Asteroid Meteoroid Streams

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We briefly review the methods for classifying meteoroids into streams and their association with parent bodies. Most streams have comets as parent bodies, while relatively little work has been done on streams of asteroidal origin, which also seem harder to identify. We discuss how the use of the geocentric variables introduced for stream identification by *Valsecchi et al.* (1999) can help in the identification of asteroidal meteoroid streams.

1. INTRODUCTION

Meteoroid streams consist of small solid particles released from active comets and, perhaps, from some near-Earth asteroids (NEAs). The ejection from comets takes place when they are sufficiently close to the Sun so that the volatiles on the surface of their nuclei can sublimate, carrying off particles. This process was first quantitatively described by *Whipple* (1950, 1951) for comets, but we still lack a satisfactory model for how an asteroid could produce and sustain a meteoroid stream. We observe a meteoroid when it penetrates the atmosphere and ablates, producing a meteor observable with various techniques (radar, photographic, TV), depending on its brightness.

The reason that meteoroids are often found to belong to streams, with orbits similar to that of the parent body, is that they are ejected at very low velocity relative to the parent, up to tens of meters per second in most cases, compared to the tens of kilometers per second of the heliocentric orbital speed. Thus the resulting orbital dispersion is very small immediately after the release. This dispersion, however, is bound to grow because the dynamical evolution of meteoroid stream orbits is chaotic because of the Earth-crossing condition. All streams will first increase in size, both in configuration and in orbital element space, and will eventually become totally dispersed into the background.

The problem of identifying meteoroid streams is similar to that of the identification of asteroid families. The difference between the orbits of potential family/stream members has to be measured by a suitably defined distance function, clusters have to be found among asteroid/meteor orbits, and then the statistical significance of the groupings obtained in this way has to be assessed.

If the asteroid/meteoroid, after having separated from the parent, were orbiting the Sun in the absence of any perturbation, it would continue to do so forever, and its orbital elements would bear a perennial memory of its origin. This is, of course, not the case, which leads to an important difference between the problems of asteroid families and of meteoroid streams. Main-belt asteroid orbits are not very chaotic, which allows the calculation of "proper elements," that is, quasi-integrals of motion that are stable over millions of years to possibly billions of years. This is not possible for meteoroid orbits, on the other hand, since they are strongly chaotic because they cross the orbit of at least one planet, Earth, and often cross the orbits of other planets.

However, *Gronchi and Milani* (2001) have recently introduced planet-crossing orbital proper elements for the secular problem in which the perturbations come from a number of planets in circular and coplanar orbits. These proper elements are quasi-integrals of the motion only as long as close encounters with the planets do not take place. Therefore, while the timescales over which asteroid families remain recognizable are of the order of the age of the solar system, meteoroid streams can only be recognized over much shorter timescales, typically on the order of 10^3–10^4 yr. With the steady growth of the number of known NEAs, a satisfactory solution to the problem of asteroidal meteoroid stream identification would open a further "window" to study this class of asteroids, as has happened for comets through the physical study of the associated meteors.

2. DATA SAMPLES

The public domain meteor data available at the IAU Meteor Data Center (MDC) were collected and tested for internal consistency by *Lindblad* (1987, 1991, 1999) and *Lindblad and Steel* (1994). The data at the MDC include the geocentric and heliocentric parameters of about 62,000 radar meteors and about 6000 meteors observed using optical techniques (photographic and TV). An extensive review of meteor data, including plots illustrating distributions of the orbital elements, was published by *Steel* (1996).

The quality of radar meteor data is poor in comparison with photographic data, but the precision of photographic orbits, where q and e are determined to ~1 ppt and angles to ~0.01°, is inferior to asteroidal orbits. Among photographic meteors, the dataset of highest quality, the Harvard dataset, includes 139 small-camera meteors (*Whipple,* 1954), 413 Super Schmidt meteors (*Jacchia and Whipple,* 1961), and 313 Super Schmidt meteors (*Hawkins and Southworth,* 1958, 1961), for a total of 865 precise orbits.

