many catalogues of observed radiants have been published over the past century, with many interpretations being open to doubt. For visual observations the count rates are relatively low, with radars being capable of much higher detection rates. Therefore radiant imaging radars, such as those described by Morton and Jones (1982), Jones and Morton (1982), and by Poole and Roux (1989), are of considerable importance in this regard.

3.4.2. Theoretical Radiants

A theoretical radiant is a value for the radiant calculated from the orbit of a putative parent object, such as an Earth-crossing comet or asteroid. The most-used technique for calculating such radiants was described by Porter (1952), and used by Drummond (1981b, 1982b) and Olsson-Steel (1987) amongst others. The technique involves a determination of the closest approach distance between the orbits of the parent and the Earth (assumed zero eccentricity orbit), and then a rectilinear transposition of the direction cosines of the parent's path to that of the Earth. This is clearly an unphysical treatment since this is *not* how a meteoroid's path alters so as to make Earth-impact possible. Thus the technique will give reasonable results if the actual orbit miss-distance is small, but will give misleading results otherwise.

A far better technique was described by Hasegawa (1990; see also Hasegawa *et al.*, 1992). This involves a rotation of the line of apsides of the comet/asteroid orbit so as to produce a node at 1 AU, the theoretical radiant then being derived in the standard way using the direction cosines for this argument of perihelion-rotated orbit. This is much closer to the actual situation which produces an Earth-intersecting stream, with precession under planetary perturbations being responsible.

However, even this has some drawbacks in that during the stream's evolution the orbital elements (a, e and i) are not constant, so that at the time that a node occurs near 1 AU these elements may have different values to those previously occupied. For example, P/Encke (with $i \simeq 12°$) is known to be the parent of the Taurid meteor showers, but the meteoroids observed hitting the Earth have $i \simeq 2°$– $6°$; however, when the comet has a node near the Earth it has a reduced inclination too (Whipple and Hamid, 1952; Steel *et al.*, 1991). This is also an excellent example of the fact that meteoroid streams trace out the orbital evolution of their parent bodies (*cf.* section 3.3). Thus any attempt at determining an accurate theoretical radiant must involve a numerical integration of the putative parent's orbit, with times when the nodes reach 1 AU being noted. However, a far simpler method which appears to give reasonable results is the use of the simple integrals of motion discussed by Babadzhanov (1990) and by Babadzhanov and Obrubov (1992b), which allows the orbital elements in epochs of Earth-interception to be determined, and hence the theoretical radiants to be derived.

The next next step in determining a genetic relationship between a hypothetical parent and a meteor shower is to compare the theoretical and observed radiants. Whilst this is not so stringent a test as one in which orbits are directly compared, it is a useful indicator; and theoretical radiants can point observers to useful areas of the sky for examination at certain times of year.

As an example, the genetic relationship between the Eta Aquarid and Orionid showers and P/Halley is clearly established by these showers having radiants close to the theoretical value for the comet. Since there are few sporadic meteoroids with similar velocities (retrograde orbits of large size), and the times of the showers agree with the nodal values of the comet, there is little argument about this link despite the fact that neither shower has an argument of perihelion coincidental with that of the comet (due to the requirement for meteor observation of a node at 1 AU). However, for a low-inclination, moderate-eccentricity orbit the situation would not be so clear cut due to the preponderance of near-ecliptic sporadic meteors (from the Jupiter-family comets).

3.4.3. Twin/Multiple Radiants

It has been discussed above how a stream may precess so as to produce a shower on Earth in this epoch which did not occur some time ago, since at that time it did not have a node at 1 AU. This also suggests that twin showers may occur from a particular stream (*e.g.* the Eta Aquarids and the Orionids from the Halleyid stream); Drummond (1982a) calculated theoretical twin shower radiants for established showers, although for reasons that will become apparent his treatment is insufficiently sophisticated. Even for a stream which precesses whilst preserving its values of (a, e, i), four streams may be produced : at the four combinations of (pre-perihelion leg, post-perihelion leg) and (ascending node, descending node). Thus the Taurid stream produces the (nighttime, pre-perihelion) Northern and Southern Taurids, and the (daytime, post-perihelion) Beta Taurids and Zeta Perseids.

However, an analysis including orbital evolution, again taking the example of the Taurids, shows that 12 distinct showers may be produced by this stream alone (Babadzhanov, 1990; Babadzhanov and Obrubov, 1992b). This is also discussed in section 4.

3. 5. STREAM ORBITS

In order to show with some confidence that a particular macroscopic object (comet or asteroid) has spawned a specific stream, a comparison of orbits is necessary. Indeed, even before this can be done, the stream itself must be demonstrated to exist, and this is best done through the comparison of individual meteor orbits. The tool used to accomplish this has generally been the orbital discriminant, or 'D-criterion', of Southworth and Hawkins (see Drummond, 1981a).

