Stream and sporadic meteoroids associated with near-Earth objects

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ABSTRACT

Near-Earth objects (NEO) are objects that come close to the Earth's orbit. If dust is ejected from them through any process, a meteoroid stream will form which may be seen on the Earth as a meteor shower. As orbits evolve rapidly in this region of the Solar system, a similarity of orbits at the present time is not sufficient to prove a relationship; integrations are needed to show that the evolution over a substantial period of time is similar.

Characteristics of streams where the parent is a comet and dust is ejected over a range of values of true anomaly and over several orbits will be very different from a stream formed through the ejection from an asteroid which is likely to occur at a single point in time. Hence a study of meteoroid streams related to NEO may tell us whether the NEO is a comet or an asteroid. In particular, several showers can be associated with the same stream if it is from a cometary origin.

Sporadic meteoroids cannot be associated with a single parent body. We can classify them only as of cometary or asteroid origin. In the past, for this purpose several dynamical criteria have been proposed, e.g. \( K \)-, \( Q \)-criterion, and they were applied to the present-day orbits. We have shown that such an approach may introduce a serious bias into the results – the fraction of cometary orbits can be understated by up to 29 per cent. To remove such a bias, we propose that a two-parameter criterion is used. Assuming that comet and near-Earth asteroids (NEA) populations are disjoint, the \( Q \)-i and \( E \)-i criteria proved to be the most reliable tool for dynamical discrimination of the NEO population. Using these criteria we have found that in our sample of sporadic meteors cometary type orbits predominate, in a set of \( \sim 78000 \) sporadic meteoroids 66–67 per cent have cometary type orbits. This fraction can differ for meteors observed by different technique; in general, it decreases with decreasing brightness of the observed meteors.

Key words: methods: numerical – comets: general – meteorites, meteors, meteoroids – minor planets, asteroids: general.

1 INTRODUCTION

A meteor is the result of the ablation of a solid particle (meteoroid) in the upper atmosphere of the Earth. Meteoroids can come from any parent that releases solid 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 it is possible that a fraction also originate from interstellar space (e.g. Baggaley & Galligan 2001; Janches et al. 2001). A meteor shower occurs when the number of observed meteoroids is significantly above the general background and where these meteoroids have a well-defined radiant on the sky. This implies that they all have similar heliocentric orbits and so they originate from a meteoroid stream whose orbital elements can be determined and this can give a strong indication of its parentage. However, the majority of observed meteoroids appear randomly, both in time and in position and are called the sporadic background. Determining the parentage of these sporadic meteoroids is a much harder task than for shower meteors.

Initially, it was believed that shower meteor originated in comets; Kirkwood (1861) suggested that they were debris of ancient comets, though others had earlier hinted at a connection. This connection was confirmed with the observed disintegration of comet 3D/Biela and the associated Andromedids meteor shower (see Williams 2011, for a review of this topic and relevant references). The notion that meteor showers could be associated with asteroids is also quite old, having first been suggested by Olivier (1925) and somewhat later by Hoffmeister (1937). Following the great expansion in radar observations of meteors some 50 years ago, Sekanina (1973, 1976) identified a number of new weak meteoroid streams and suggested...
that asteroid 2101 Adonis was associated with the σ Capricornids meteor shower.

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 through gas drag. Whipple (1951) investigated this and produced an expression for the ejection velocity $V$ of the meteoroids relative to the comet nucleus of radius $R_\text{c}$ in kilometres at a heliocentric distance $r$ in astronomical units as

$$V^2 = 4.3 \times 10^5 R_\text{c} \left( \frac{1}{br} + 0.013 R_\text{c} \right),$$

where $\sigma$ and $b$ are the bulk density and radius of the meteoroid, and all the other quantities are in cgs units. Others (e.g. Crifo 1995; Jones 1995; Ma, Williams & Chén 2002) have modified this model, but the results are similar with the velocity generally being less than a few 100 ms$^{-1}$. It is also possible that the comet nucleus may fragment or totally disintegrate, but the dust speed relative to the nucleus is still of a similar magnitude. In the case of asteroids, the number of mechanisms that can cause meteoroid ejection is larger, for example inter-asteroid collisions, leading to either disruption or cratering; internal re-adjustment leading to a release of energy; tidal effects and Yarkovsky-O'Keefe-Radzievski-Paddack (YORP) spin-up leading to rotational instability, but the velocity will still be in the same general range.