3. STREAM IDENTIFICATION

3.1. Distance Functions

A meteoroid stream may be defined in terms of geocentric and/or heliocentric parameters, but in any definition this measure of meteoroid orbital similarity is crucial. *Southworth and Hawkins* (1963) first formulated such a quantitative measure by drawing an analogy with a five-dimensional orthogonal coordinate system and considering each orbital heliocentric element as a coordinate. In that space, a meteoroid orbit is represented by a point, and the distance between two points is a measure of the degree of similarity between two meteoroid orbits. These authors developed all the components necessary for a computer cluster analysis:

1. Distance function D. In terms of the osculating orbital elements q, e, i, ω, Ω, for two meteoroids k and l, the D criterion for orbital similarity is defined by *Southworth and Hawkins* (1963) (D_{SH}) as

$$D_{SH}^2 = (e_k - e_l)^2 + (q_k - q_l)^2 + \left(2\sin\frac{I_{kl}}{2}\right)^2 + \left(\frac{e_k + e_l}{2}\right)^2\left(2\sin\frac{\pi_{kl}}{2}\right)^2 \tag{1}$$

where I_{kl} is the angle between the orbital planes and π_{kl} is the difference between the longitudes of perihelion measured from the common node of the orbits

$$\left(2\sin\frac{I_{kl}}{2}\right)^2 = \left(2\sin\frac{i_k - i_l}{2}\right)^2 + \sin i_k \times \sin i_l \left(2\sin\frac{\Omega_k - \Omega_l}{2}\right)^2$$

$$\pi_{kl} = \omega_k - \omega_l \pm 2\arcsin\left(\cos\frac{i_k + i_l}{2} \times \sin\frac{\Omega_k - \Omega_l}{2}\sec\frac{I_{kl}}{2}\right)$$

where the minus sign applies when $|\Omega_k - \Omega_l| > 180°$.

2. Rule for calculating the threshold value D_c for orbital similarity

$$D_c = 0.2\left(\frac{360}{N}\right)^{1/4} \tag{2}$$

where N is the meteor data sample size.

3. A stream-searching algorithm. Together with the D criterion and D_c, this leads to the definition of a meteoroid stream.

Since that time several similar D functions, all based on the orbital elements, have been proposed. In particular, *Drummond* (1981) and *Jopek* (1993) introduced modified functions, in which the relative weights of the different elements were varied with respect to those of D_{SH}.

The suitability of the above mentioned D functions was established empirically on known streams or by comparison of the results obtained by two different D functions. Many authors, starting from *Southworth and Hawkins* (1963), have proven the utility of D functions in computer stream classifications. However, all D functions based on the osculating orbital elements have a critical shortcoming: The elements q, e, i, ω, Ω, are dynamical invariants only in the two-body problem. Meteoroids are subject to other perturbations, and their orbital elements can change significantly on timescales of about 10^4 yr because of secular perturbations (*Hamid and Whipple,* 1963; *Kozai,* 1962; *Babadzhanov and Obrubov,* 1980; *Froeschlé et al.,* 1993).

Recently a new approach to the problem of measuring meteoroid orbital similarity was introduced. Based on geocentric variables, *Valsecchi et al.* (1999) proposed the following D function for two meteoroids k and l

$$D_N^2 = (U_k - U_l)^2 + w_1(\cos\theta_k - \cos\theta_l)^2 + \Delta\xi^2 \tag{3}$$

where

$$\Delta\xi^2 = \min(w_2\Delta\phi_I^2 + w_3\Delta\lambda_I^2,\ w_2\Delta\phi_{II}^2 + w_3\Delta\lambda_{II}^2)$$

$$\Delta\phi_I = 2\sin\frac{\phi_k - \phi_l}{2}$$

$$\Delta\phi_{II} = 2\sin\frac{180° + \phi_k - \phi_l}{2}$$

$$\Delta\lambda_I = 2\sin\frac{\lambda_k - \lambda_l}{2}$$

$$\Delta\lambda_{II} = 2\sin\frac{180° + \lambda_k - \lambda_l}{2}$$

and w_1, w_2, w_3 are weighting factors that can be set to 1 or can be determined on the basis of information from modeling the background or stream dispersion. The quantities U, θ, ϕ come from Öpik's theory of close encounters, described in *Öpik* (1976) and *Carusi et al.* (1990), and λ is the ecliptic longitude of the meteoroid at the time of the meteor apparition.

