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The Origin of stream and sporadic meteors, comets or asteroids

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Abstract. Asteroids and Comets that come close to the Earths orbit are called Near Earth Objects (NEOs). Any dust ejected from them, meteoroid streams will formed a meteoroid stream with orbits that are similar to that of the parent body. If the Earth passes through such a stream, the meteoroids will ablate and produce meteors that are as meteor showers. In this region, orbits evolve rapidly, hence, over time the orbits of stream meteoroids will progressively diverge both from each other and from the orbit of the parent body, so that instead of being observed as a meteor shower, these meteoroids become part of the sporadic background.

When a meteor shower is observed, a similarity in the orbits should indicate the parent and several test for this are discussed. If the parent is active, then it is a comet, but if no activity is found then it could either be an asteroid or a dormant comet. In this case, the behaviour of the meteor in the atmosphere will indicate whether the parent body was likely to be an asteroid or a comet.

For sporadic meteoroids the situation is more complicated as they can not be associated with a given parent body. All that can be done is to classify the orbits as being of comet or asteroid origin. Several criteria have been proposed and applied to the present day orbits of sporadic meteors. Using a single criterion can introduce a serious bias into the results with the fraction of comet orbits understated by up to 29%. Two parameter criteria have been suggested to remove this bias. Using these criteria on a set of ∼78000 sporadic meteoroids 66–67% have comet type orbits. This fraction can differ for meteors observed by different techniques, i.e. video, photographic and radar, in general it decreases with decreasing brightness of the observed meteors.

Keywords: near-Earth asteroids, comets, parent bodies, meteors, meteoroids, meteoroid streams, sporadic meteoroids, orbital classification

1. Introduction

A meteor is the result of the ablation of a solid particle (meteoroid) in the atmosphere of the Earth. They vary in size from tens of microns (which can only be detected by radar) to several tens of meters such as the recently observed Chelyabinsk fireball that was seen with the naked eye in daylight. Meteoroids can come from any parent that releases particles into the near-Earth environment. The majority of the meteoroids in the inner solar system come from two sources, asteroids and comets, though a few originate from the surface of other solar system bodies (mostly the Moon and Mars) while a fraction may also originate from interstellar space (e.g Baggaley & Galligan, 2001; Janches et. al., 2001). In principle, meteors can be observed on any other body that has an atmosphere so that the impinging meteoroid ablates and Christou (2010) has investigated the possible occurrence of showers on Venus and Mars.

A meteor shower occurs when the number of meteors that are observed is significantly above the general background and where these meteors have a well-defined radiant on the sky. The existence of a radiant point indicates that the meteoroids were moving on parallel paths when they entered the Earth's atmosphere. To do this, they all must have similar heliocentric orbits, and so there exists in the inner Solar System families of meteoroids moving on similar orbits, meteoroid streams. Multi-station observations of these meteors allow the orbital elements of the heliocentric orbit to be determined. This gives a strong indication of parentage of the stream. The historical development of ideas concerning the association of meteoroid streams with asteroids and comets can be found in Williams (2011). In a comet, there are two principal ways in which a meteoroid stream can be formed. As a comet approaches the sun, solar heating causes the ices to sublimate and the resulting gas outflow carries away small dust grains with it as was first proposed by Whipple (1951). Others (e.g. Crifo 1995; Ma, Williams & Chen 2002) have modified this model, but the results are similar with the ejection velocity of the meteoroids generally being less than a few 100 ms^{-1}. Many comets have been observed to either fragment or totally disintegrate. Such a process will also release a large number of meteoroids. Again, the speed of the meteoroids relative to the nucleus will be small.

In the case of asteroids, the number of mechanisms that can cause meteoroid ejection is larger, for example inter-asteroid collisions, internal re-adjustment, tidal effects and a YORP spin-up leading to rotational instability. The mechanism that will form the strongest streams is a collision, as was initially suggested by Piotrowski (1953) and Fesenkov (1958). Proof that asteroids can indeed release dust in this manner came with the image of 2010A2 (Linear) an asteroid with a dust tail caused by a collision between two asteroids, in 2009 (Jewitt et al., 2010; Snodgrass et al., 2010). The velocity of the meteoroid relative to the parent asteroid will still be small compared with the heliocentric velocity. Thus, in all cases the orbit of the parent and the initial orbits of the meteoroids will be similar and a meteoroid stream is formed. (For a mathematical formulation of the physics involved, see Williams, 2002, 2004).