Thus, in all cases, a large number of meteoroids are released from a parent with velocities that are small compared to the orbital speed of the parent so that a stream is generated. This implies that the orbit of the parent and the initial orbits of the meteoroids will be similar. [For a description of all the physics and mathematics involved in the process, see for example Williams (2002), or a shorter version in Williams (2004).] An individual meteoroid can experience significantly different perturbations from the others, for example through a close planetary encounter (Hughes, Williams & Fox 1981; Jenniskens 1998). In this case, though the majority of the meteoroids will over time behave similarly a significant number will at any given time be moving on a different orbit. A further possibility is that some of the meteoroids become trapped in a resonance so that those particular set of meteoroids will preserve their initial structure, but the remainder will evolve very differently (Froeschlé & Scholl 1986; Wu & Williams 1995; Asher, Bailey & Emel’yanenko 1999). Other processes may also play a role in the evolution of a stream. For example, mutual collisions between stream meteoroids and its parent (Williams et al. 1993) and fragmentation or collisions with interplanetary dust particles (Trigo-Rodríguez et al. 2005). Hence, as the stream gets older, eventually resulting in a set of sporadic meteors, it becomes harder to determine whether its parent was an asteroid or a comet.

2 METHODS FOR DETERMINING THE PARENT OF A METEOR

In principle, it is to be expected that a meteoroid which originated from an asteroid would have a bulk density of the order of 3000 kg m$^{-3}$ while one originating from a comet would have bulk densities of the order of 500 kg m$^{-3}$. There are two main difficulties in determining the density of a meteoroid from studies of the meteor. First, it is necessary to determine both the deceleration and the brightness of the meteor as it passes through the atmosphere and any errors in measurement can significantly alter the determined orbit. Secondly, 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, Verniani & Briggs (1967) obtained 260 kg m$^{-3}$ as the typical bulk density of meteoroids, while Verniani (1969) found that the bulk density of meteoroids in showers varies from 140 to 630 kg m$^{-3}$ while the average for sporadic meteoroids was 280 kg m$^{-3}$. In contrast, Cephele (1967) found that meteoroid densities lay in the range 1400–4000 kg m$^{-3}$, an order of magnitude higher. Babadzhyanov (1993) found that the densities ranged from 2500 kg m$^{-3}$ for the Leonids to 5900 kg m$^{-3}$ for the Geminids. Somewhat later, Babadzhyanov (2002) improved his model and found a range from 400 kg m$^{-3}$ for the Leonids to 2900 kg m$^{-3}$ for the Geminids. The range of values obtained makes using bulk densities alone a rather unreliable tool for determining the parentage of a meteoroid.

A few meteoroids do reach the surface of the Earth as meteorites, but the number that can be associated with a specific asteroid or comet based on a determination of its orbit prior to encountering the Earth is very small, of the order of 10. All those confirmed to date have an asteroid as a parent and the bulk densities of the meteorite roughly match those of asteroids.

Hence, it is not surprising that up to now the major tool for determining a pairing of parent and stream has been orbit similarity and a number of criteria have been developed to quantify this, for example Southworth & Hawkins (1963), Drummond (1981), Jopek (1993), Valsecchi, Jopek & Froeschlé (1999), Jopek, Rudawska & Bartczak (2008), Nesvorný & Vokrouhlický (2006). One of the problems of comparing orbits in the near-Earth locality is that the argument of perihelion $\omega$ and longitude of the ascending node $\Omega$ can both significantly change on a time-scale that is comparable with the age of the meteoroid stream. Hence, a simplified $D$-criterion suitable for asteroid–meteoroid stream comparison was proposed by Steel, Asher & Clube (1991), which is defined by

$$D^2 = \left( \frac{a_1 - a_2}{3} \right)^2 + (e_1 - e_2)^2 + [2 \sin((i_1 - i_2)/2)]^2,$$

where subscripts 1 and 2 refer to the two orbits being compared.

Based on such orbital similarity, many authors have suggested associations between near-Earth asteroids and meteoroid streams, including Drummond (1982), Babadzhyanov & Obrubov (1983), Olsson-Steel (1988), Kresak & Stohl (1990), Hasegawa, Ueyama & Hotsuka (1992), Ryabova (2001a), Babadzhyanov (2003), Langbroek (2003), Terentjeva & Barabanov (2004) and Jopek (2011). Most of the associations of asteroids and meteor showers mentioned by the above authors have been with relatively minor showers and a list of some potential pairings is given in table 9 of Jenniskens (2006). However, there are three associations between asteroids and very major showers, again initially based on orbit similarity, that need to be discussed.