To define U, θ, and ϕ, let us assume that Earth moves on an unperturbed circular orbit of radius equal to 1, lying on the ecliptic, that the constant of gravity and the mass of the Sun are equal to 1, and that the heliocentric velocity of Earth is exactly $V_\oplus = 1$ instead of $V_\oplus = \sqrt{1 + M_\oplus}$. With these conventions the magnitude of the unperturbed geocentric velocity of the meteoroid $\vec{U}$ when crossing the Earth's orbit is

$$U = \sqrt{3 - \frac{1}{a} - 2\sqrt{a(1-e^2)}\cos i} \tag{4}$$

In a reference frame centered on Earth, with the z-axis perpendicular to the ecliptic, the y-axis in the direction of Earth's velocity, and the x-axis pointing away from the Sun, $\vec{U}$ has components

$$\begin{pmatrix} U_x \\ U_y \\ U_z \end{pmatrix} = \begin{pmatrix} U \sin\theta \sin\theta \\ U \cos\theta \\ U \sin\theta \cos\theta \end{pmatrix}$$

where θ is the angle between $\vec{U}$ and the y-axis (the direction of motion of Earth) and ϕ is the angle between the y-z plane and the plane containing $\vec{U}$ and the y-axis. For encounters at the ascending node, $-90° < \phi < 90°$, and for encounters at the descending node, $90° < \phi < 270°$. Expressions can be given to pass directly from any of the three sets (U, θ, ϕ), (U_x, U_y, U_z), (a, e, i) to any other (*Carusi et al.,* 1990; *Valsecchi et al.,* 1999).

In the case of meteoroids, U, θ, and ϕ can be computed from U_x, U_y, and U_z, which in turn can be calculated from the observed quantities that characterize a meteor, the geocentric velocity V_G, and the equatorial coordinates of the meteor radiant α_G and δ_G. In fact, we have

$$U = \frac{V_G}{29.8} \tag{5}$$

$$\begin{pmatrix} U_x \\ U_y \\ U_z \end{pmatrix} = \hat{\mathbf{r}}(\lambda) \times \hat{\mathbf{p}}(\varepsilon) \times U \times \begin{pmatrix} -\cos\delta_G \cos\alpha_G \\ -\cos\delta_G \sin\alpha_G \\ -\sin\delta_G \end{pmatrix} \tag{6}$$

where V_G is in km/s, $\hat{\mathbf{p}}(\varepsilon)$, $\hat{\mathbf{r}}(\lambda)$ are rotational matrixes around the x- and z-axis respectively, and the angle ε is the obliquity of the ecliptic plane to the plane of the celestial equator.

This set of geocentric parameters has an important property: U and θ are invariants of the problem in which the proper elements by *Gronchi and Milani* (2001) are defined. In fact, in the absence of close planetary encounters, the most important secular perturbation to take into account is the one related to the cycle of ω (*Kozai,* 1962). Assuming that all the perturbing planets are on circular and coplanar orbits, and furthermore assuming that the small body is not near any mean-motion or secular resonance, this secular perturbation leaves invariant the z component of the orbital angular momentum

$$L_z = \sqrt{a(1-e^2)}\cos i \tag{7}$$

and also, because of the assumed lack of close encounters, the specific orbital energy

$$E = -\frac{1}{2a}$$

But then

$$\begin{aligned} U &= \sqrt{3 - \frac{1}{a} - 2\sqrt{a(1-e^2)}\cos i} \\ &= \sqrt{3 - 2(L_z - E)} \end{aligned}$$

is constant. However, if a and U are conserved, so is cos θ, since

$$\cos\theta = \frac{1 - U^2 - 1/a}{2U} \tag{8}$$

(*Carusi et al.,* 1990). Thus, the point representing a meteoroid orbit in the U-cos θ plane does not change with time under the action of the Kozai perturbation even if both e and i undergo very large variations, such as in the case of the Quadrantids and δ Aquarids streams (*Hamid and Whipple,* 1963; *Babadzhanov and Obrubov,* 1993; *Valsecchi et al.,* 1999).

3.2. Meteoroid Association into Streams

Two meteoroids k and l are considered associated if the value of $D_{k,l}$ calculated by a distance function, does not exceed a certain threshold D_c. The choice of the threshold D_c is therefore the crucial point of any association procedure; its value can be estimated by equation (2) or the slight modification given by *Lindblad* (1971b). Both formulae are very easy to apply, but they are only approximations. According to *Jopek* (1993), the application of these formulae may not always be justified because of differing precision and statistical distributions in meteor data. Therefore, *Jopek and Froeschlé* (1997) developed a numerical procedure to obtain values of D_c for meteoroid association thresholds corresponding to the probability for the chance occurrence of a stream with a given number of members to occur in a random data sample.