Individual meteoroids can experience significantly different perturbations, for example through a close planetary encounter resulting in significant orbital changes (Hughes, Williams & Fox, 1981; Jenniskens, 1998).

An other important effect is solar radiation, through radiation pressure and the Poynting-Robertson drag, first discussed in the context of meteoroids by Wyatt & Whipple (1950) and reviewed by Klacka & Williams (2002). Other processes may also remove meteoroids from the stream, for example, collisions between stream meteoroids and its parent (Williams et. al., 1993) or collisions with interplanetary dust particles (Trigo-Rodriguez et. al., 2005). Hence, as the stream gets older, meteoroids are lost from it, while the population of meteoroids moving on independent orbits gets fed. This population gives rise the sporadic meteor population, which is more numerous than the population of meteors in showers, with only 25-35% being in showers. By the very way they come into existence, the sporadic meteors can not be associated with any given parent body and all that might be inferred is whether its original orbit was likely to be similar to those of asteroids or comets. The purpose of this paper is to critically review the methodologies used and results obtained in determining the relative proportions of meteoroids originating from asteroids and comets.

2. Methods for determining the parent of a meteor

2.1. Density considerations

It is to be expected that the bulk density of a meteoroid which originated from a rocky or metallic asteroid would be of the order of 3000 kg m^{-3} or higher while one originating from a comet would be between 500 and 1000 kg m^{-3}. A few meteoroids reach the surface of the Earth as meteorites. All those have bulk densities that roughly match those of asteroids. However, there is a selection effect here, only relatively strong meteoroids can survive the passage through the atmosphere. The number of meteorites that can be associated with a specific asteroid or comet based on its orbit prior to encountering the Earth is very small, of the order of 10 and so no conclusions can be drawn regarding the general percentage of meteoroids originating from comets or asteroids.

There are other difficulties in using the density as the main discriminator for determining the parentage of meteoroids. First, it is necessary to determine both the deceleration and brightness of the meteor as it passes through the atmosphere and any errors in measurement can significantly alter the results. Determining the deceleration requires a measurement of the velocities at various points, necessitating multiple site observations with accurate timings. This introduces a strong bias towards brighter meteors that are in streams. Second, the derived density depends critically on the model used for the ablation and in particular whether or not fragmentation takes place. Assuming that meteoroids were porous and crumbly, Jacchia et al.(1967) obtained a typical bulk density for meteoroids of 260 kg m^{-3}, while Verniani (1969) found from 140 kg m^{-3} to 630 kg m^{-3} for stream meteoroids and 280 kg m^{-3} for sporadics. Ceplecha (1958) modelled the ablation based using the heat conductivity equation through a solid body and found (Ceplecha, 1967) that meteoroid densities lay in the range $1400-4000$ kg m^{-3}, an order of magnitude higher. With the same model, Babadzhanov (1993) found that the densities ranged from 2500 kg m^{-3} for the Leonids, to 5900 kg m^{-3} for the Geminids. Thus, if it is assumed that the meteoroid structure is comet-like, a comet-like density is obtained, while assuming an asteroid structure give an asteroid density. Babadzhanov (2002) improved the model and found a range from 400 kg m^{-3} for the Leonids to 2900 kg m^{-3} for the Geminids.

There is also the problem that, while a comet nucleus is primarily composed of water-ice and is very porous, there are embedded within it small non-icy particles that become meteoroids and these could have a higher density. Conversely, asteroids can have crumbly meteoroids on their surface. Hence, it is not surprising that up to now the major tool for determining a pairing of parent and stream has been orbit similarity.