Over the past few years there have been several small-camera measurements of meteor orbits, producing a few hundred such determinations. However, the largest number of meteor orbits generally available are those stored at the IAU Meteor Data Center (IAUMDC) in Sweden, with about 6,000 optical (photographic and TV) and 62,000 radar orbits being archived there (Lindblad, 1991; Steel, 1991). Other radar surveys have been carried out, in particular in the former Soviet Union, from which the data have not been made available. A new survey in New Zealand (Baggaley and Taylor, 1992) has produced more that 350,000 orbits, and these will eventually be archived at the IAUMDC.

These orbits have been used in stream searches too numerous to mention here. Many of the likely stream/comet relations have been tabulated by Cook (1973), and also tested through the simplistic D-criterion test by Drummond (1981a). However, with the orbital evolution discussed in section 3.3 in mind, it is clear that rather more sophisticated testing techniques are required; in particular the parent must be integrated so as to determine its orbit when it is Earth-approaching (*e.g.* see Babadzhanov and Obrubov, 1992b).

Another problem is that of the differentiation of a stream from the background sporadic meteors. To some extent this problem has been addressed by Olsson-Steel (1988) who showed that many Apollo-type asteroids have associated streams, in contradiction to Drummond (1981a, 1982b), but there is still much to be done in this area; see also Porubčan *et al.* (1992).

Whilst it may seem that the number of orbits available should be sufficiently-plentiful for most purposes, in fact for certain showers there is a great sparcity of data. During the 1980's, with the booming interest in P/Halley, there were several studies of the Halleyid stream's orbital evolution (see the papers listed in section 3.3 and references therein). However, Lindblad (1990) showed that the stream orbit listed by Cook (1973), and used by various researchers, was in fact derived from one meteor only. Lindblad found a total of 16 Eta Aquarid orbits amongst the data at the IAUMDC, putting matters on a slightly better footing, but these are now superseded by the 1000+ high-quality orbits from this stream measured in New Zealand (Baggaley *et al.*, 1992, give a preliminary analysis).

4. Stream formation and evolution

Whilst the mechanisms of stream formation remain poorly understood, in particular the source of meteoroid speeds larger than 50 m/sec relative to the parent (as are required by the shower durations discussed in section 2), over the past decade or so our knowledge of the orbital evolution of streams has undergone a great improvement. Before passing on to that subject, some mention of a possible cause of the problematic relative speeds is given.

Gas dynamic drag cannot provide a sufficiently high relative speed, so that some other mechanism is required. However, the foundation of the idea of Whipple (1951) of this gas dynamic drag was that the nucleus of a comet is the source of the outflowing gas in the coma. In fact the data from the spacecraft sent to P/Halley showed that the coma has an extended source : that is, it is evaporation from the lumps of solid material which is the predominant source of gas in the coma. If each of these lumps were to be considered as mini-comets composed to a large degree of volatile material, in accord with our knowledge of cometary nuclei, then clearly the evaporating material will produce a jet force similar in nature to the non-gravitational force that perturbs the orbits of comets themselves. The released mini-comets/meteoroid progenitors will therefore be accelerated relative to the parent comet. Modelling of this effect is commended to any interested reader.

As aforementioned, meteoroids are released from their parent bodies with relatively low speeds, although these may be accelerated by other factors soon after release. Meteor storms occur when the Earth cuts close by the orbit of an active comet, with the comet being in the vicinity (although storms have occurred with no known parent comet being observed; for example, the December Phoenicids in 1956 : see Cook, 1973, but also Ridley, 1962). Such particles will become dispersed around the cometary orbit by the effects of radiation pressure, but complete smearing around that orbit will take some time : see Jones (1982) for a discussion of the Geminids. Other radiative forces, including the Poynting-Robertson effect (Burns *et al.*, 1979) can also cause dispersal and mass segregation.

Another question is that of the dispersal of streams into the sporadic background. This occurs predominantly through the effect of close approaches to Jupiter, at least for the Jupiter-family (period < 20 yr) streams (Olsson-Steel, 1986). Characteristic time-scales are of the order of 10^4 yr for dispersal, and 10^5 yr for physical loss due to impacts with zodiacal dust particles.

There have been many reviews of stream formation and evolution published in the past few years, and here the reader is merely referred to a few suitable papers. These include Lebedinets *et al.* (1990), Williams (1990, 1992), Hajduk (1991), McIntosh (1991), and Babadzhanov and Obrubov (1992b).

Over the past decade work on one stream in particular has provided some insight into the generalities of stream orbital evolution, and this stream is that which produces the strong Quadrantid shower. Soon after the discovery of P/Machholz (1986 VIII) it was realized that this comet was very probably the parent not only of this shower, but also of seven other showers, including the Daytime Arietids, the Delta Aquarids, and the Ursids; however, association of this complex stream with Comet 1491 I cannot be ruled out (Williams and Wu, 1993), which may indicate that the complex was formed from the break-up of a single larger comet. The relationship is particularly surprising in that the orbital elements are very different for these showers and comets (*e.g.* the Quadrantids, Ursids, Delta Aquarids, Daytime Arietids, P/Machholz and 1491 I have $q = 0.977$, 0.968, 0.07, 0.09, 0.127 and 0.761 AU respectively). Recent papers on the orbital evolution of the stream include Zausaev and Pushkarev (1989), McIntosh (1990), Babadzhanov and Obrubov (1992a), Jones and Jones (1992), and Wu and Williams (1992b)