A meteoroid stream may be considered as a concentration of points around some center representing the mean orbit of the stream. A number of different ways to define the concentration have been used:

1. A stream consists of the points inside a small hyperparallelepiped in the space of either the orbital elements (*Nilsson,* 1964) or the geocentric quantities V_G, α_G, δ_G, T, where T is the time of the meteor fall (*Kramer and Shestaka,* 1983).

2. A stream consists of the points inside a hypersphere of radius D_c, given *a priori*, centered at the mean orbit in the space of orbital elements, with the distance from the center evaluated with D (*Southworth and Hawkins,* 1963).

3. *Sekanina* (1970, 1976) also defined a meteoroid stream using D_{SH}, but instead of requiring that stream members be inside a hypersphere of radius D_c, he proposed an iterative procedure to determine the mean stream orbit. Consequently, a meteoroid stream is the set of points inside a hypersphere of radius D_c, but as one iterates, the center of the sphere moves until it converges to the final mean orbit.

4. *Southworth and Hawkins* (1963) used a hierarchical clustering based on the linking of the nearest neighbor. Starting from any point of the data sample, and accepting the link only if the distance is below a certain value D_c, this method can be applied either in the space of orbital elements using D_{SH} (*Southworth and Hawkins,* 1963; *Lindblad,* 1971a,b), or in the space of U, θ, φ, λ, using D_N (*Jopek et al.,* 1999).

The last definition has the advantage of not requiring any *a priori* orbital information on the meteoroid stream, while the others are useful for finding members of known streams that may exist in a given meteor sample.

The very first computer search by *Southworth and Hawkins* (1963) applied the second and fourth definitions to a sample of 359 meteoroid orbits. Since then, many authors have searched meteoroid orbits for streams, making use of one of the definitions given above in most cases. The number of identified streams has ranged from 7 to 275, with streams including from 7.5% to 83% of the searched orbital samples. This wide spectrum of results looks suspicious. The differing sizes of the meteor samples are one of the obvious reasons for the different numbers of streams detected. Other factors relate to observational selection effects, e.g., the location of the stations on Earth's surface and the timespan over which the data of a specific sample were collected.

At any rate, there are still a number of open problems: Which cluster analysis method is the best for a given meteor sample? What is the optimal way to find the threshold for meteoroid orbital similarity? What parameters should one use for this purpose? At the moment we do not have satisfactory answers to these questions, and the situation appears in some way similar to that of asteroid families in the 1980s (*Carusi and Valsecchi,* 1982; *Valsecchi et al.,* 1989), when only a small number of major families could be trusted and all the smaller ones looked questionable. Likewise, at present the reliability of most minor meteoroid streams is rather poor.

4. IDENTIFICATION OF PARENT BODIES

The fact that some comets are the parent bodies of meteoroid streams was first noticed in the nineteenth century. When meteoroid orbits began to be determined photographically, the origin of several meteoroid streams was established. The first hyphotheses about an asteroidal origin for some meteoroids can be found in works by Whipple and Hoffmeister. These hypotheses were not considered much more than speculations at the time they were put forward. [Nevertheless, Hoffmeister was always in favor of the asteroidal nature of some meteoroid streams (*Lindblad,* 1986).]

More thorough studies could take place as the number of NEA discoveries increased significantly. To our knowledge, *Sekanina* (1973, 1976) and *Drummond* (1981, 1982) were the first to make computer searches for meteoroid parent bodies among the known comets and NEAs. A notable result of these studies was the possibility that a single parent body (comet or asteroid) could give origin to more than one shower, as was confirmed by the search done by *Olson-Steel* (1988) among the southern hemisphere radio data. Furthermore, various studies (*Drummond,* 1991, 2000; *Obrubov,* 1991; *Shestaka,* 1994; *Babadzhanov,* 2001) have pointed to the existence of dynamical groups, called complexes, that include comets, asteroids, and meteoroid streams. A natural consequence of the establishment of these complexes is the hypothesis that their members originate from a single large parent body. However, many of these results seem to be uncertain, since some authors have given conflicting lists of members. The picture is further complicated since a number of NEAs are considered to be the exinct cometary nuclei, sometimes because of the presumed association with a meteoroid stream (see *Weissman et al.,* 1989).