2.2. Orbital similarity

A number of authors have proposed criteria to quantify the differences between two known orbits, for example Southworth & Hawkins (1963), Drummond (1981), Steel, Asher & Clube (1991), Jopek (1993), Valsecchi, Jopek & Froeschlé (1999), Jopek et al. (1999, 2008), Nesvorny & Vokrouhlicky (2006). These were summarised in Jopek & Williams (2013). The relationship between well-known meteor showers and comets have been firmly established using one of these criteria. The best known are the Perseids and 109P/Swift-Tuttle, the Leonids and 55P/Temple-Tuttle, the October Draconids and 21P/Giacobini-Zinner and both the Orionids and the Eta Aquariids with 1P/Halley. There are two associations between bodies that have been designated as asteroids and very major showers,(3200) Phaethon and the Geminids and (196256) 1993EH1 and the Quadrantids. Many asteroids have been suggested as being associated with the Taurid complex. There are many other established pairings between both comets and asteroids and streams. Lists can be found in books such as Jenniskens (2006).

There are a number of questions that arise when claims are made that a particular body is the parent of a given stream based on orbital similarity. First, is the orbital similarity due to chance. If it is, then we can draw no conclusions regarding the cometary or asteroidal origin of that stream. The systematic monitoring of the skies, has led to a vast increase in the number of known NEOs. Babadzhanov, Williams & Kokhirova (2008a) calculated that there is a 1/5 chance that a randomly chosen set of orbital elements will match the orbital elements of some NEO. Further, the typical period of variations in the orbital elements of Near-Earth asteroids is 5000 to 10000 years (see for example Babadzhanov, Williams and Kokhirova, 2012) so that even if orbits were not initially similar, orbital changes can cause them to become similar at the present time. Porubčan, Kornoš & Williams (2004) suggested that similarity of orbits should be maintained for 5000 years before a generic association could be claimed. Second, if the association is genuine, the question of whether the stream formed through dust ejection from the associated asteroid or did the dust came from a comet that has since become dormant or disintegrated leaving dormant fragments that are now indistinguishable from asteroids. Meteoroid stream can be formed through mutual collisions between asteroids. Streams formed in this way contain far less mass and are far more diffuse than those from a comet origin (Williams, 1993) but the Geminids, the Quadrantids or the Taurids are all very massive streams.

According to Wiegert, Houde & Peng (2008), the probability of a chance alignment between (3200) Phaethon and the Geminids is less than 0.001. Soon after the discovery of (3200) Phaethon, Fox, Williams & Hughes (1983) pointed out that it had all the characteristics necessary to be the parent of the Geminid meteoroid stream assuming that ejection takes place continuously over a wide range of true anomaly, or comet-like. Other papers confirm that the structure of the stream is best explained by ejection from a comet (Hunt, Williams & Fox, 1985; Williams & Wu, 1993a; Ryabova, 2001; 2007), but no comet on the required orbit has been found. Phaethon brightened by at least 2 magnitudes on 2009 June 20 (Battams & Watson 2009), though no activity had been observed prior to that date (Hsieh & Jewitt 2005; Wiegert, Houde & Peng 2008). Ryabova (2012) concluded that meteoroids ejected during this outburst could be seen as a weak meteor shower in 2050, but such outbursts can not be the source of the vast majority of meteoroids in the very strong Geminid stream. Asteroid 2005 UD and 1999 YC have very similar orbits to that of Phaethon (Ohtsuka et al., 2006, 2008; Jewitt & Hsieh, 2006; Kinoshita et al., 2007; Kasuga & Jewitt, 2008), giving support to the comet fragmentation hypothesis.