In 1983, Whipple (1983) stated that the orbit of the newly discovered asteroid 1983TB, now known as (3200) Phaethon, was very similar to the mean orbit of the Geminid meteoroid stream. The orbital elements for (3200) Phaethon are

$$q = 0.140, \ e = 0.890, \ i = 24.19, \ \omega = 325.25, \ \Omega = 262.50,$$

while for the Geminid stream they are

$$q = 0.141, \ e = 0.900, \ i = 23.88, \ \omega = 324.40, \ \Omega = 260.78$$

(Williams & Wu 1993a). The similarity is obvious.

Soon afterwards, Clube & Napier (1984) suggested that the Taurid meteor complex had many asteroids associated with it. Since that date there have been many other asteroids that have been suggested...
as being associated with the Taurid complex (e.g. Asher, Clube & Steel 1993b; Steel & Asher 1996; Babadzhanov 2001; Porubčan, Kornoš & Williams 2006; Babadzhanov, Williams & Kokhirova 2008a; Napier 2010; Jopek 2011). The number of suggested near-Earth asteroids associated with the Taurid complex that we have found in the literature is about 130, including some large asteroids such as 2101 Adonis, 2201 Oljato, 2212 Hephaistos, 4183 Cuno, 4341 Poseidon and 4486 Mithra. There is no scientific merit in listing all of these asteroids.

Another well-known pairing is between the Quadrantid meteor shower and near-Earth asteroid 2003 EH1 (Jenniskens 2004). The orbital elements for 2003 EH1 are

\[ q = 0.979, \ e = 0.687, \ i = 70:78, \ \omega = 171:37, \ \Omega = 282:95 \]
while those for the Quadrantid stream are

\[ q = 0.979, \ e = 0.679, \ i = 72:0, \ \omega = 172:0, \ \Omega = 283:3 \]
(Jenniskens 2006).

These three potential pairings will be discussed in more detail in a later section.

3 THE ORIGIN AND NATURE OF THE ORBITAL SIMILARITY BETWEEN METEOROID STREAMS AND ASTEROIDS

In view of the large number of known asteroids, there are two questions that arise in discussing any association between asteroids and meteoroid streams. First, is the orbital similarity due to chance or does it signify a generic relationship between the two. Secondly, if there is a generic relationship, what is the nature of this relationship? We will discuss these in turn.

3.1 The cause of orbital similarity

The systematic monitoring of the skies, principally to identify asteroids that may present a danger to Earth, has led to a vast increase in the number of known asteroids. In turn, this has naturally led to a vast increase in the number of asteroids that are on similar orbits to the orbits of meteoroid streams, with a corresponding increase in the number of claimed associations between meteoroid streams and asteroids, especially for short period streams that are near the ecliptic [since most near-Earth objects (NEOs) are close to the ecliptic]. Babadzhanov, Williams & Kokhirova (2008b) calculated that the probability of any two orbits in the near-Earth environment having a \( D \) value less than 0.3 (a typical value used in the field) was nearly 20 per cent. In other words, there is a 1/5 chance that a randomly chosen set of orbital elements will coincide with the orbital elements of some NEO. Porubčan, Kornoš & Williams (2004) found that using a critical value of 0.30 for \( D \), 76 asteroids had associations with 42 fireball streams. Decreasing the critical value of \( D \) to 0.12 reduced the number to 26 asteroids associated with 20 streams. Further, the typical period for secular variations in the orbital elements of near-Earth asteroids is 5000 to 10 000 years (see e.g. Babadzhanov, Williams & Kokhirova 2012) so that even if orbits were not initially similar, orbital changes can cause them to be similar at the present time, but they will drift apart again in the future. Porubčan et al. (2004) suggested that similarity of orbits should be maintained for a 5000 year period before a generic association could be claimed. Imposing such a condition reduced the possible pairings mentioned above to 9. Using the evolution condition, Porubčan et al. (2006) found that the number of asteroids associated with Taurid stream was considerably reduced to only 10. Hence, though many claimed associations are probably spurious, there are undoubtedly some asteroids that are associated with meteoroid streams.