In our opinion, these difficulties are similar to those described by *Valsecchi et al.* (1989) in the case of asteroid families, where disagreements between classifications were due to various causes, including the poor quality of proper elements and, in many cases, the absence of strict statistical criteria to assess the significance of the groupings. Improvements in both these areas over the last decade have led to a much more satisfactory situation at present (see *Bendjoya and Zappalà,* 2002). However, in the case of asteroidal meteoroid streams, we are still far behind.

Attempts to identify minor stream parent bodies among NEAs have been made with several methods using various meteor data. We prefer to discuss here the streams identified among the 865 most precise photographic meteors, in order to minimize the effects of generally low precision in meteoroid orbital data. The first search in this dataset of photographic meteors was performed by *Lindblad* (1971a) and was recently followed by another using D_N (*Jopek et al.,* 1999). The two searches give essentially equivalent results, except for some low-inclination streams, and in the following we discuss the streams found by *Jopek et al.* (1999). Table 1 reports the relevant data, i.e., the mean orbital and geocentric data for the streams, and the parent body, if known, of the streams with three or more members

TABLE 1. Stream orbital and geocentric data.

Stream Name	q	e	i	ω	Ω	V_G	θ	ϕ	Parent
Leonids	0.98	0.92	162	173	235	71	170	168	55P/Tempel-Tuttle
ε Geminids	0.81	0.96	174	231	203	70	166	258	C/1964N1 Ikeya*
Orionids	0.57	0.97	165	83	29	66	155	288	1P/Halley
Perseids	0.95	0.95	113	150	139	59	139	164	109P/Swift-Tuttle
σ Hydrids	0.24	0.98	126	122	78	58	137	295	
Lyrids	0.92	0.99	80	214	32	47	119	198	C/1861G1 Thatcher
Monocerotids	0.18	1.00	37	129	80	43	112	286	D/1917F1 Mellish
Quadrantids	0.98	0.68	72	171	282	41	116	176	96P/Machholz 1
S. δ Aquarids	0.08	0.97	27	151	308	41	118	278	96P/Machholz 1
N. δ Aquarids	0.10	0.95	21	328	142	38	117	262	96P/Machholz 1
Geminids	0.14	0.90	24	324	261	35	117	258	(3200) Phaethon
α Virginids (S)	0.32	0.87	7	118	198	31	103	275	
Taurids (N)	0.32	0.85	3	299	213	30	104	267	2P/Encke
Taurids (S)	0.34	0.82	6	118	27	28	104	275	2P/Encke
χ Orionids (N)	0.38	0.83	3	291	265	28	101	267	
α Virginids (N)	0.41	0.83	8	288	34	28	99	263	
κ Cygnids	0.98	0.76	39	202	147	25	88	194	
χ Orionids (S)	0.51	0.79	5	96	77	25	93	276	
α Capricornids (N)	0.58	0.78	6	268	134	23	89	262	45P/Honda-Mrkos-Paidušáková
ε Piscids (N)	0.58	0.76	5	268	190	22	89	263	
ε Piscids (S)	0.61	0.73	4	85	5	21	88	276	
α Capricornids (S)	0.63	0.62	4	89	329	18	89	276	45P/Honda-Mrkos-Paidušáková
α Pegasids	0.97	0.68	7	200	230	11	42	226	

* *Olsson-Steel* (1987) found that Comet C/1987B1 Nashikawa-Takamizawa-Tago is as good a candidate to be the parent of the ε Geminids as is C/1964N1 Ikeya (*Drummond,* 1981).

found by *Jopek et al.* (1999) using D_N among 865 precise photographic meteoroid orbits. The orbital elements i, ω, and Ω are given for B1950.0. All angles are in degrees, q is in AU, and V_G is in km/s. For streams identified as possessing both a northern and a southern branch, the data are given separately for each branch. The streams are listed in order of decreasing V_G, and the last column gives the presumed stream parent, taken from the literature.

There are at least two immediate conclusions that can be drawn from an inspection of Table 1: (1) In almost all cases in which a generally accepted association with a parent body has been established, the parent body is an active comet. To date, the only significant exception is the Geminid stream, whose parent is (3200) Phaeton. (2) Parent bodies have been found for almost all the streams with $V_G > 37$ km/s, and for very few others.