Despite its strength and regularity in the current epoch, no records of the Quadrantids exist prior to about AD1800. Integrations (Murray, Hughes & Williams,1980; Hughes, Williams & Fox, 1981; Froeschlé & Scholl, 1982, 1986; Babadzhanov & Obrubov, 1987; Wu & Williams 1992) show that large changes in the orbital element of the Quadrantids take place over a few thousand years, which may explain the lack of early observations. However, it is also possible that the strong stream we observe today only formed a few centuries ago as was suggested by (Wiegert & Brown, 2004; 2005). No present-day comet has been unambiguously associated with the stream, though there have been many contenders (see Williams et al. 2004). McIntosh (1990) suggested that comet 96P/Machholz was a possible candidate since the orbits were similar several millennia ago. The characteristics of the orbital evolution of the comet and stream are also very similar, both showing changes with a 4000-yr period (Gonczi Rickman & Froeschlé 1992), but this requires the stream to have formed at least several millennia ago. The narrowness of the central peak in the activity profile led Jenniskens et al.(1997) to conclude that most of the meteoroids observed today are quite young. The mean orbit of the Quadrantids was integrated back to 1491 by Williams & Wu (1993b) and these elements are in remarkably good agreement with those given by Hasegawa (1979) for C/1490 Y1. Jenniskens (2004) suggested that 2003EH1 was a fragment from the break-up of C/1490 Y1 while Williams et al. (2004) showed that the orbit of 2003 EH1 in 1490 could produce the path on the sky described by Hasegawa. Comet 96P/Machholz is known to fragment and a possible scenario is that several millennia ago it fragmented, with a smaller part becoming C/1490 Y1. A fragmentation of C/1490 Y1 a few hundred years ago produced 2003 EH1 as well as a large number of meteoroids that are responsible for the strong narrow peak in the activity curve.

The Taurids can not be regarded as a single stream with many radiants located in both Taurus and Aries (Denning, 1928). Numerous authors (Olsson-Steel 1988; Babadzhanov, Obrubov & Makhmudov 1990; Štohl & Porubčan 1990; Steel Asher & Clube 1991) agree that the stream is a complex of several smaller meteoroid streams and filaments. Unlike the Geminids and the Quadrantids, the Taurids has an active comet, 2P/Encke associated with it. Many asteroids are also in the complex (Asher, Clube & Steel, 1993a; Clube & Napier (1984); Steel & Asher, 1996; Asher, Bailey Emel'yanenko, 1999; Babadzhanov, 2001; Porubčan Kornoš & Williams, 2006;

Table 1. The percentage of 7830 NEAs and 780 periodic comets not correctly classified by the various criteria.

Q [%]	E [%]	T [%]	Pe [%]	K [%]	
3.9	3.8	7.2	10.7	16.4	NEAs
1.0	1.5	2.2	5.8	13.8	Comets

Babadzhanov, Williams & Kokhirova, 2008b; Napier, 2010; Jopek, 2011). Asher, Clube & Steel (1993b) suggested that the whole complex could, have formed by the fragmentation of a giant comet 20-30 Ky ago.

Thus the population of meteoroids in known streams is dominated by those of cometary origin. For the sporadic meteors, there is by definition, no associated parent body and so the criterion for similarity of orbits discussed above can not be used and different methodologies have been developed.

2.3. Differentiating between types of orbits

In order to discriminate between the orbits of comets and asteroids, Whipple (1954) proposed $K = \log\left[a(1+e)/(1-e)\right] - 1$, the K-criterion. When $K \geqslant 0$ the orbit is of a comet type. Using this K-criterion Whipple (1954) found that 96% of known comets and 99.8% of known asteroids were correctly classified. The criterion can also be applied to meteoroids, and Whipple classified 90% of 144 bright photographic meteors as being of comet origin.

Several other criteria can be used. The T-criterion is based on the Tisserand invariant: $T = a^{-1} + 2a_J^{-1.5}\left[a(1-e^2)\right]^{(0.5)}\cos I$ where a_J is the semi-major axis of Jupiter's orbit and I the inclination of the meteoroid orbit relative to the Jupiter orbital plane. Kresak (1969) used the condition $T < 0.58$ to define a comet type orbit. Variants of this criterion are widely used in the NEO field (eg Jewitt, 2012; Babadzhanov, Williams & Kokhirova, 2013).

Two additional criteria, the P and Q criterion defined by $P = k^2 a^{1.5} e$, where k is the Gauss gravity constant and $Q = a(1+e)$ were proposed by Kresak (1967, 1969). For a comet orbit $P > 2.5$, and $Q > 4.6$ AU. Q is aphelion distance and so this condition simply requires that the orbit does not go beyond the asteroid belt.