Another stream of particular interest, at least to the author, is the Taurids, which may be related to episodes of terrestrial catastrophism within the past 20,000 years (Steel *et al.*, 1991). As mentioned in section 3.4.3, up to 12 distinct showers may result from this stream (Babadzhanov *et al.*, 1990; Babadzhanov and Obrubov, 1992b), and it is particularly interesting since it it is associated with the shortest-period comet (P/Encke : see *e.g.* Whipple and Hamid, 1952; Jones, 1986) and ten or more known Earth-crossing asteroids (Asher *et al.*, 1993), and also a large fraction of the broad sporadic stream modelled by Štohl and Porubčan (1990, 1992). The breadth of this stream (*i.e.* the duration over which the showers are active) is due in part to its low inclination, leading to a wide range in nodes on the ecliptic.

Most of the above work has been concerned with the relatively short-term evolution of comets of the Jupiter and Halley-type families (*i.e.* those producing most of the recognized meteoroid streams), and have used physical theories based upon simple analytical techniques. Emel'yanenko (1992) has developed methods by which the long-term motion of comets with large eccentricities may be investigated, and thus the diffusion of streams associated with them delineated.

5. The physics of meteoroid streams

In the previous sections of this chapter the main point of discussion has been meteoroid astronomy; to complete this review I will made a brief mention of some aspects of meteoroid physics, such as the masses of streams, their ages, and the physical sources of meteoroids. Although all of these topics have been touched upon above, few suitable references have been given to start the interested reader on the path to an understanding of what is known, what is not known, and what techniques have been applied.

Total stream masses have been computed by Hughes and McBride (1989). That paper reviews work on that topic, and finds that the masses of the streams generally are comparable to the estimated masses of the parent comets. This not only points to the original cometary size, but also provides an estimate of the time since the formation of the stream began. Indeed this technique was used by Jones *et al.* (1989) to derive a range of ages ($0.25\text{–}6.2\times10^4$ yr, most probably age 2.3×10^4 yr) for the Orionid (Halleyid) stream. Gustafson (1989) traces back a handful of Geminid meteoroid orbits to their parent asteroid, 3200 Phaethon, and in that ways finds an age of 600–2,000 yr, in accord with several alternate estimates using other techniques (such as the largely-invariant Geminid activity from one year to the next : Jones, 1982).

Whilst the formation and evolution of streams have been addressed in a general sense, the sources of meteoroids have not except to say that they are released from active comets, with some streams from asteroids being known; these may have been active comets when the streams formed (*cf.* the non-detection of P/Encke until two centuries ago, and P/Machholz until 1986, these perhaps being examples of re-activated comets which had undergone a period of quiescence during which they would have appeared as asteroids, if they had been observed). The supply of meteoroidal material was discussed by Whipple (1967), and more recently by, for example, Štohl (1987) and Fulle (1990).

As mentioned in section 4, the residence lifetime of meteoroids in streams is, in general, limited by the effects of close approaches to Jupiter which perturb the particles out of the stream into the sporadic background, but the limiting physical lifetime of meteoroids is due to impacts with zodiacal dust grains (Grün *et al.*, 1985; Olsson-Steel, 1986) which may also remove significant fractions of meteoroids from streams, especially for the longer-period streams which have high-speed encounters with Jupiter and are therefore largely-unaffected by such planetary encounters (*e.g.* the Perseids or the Halleyids). The deduced physical lifetimes of order 10^5 yr are supported by the solar cosmic ray exposure ages of collected dust samples (Bradley *et al.*, 1984; Sandford, 1991). However, the supply of meteoroids and their decay into interplanetary dust remain outstanding problems (Grün *et al.*, 1985).

6. Summary

In the past few years major steps forward have been taken in the search for an understanding of meteoroid streams. In my personal view, the main barrier to a near-complete understanding is our ignorance of how a meteoroid leaves its parent object : if it is accelerated to a large speed, by what mechanism does this acceleration occur?

The dynamics of streams has been a subject of considerable study, with significant breakthroughs occurring. My own personal view puts the following at the top of the list of streams of interest, if a general understanding is to be brought about, for the given reasons :

Geminids : Many individual orbits available, good rate profiles, known parent object, old stream?, very short period, $Q < 4$ AU, so never approaches Jupiter, four associated showers.

Perseids : Many individual orbits available, good rate profiles, old stream, known parent object, long period but never approaches any of the giant planets.

Taurids : Many individual orbits available, known parent (P/Encke but several Apollo asteroids also apparently related), moderate period, twelve associated showers?, orbital evolution dominated by Jovian secular perturbations.

Leonids : Good number of orbits available, known parent, young stream, recurrent storms (one due soon).

Halleyids : Good number of orbits available, known parent, old stream, stream good indicator of the history of the parent comet.

Quadrantids : Good number of orbits available, known parent, fascinating orbital evolution, eight associated showers.

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