These two points are linked to each other because the geocentric velocities of comets are generally higher than those of asteroids. To better appreciate the situation, we can look at the distributions of meteoroids, comets, and asteroids in the U-cos θ plane as shown in Figs. 1, 2, and 3. In the U-cos θ plane, meteoroid orbits are not found everywhere below the parabolic limit curve, but rather in specific areas. The density of points varies significantly in the various regions of the plot, providing clues about their parent bodies. In fact, parent bodies might be found in the regions where the density of meteoroid orbits is high.

Looking at the distributions of comets and asteroids, one notices that the vast majority of these two classes occupy almost disjoint regions of the U-cos θ plane, with essentially very little degree of overlap. Very few asteroids can be found above the line a = 3 AU, consistent with the fact that asteroids leaving the main belt on chaotic routes associated with the 3:1 and especially the 5:2 mean-motion resonances with Jupiter are quickly removed by encounters with

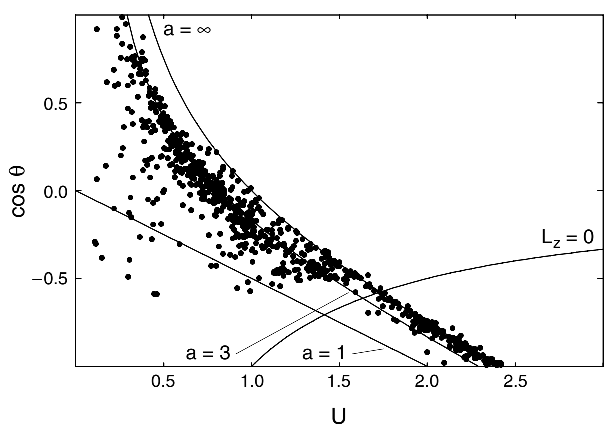

Fig. 1. The positions of 865 precisely measured photographic meteoroid orbits in the U-cos θ plane. Four continuous lines denote various conditions. The two curves going from cos θ = 1 to cos θ = –1 represent heliocentric parabolic orbits (upper curve) and orbits with a = 3 AU, the straight line on the lower left represents orbits with a = 1, and the remaining curve shows the condition $L_z = 0$.

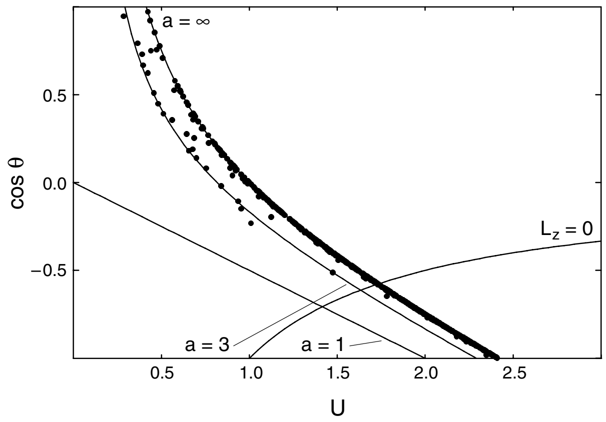

Fig. 2. The positions of comets in the U-cos θ plane. The various lines have the same meaning as in Fig. 1.

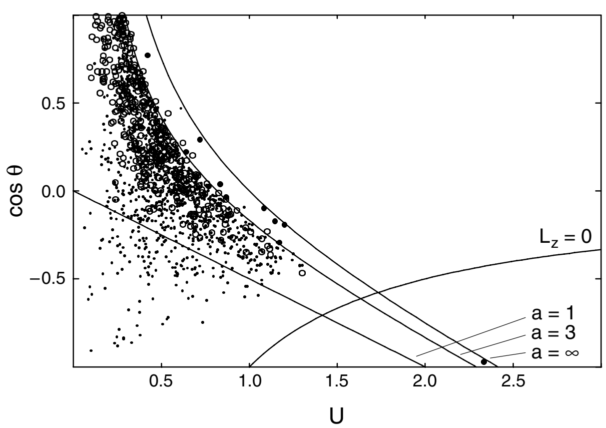

Fig. 3. The positions of Apollos, Atens, Amors, and other asteroids in unusual orbits in the U-cos θ plane. The various lines have the same meaning as in Fig. 1. Apollos and Atens are represented with small dots and are recognizable by their position with respect to the a = 1 line, Amors are represented by empty circles, and the asteroids on unusual orbits are represented by large full dots.

that planet as soon as their aphelion distances become large enough, as found in numerical integrations (*Farinella et al.,* 1994; *Valsecchi et al.,* 1995; *Gladman et al.,* 2000).