Jopek & Williams (2013) proposed a new criterion, the E criterion (the orbital energy E) given by $E = -0.5k^2 a^{-1}$ with $a > 2.8$ AU for comet orbits.

The reliability of these methods was investigated by Starczewski & Jopek (2004). The Q-criterion proved to be the most reliable, producing the smallest number of exceptions. Jopek & Williams (2013) repeated this reliability test, applying all the criteria to the orbits of 780 comets given in Marsden & Williams (2008) and 7830 near-Earth asteroids given in the NEO Dynamic Site, 2012. Their results are summarized in Table 1. It is clear that the Q and E criterion are the most reliable while the K criterion produced the most exceptions.

3. Comet-asteroid classifications applied to meteoroid orbits

3.1. Historic investigations and recent works

To classify meteoroid orbits the various criteria have been used by several authors. Using the K-criterion, Whipple (1954) found that 90% of 144 orbits obtained using a small camera, 90% were of comet type. However this sample contained many stream meteoroids. Using photographic data obtained by Super Schmidt cameras Jacchia et al. (1967) found that 99.8% of orbits were of comet type, while Jones & Sarma (1985) found that the TV meteors were about equally divided into comet and asteroid types. Steel (1996a) found more comet orbits within photographic data but roughly the same number of orbits of both types amongst the Canadian TV meteors and the Adelaide radio meteors. However, in the Kharkov radio meteors he found more asteroid orbits a result contradicted by Voloshchuk et al. (1997) who that found 63% of the Kharkov meteors were on comet orbits. Using the Q-criterion and selecting only sporadic meteors, Starczewski & Jopek (2004) found that 78% radio meteors, 48% of photographic and 53% of video meteors moved on asteroid type orbits. For the photographic and video meteor samples, the results of Starczewski & Jopek are consistent with those given by Steel (1996a), but for radio meteors are very different from those of Voloshchuk et al. (1997).

Jopek & Williams (2013) studied approximately 78000 observations of meteors collected from many sources. From this data set, only elliptical orbits which passed the internal consistency check (see Jopek et al. 2003) were used. The primary aim of the investigation was to investigate sporadic meteors and so stream meteors were removed using the method described in Jopek et al. (2008).

3.2. Discussion of the results of the C-A classification

Jopek & Williams (2013) used all the criteria listed earlier so that differences between them could also be assessed. Their results are summarized in Table 2. The E-criterion gives the smallest fractions of meteoroids moving on comet orbits, with the fraction increasing through the Q, P and T-criterion, the K-criterion giving the largest. The differences between the results obtained are in the range 10-15%. Jopek & Williams (2013) illustrated the reason for the differences in reliability by means of plots of $1/a$ against e showing the threshold values of all the criteria discussed above. The observed meteoroids must lie between the boundaries $Q = 1$ and $q = 1$, and they occupy almost all this region. The E-curve occupies the lowest position in the region so that all the meteoroids classed by the E-criterion as comet were classed as comet by all the other criteria. Starczewski & Jopek (2004) used a similar classification method and partly used the same meteor data as Jopek & Williams (2013). Two discrepancies between them are clear. First, Starczewski & Jopek (2004) found lower fractions of comet orbits amongst all sporadic meteoroids and also amongst the data obtained by each observation techniques. In general Jopek & Williams found about 20% more sporadic meteoroids moving on comet orbits with the increase being smallest for the radio meteoroids and highest for the video data. Jopek & Williams used a larger sample of the video meteoroids, mainly obtained by SonotaCo group (SonotaCo 2009, 2011) where the mean magni-

Table 2. C - A one parameter classification. In the separate rows we give the percentages of meteors among the whole sporadic component, radar, video and photographic meteors, respectively. The last part gives the results by Starczewski & Jopek (2004).

Q [%]	E [%]	T [%]	P [%]	K [%]	Sample size and type	
44.0	41.8	56.8	49.0	61.8	77869	all meteoroids
23.4	21.4	36.1	28.1	44.8	45539	radio -,-
73.4	71.0	86.6	78.9	86.1	30899	video -,-
65.5	59.6	70.6	68.4	76.5	1431	photo -,-
23.6	-	35.5	28.7	42.8	55891	all meteoroids
22.2	-	34.0	27.1	41.4	52993	radio -,-
46.9	-	64.9	54.2	63.6	1221	video -,-
51.7	-	60.2	62.4	71.7	1677	photo -,-

tude was -1^m, so that they should probably be regarded as "photographic" rather than video. The orbits used by Starczewski & Jopek (also included in the Jopek & Williams set) obtained using cameras in Canada and Ondrejov had a limiting magnitude of 6^m–8^m.

The second discrepancy concerns the small but clear differences between the percentages of comet orbits found amongst both the radio meteors and the photographic meteors, where the same sources were used. However, different methods were used to eliminate the stream component. Starczewski & Jopek (2004) made only a limited search for streams, finding that only 15% of the sample belongs streams while Jopek & Williams (2013) found that 33.4% were in streams. Thus more comet orbits were eliminated. It is clear that the results depend on how well the stream component is eliminated.

4. Limitation of the one parameter C-A classification

The foregoing discussion shows that the conclusions depend on the criteria used. This is illustrated in Figure 1, reproduced from the paper of Jopek & Williams (2013). According to the Q-criterion, all meteoroids with $Q < 4.65$ are moving on asteroid type orbits. However, in Figure 1, there are many such meteoroids for with $i > 75°$. Very few real asteroids have such high inclinations and only one NEA, (2009 HC82), with $Q < 4.6$ [AU] and $i > 75°$ exists. There are no comets with such orbital properties. Therefore, the source of all sporadic meteoroids found in this region of the plot is an interesting question. The highest fraction of such orbits, 28% were in radio meteor data, with 15% in the video data and only 5% in the photographic data. These meteoroids are thus predominantly small.

With the E-criterion (see Figure 1), a similar percentage (23.2%) of "asteroid" meteoroids move on orbits for with $i > 75°$. For the remaining criteria the percentages of such "asteroid" meteoroids can be found in the paper of Jopek & Williams (2013) and are of the same order.

Some insight into the source of these sporadic meteoroids with $Q < 4.6$ AU and $i > 75°$ can be obtained by using the Hammer-Aitoff equal area diagram. It was first used by Hawkins (1956) and by many others since (eg Elford & Hawkins,

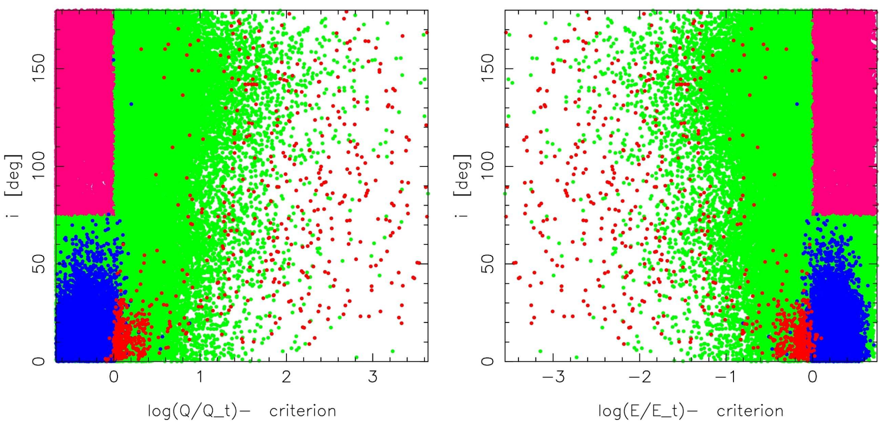

Figure 1. Left panel — 780 Comets (red), 7830 NEAs (blue) and 60412 sporadic meteoroids (green) on the i-$log(Q/Q_t)$ plane. Additionally, 17457 "asteroid" meteoroids for which inclinations $i > 75°$ and aphelia distances $Q < 4.6$ [AU] are plotted as magenta rectangles. The right panel — 780 Comets (red), 7830 NEAs (blue) and 59810 sporadic meteoroids (green) on the and i-$log(E/E_t)$ plane. Additionally, 18059 "asteroid" meteoroids for which the inclinations $i > 75°$ and the semi-major axes $a < 2.8$ [AU] are plotted as magenta rectangles.