The opposite is true for comets, whose population lies almost entirely above the a = 3 AU line in a rather narrow band confined on the other side by the parabolic limit. In fact, not many Jupiter-family comets reach semimajor axes below the 2:1 mean-motion resonance with Jupiter at 3.27 AU, and only some of these can become Earth-crossing (*Fernàndez,* 1984). It must be noted that not all asteroidal and cometary orbits can be plotted on the U-cos θ plane, but only those that have values of E and L_z such that

$$T = \frac{1}{a} + 2\sqrt{a(1-e^2)}\cos i \leq 3$$

$$\left|\frac{1 - U^2 - 1/a}{2U}\right| \leq 1$$

where T is the Tisserand parameter with respect to Earth. These are necessary conditions for a small body orbit to become Earth-crossing; whether it actually can become Earth-crossing depends on the value of the Kozai integral (*Kozai,* 1962), the third proper element of *Gronchi and Milani*'s (2001) theory.

Comparing the distribution of meteoroid orbits with those of asteroids and comets, it appears clear that a sizable fraction of meteoroids, those below the a = 3 AU line, must be of asteroidal origin, because there are less than a handful of comets below that line (one of them being Comet 2P/Encke). The meteoroids in this asteroidal region, however, are found far from the few comets here.

The preceding discussion has been based on the positions of individual orbits in the U-cos θ plane, and the condition a = 3 AU has turned out to be a reasonably good discriminator between asteroidal and cometary orbits in that diagram. One may then ask, why not simply adopt the same dividing line (at a = 3 AU) in orbital-element space when analyzing meteoroid orbits? The answer has to do with the observable quantities from which the orbital elements of meteoroids are deduced, and in particular with the strong nonlinearities existing in the relationships between the two sets of quantities.

As evidenced by equation (8), the semimajor axis of a meteoroid orbit can be determined by simply measuring the magnitude of U and the angle θ. However, for a given U, we have cos θ proportional to –1/a. Therefore, a small error in the measurement of U and/or θ has a large effect on a, as shown by the varying distances among the three lines a = 1 AU, a = 3 AU and a = ∞ in Figs. 1, 2, and 3. In particular, close to the line a = ∞, and especially for negative values of cos θ, an error of, say, 3 km/s can make the difference between a hyperbolic orbit and an orbit with a < 3 AU. The fraction of meteoroid orbits whose velocity is measured to better than this accuracy is very small in nonphotographic data samples. This suggests that in order to make a meaningful search for asteroidal meteoroid streams, only good-quality photographic meteors should be used. Unfortunately, the best such unbiased data is the 865-meteor Harvard dataset discussed above, collected almost half a century ago.

5. DISCUSSION AND CONCLUSIONS

The problem of the identification of asteroidal meteoroid streams seems to be still largely unresolved. While the comparison of Figs. 1 and 3 shows that a good fraction of the photographic meteors is in the same region occupied by asteroids, Table 1 shows that the majority of low-velocity streams, those for which an asteroidal origin is more likely, still lack an identified parent body. This situation is of course unsatisfactory, but unfortunately it does not seem likely that it will change in the near future. Although it is true that the study of the dynamics of objects in Earth-crossing orbits has recently made substantial progress, both on the numerical and on the theoretical side, and we can expect an improvement in the dynamical criteria for stream identification, the obstacle seems to be the availability of high-precision meteoroid orbits.

As mentioned, the only dataset of photographic meteors with the quality needed for meaningful work on this subject is composed of only 865 orbits, and was produced a long time ago. Because of the limitations of the then-available technology, only bright meteors could be recorded, thus limiting the number of slow meteoroid orbits in the sample, which are precisely the most interesting for us since the meteor magnitude is a very steep function of V_G (*Hughes and Williams,* 2000). We therefore need a new campaign aimed at obtaining high-precision meteoroid orbits in substantial numbers, and extending over several years in order to sample the vicinity of the orbit of Earth at all longitudes. The number of orbits, as well as their precision, must be considerably higher than those in the Harvard dataset if we want to have the resolution needed to distinguish among the ever-growing number of NEAs. These goals should be achieved using precise optical and radar techniques from not only the northern hemisphere but from the southern hemisphere as well, since NEAs approaching Earth do so from all directions.

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