1964; Sekanina, 1973; Galligan & Baggaley, 2005; Campbell-Brown 2008). Jopek & Williams (2013) found that for the 60412 meteoroids with $Q > 4.6$ [AU] or $i < 75°$, (all the meteors that we are NOT interested in) the regions corresponding to the helion, antihelion, north and south apex and north and south toroidal concentrations, first identified by Elford & Hawkins (1964), were all visible. On the other hand, the 17457 meteoroid with $Q < 4.6$ [AU] and $i > 75°$ were connected only with the apex concentration, with essentially none elsewhere. These meteoroids entered the Earth atmosphere with a speed $V_g > 30$[km/s].

4.1. The origin of meteoroids with $Q < 4.6$ AU and $i > 75°$

According to Davies (1957), the aphelion distance of small meteoroids moving on high-inclined orbits would be reduced on realistic time-scales so that the orbits became more circular. Dycus & Bradford (1964) confirmed that P-R drag can decrease the aphelion of comet type orbits, changing the trajectories to asteroid type. Arter & Williams (1995) showed that P-R drag reduced the aphelion of meteoroids in the April Lyrids shower. Jones et al.(2001), Wiegert et. al. (2009) and Nesvorny et. al. (2011) have shown that the apex and toroidal meteoroids may originate through this mechanism from long period or Oort Cloud comets. Therefore the observed meteoroids moving on highly-inclined "asteroid" orbits evolved similarly and are of comet origin. With such a large influx of meteoroids that originated in comets, but now miss-classified as on asteroid type, it is clear that none of the one parameter criteria proposed to date are able to correctly classify all sporadic meteoroids and that the asteroid population is overstated.

Table 3. Cometary orbits among the sporadic meteoroids. The fractions in percentages, were found by the two parameters C-A classifications (see the text). In round brackets the limiting magnitude of the observation system are given. Notation e.g. $Mg > 2^m$ means that only meteors fainter then 2 magnitude has been classified.

Q-i [%]	E-i [%]	T-i [%]	P-i [%]	K-i [%]	Sample size	Sample type and remarks
66.4	66.9	70.3	69.4	78.4	77869	all meteoroids
51.3	49.9	56.0	54.6	67.8	45539	radio orbits
88.5	87.2	91.3	91.1	95.2	30899	video orbits
68.0	64.4	72.3	72.0	79.2	1431	photo orbits
48.3	43.4	54.9	55.2	61.9	286	photo bolides
67.5	63.1	71.3	70.7	79.7	670	photo Super Schmidt
80.6	78.7	84.2	83.8	88.8	475	photo small camera
59.9	58.1	63.7	63.0	68.6	322	video Canada ($+8.5^m$)
70.5	68.7	73.0	73.2	82.3	485	video Ondrejov ($+5\text{-}6^m$)
86.3	85.5	88.0	87.3	91.3	393	video DMS ($+6^m$)
88.9	87.7	91.9	91.5	95.7	7816	video SonotaCo 2007
90.0	88.8	92.7	92.6	96.0	9318	video SonotaCo 2008
88.6	87.2	91.5	91.3	95.7	12565	video SonotaCo 2009
55.9	54.1	60.0	60.6	74.1	170	video Ondrejov $Mg > 3^m$
69.0	67.8	74.7	72.4	82.8	87	video SonotaCo 2007, $Mg > 2^m$
70.9	70.9	75.7	75.7	80.6	103	video SonotaCo 2008, $Mg > 2^m$
64.4	61.6	70.5	71.1	83.5	315	video SonotaCo 2009, $Mg > 2^m$
62.2	59.6	67.2	66.2	83.3	1397	radio Adelaide1 ($+6^m$)
65.9	63.5	71.1	69.6	83.4	1106	radio Adelaide2 ($+8^m$)
46.3	44.8	51.8	50.0	65.2	14335	radio Harvard1 ($+12\text{-}13^m$)
41.9	40.6	47.1	45.2	56.7	13968	radio Harvard2 ($+12\text{-}13^m$)
56.3	55.0	59.4	58.6	69.4	4136	radio Kharkov ($+12\text{-}13^m$)
74.0	73.1	76.9	75.8	80.8	6637	radio Obninsk ($+6\text{-}8^m$)
52.0	49.5	56.2	56.3	82.6	3960	radio Mogadishu ($+6\text{-}8^m$)

5. Two parameter C-A classification

To overcome this, Jopek & Williams (2013) proposed that a two parameter approach should be adopted by adding inclination to each of the other criteria that have been discussed. Thus, if $i > 75°$ the meteoroid is classed as comet type, irrespective of what the previous classifications determine. The new classifications are listed in full in Jopek & Williams (2013).

Jopek & Williams applied these new constraints to the sample of ~ 78000 sporadic meteoroids and found that, as expected, the fractions of comet meteoroids becomes significantly higher. The detailed results are reproduced in Table 3.

Both the *Q-i* and *E-i* criteria, now show that, 66–67% of the sporadic meteors were on comet orbits, the smallest fraction, 50–51%, was found among the radio meteors. For the video and photographic sub-samples, the fractions on comet orbits were 87–89% and 64–68%, respectively.

As mentioned earlier, Jopek & Williams and Starczewski & Jopek used different video samples in their analysis. To remove this discrepancy, in the "video" section in Table 3 the results for each video sub-sample used by Jopek & Williams are given. It can be seen that the fraction of meteoroids on comet orbits observed in Canada is about 30% less than in case of the meteors observed in Japan by SonotaCo. The meteors observed in Japan and Canada correspond to different ranges of magnitudes, the mean magnitude of meteors observed by SonotaCo being -1^m, but for meteors observed in Canadian the mean magnitude was close to 4.5^m.

Concentrating only on the faint meteors by removing all meteors with absolute magnitudes $Mg < 3^m$ from the Ondrejov results and $Mg < 2^m$ from the SonotaCo data, the fraction of meteors on comet orbits in the Ondrejov data is 14% less. In case of the SonotaCo data number classified as comet type orbits decreased by 14–20%.

Different results were found amongst the radio data. The smallest fraction 40–42% of meteors on comet orbits occurred among the Harvard2 "synoptic year" sample. For the Harvard1 sample, using the same criteria, the results were 4% higher. In the radio data from the Kharkov radar with a similar sensitivity to the Harvard equipment, comet orbit accounted for 55–56% of the total. A significantly less sensitive radar was used in Mogadishu and the percentage of meteors on comet orbits is smaller, 50–52%.

The radar equipments used in Adelaide and in Obninsk have a sensitivity comparable to that used in Mogadishu. In the Australian data many more meteoroids were found to be moving on comet type orbits. Some of these discrepant results are probably caused by selection effects arising from the observing strategy used. For example the Obninsk radio meteor data consist solely of meteors observed at their descending nodes, and hence all observed radiants have ecliptic latitude $\beta \geqslant 0$, but there is insufficient data available on most of the observing strategies to allow a definitive conclusion to be reached.

In the photographic results, the fraction on comet orbits was low, 43–48% .

6. Conclusion

The meteoroid associated with the three major streams, the Geminids, the Taurids and the Quadrantids, were mostly of cometary origin, though there are bodies that are classified as asteroids associated with them.

To classify the sporadic meteoroids properly into comet or asteroid populations a two parameters criterion needs to be used. Using only one parameter criteria causes the fraction of sporadic meteoroids on comet type orbits to be understated. For the photographic meteors, the underestimation is quite small, 2–5%. In case of radio data, the underestimation can reach 15–29%.

This underestimation comes about because there are many orbits that are classified as asteroid ($Q < 4.6$ AU) but are on high inclination orbits ($i > 75°$). These are mostly meteoroids that were originally on comet orbits but where P-R drag has reduced the aphelion distance Q so that they now satisfy the Q-criterion for being classed as asteroid type.

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