3.2 The nature of generic relationships between asteroids and meteoroid streams

The fundamental question that needs to be asked is whether the three major streams that appear to have asteroids associated with them formed through dust ejection from an asteroid body, that is a body that is predominantly rocky in nature or whether the majority of the dust came from a comet that has since become dormant or disintegrated leaving dormant fragments that are now indistinguishable from asteroids on a similar orbit to the meteoroids. As mentioned already, it is possible that a meteoroid stream can be formed through mutual collisions between asteroids. 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 recent collision between two asteroids, in 2009 February or March (Jewitt et al. 2010; Snodgrass et al. 2010). Williams (1993) claimed that streams formed in this way would contain far less mass and be far more diffuse than those from a comet origin. This subject was reviewed by Obrubov (1999). It is unlikely that such a collision can release enough dust to account for the three major streams that we are discussing. It also does not follow that the formation mechanism is the same in all three cases. For this reason, it is necessary to discuss individually the three major streams under consideration, namely the Geminids, Quadrantids and Taurids.

4 THE THREE MAJOR STREAMS WITH ASSOCIATED ASTEROIDS

4.1 The Geminids

As mentioned already, Whipple (1983) in an IAU telegram pointed out the orbital similarity between the Geminid stream and (3200) Phaethon. Soon afterwards, Fox, Williams & Hughes (1983) pointed out that Phaethon had all the characteristics necessary to be the parent of the Geminid meteoroid stream assuming the ejection mechanism was Cometary, that is where ejection takes place continuously over a wide range of true anomaly. 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 2001b, 2007). Despite stream models suggesting that meteoroids were ejected from a comet in the recent past, no comet on the required orbit can be found in catalogues of old comets and no activity had been observed (e.g. Hsieh & Jewitt 2005; Wiegert, Houde & Peng 2008). The link between Phaethon and the Geminids was thus based only on the similarity of their orbits. However, the probability of a chance alignment is less than 0.001 according to Wiegert et al. (2008). Battams & Watson (2009) reported that Phaethon brightened by at least 2 mag at UT 2009 June 20. The transition to the bright state was very rapid, taking only a few hours after which it decayed slowly when Jewitt & Li (2010) found very weak activity. Ryabova (2012) investigated this outburst and concluded that meteoroids ejected during the activity could be seen as meteors in 2050, while Jewitt (2012) has investigated various possible mechanisms to explain the outburst. Whatever the cause of the recent outburst, similar outbursts cannot be responsible for the source of the vast majority of meteoroids in the very strong Geminid stream. Whether Phaethon is a dormant comet that was active when the stream formed or whether it is a fragment of the parent comet
that has now completely disintegrated remains an open question. The ~1.3 km diameter asteroid 2005 UD has a very similar orbit to that of Phaethon and both are optically blue. Since blue asteroids constitute only about 4 per cent of the general asteroid population, it is very likely that they are related and may have a common origin (Ohtsuka et al. 2006, 2008; Jewitt & Hsieh 2006; Kinoshita et al. 2007). Asteroid 1999 YC may also be dynamically related to Phaethon but its surface appears more nearly neutral with respect to the colour of the Sun (Kasuga & Jewitt 2008). The suggestion, originally made by Lebedinets (1985), that the high level of outgassing that a comet nucleus would experience when close to the Sun can significantly alter the orbit, changing it from a normal Jupiter family type orbit to one that lies almost completely with the Earth’s orbit, deserves further investigation. During such an event, fragmentation of the original nucleus might also be expected.

4.2 The Quadrantids

The Quadrantid shower was identified as early as 1835 (Fisher 1930), making it one of the first identified showers. However, despite its strength and regularity in the current epoch, no records of the Quadrantids appear to exist earlier than the beginning of the nineteenth century which is fairly remarkable since Chinese and Japanese records date back for two millennia (Hasegawa 1993) and mentions of the Perseids, the Leonids and the Lyrids are plentiful. Murray, Hughes & Williams (1980) demonstrated that perturbations by Jupiter caused small changes in the nodal distance of the mean stream so that the Earth did not intersect the stream prior to the nineteenth century. Numerical integrations by Hughes et al. (1981), Froeschlè & Scholl (1982, 1986), Babadzhanov & Obrubov (1987) and Wu & Williams (1992) all show that large changes in the orbital element of Quadrantid meteoroids can take place with a time-scale of a few thousand years, so that orbital changes 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).

Though no present-day comet has so far been unambiguously identified as the parent of the Quadrantid stream, there have been many contenders proposed. These have been summarized in Williams et al. (2004), but none is really credible. In the activity profile there is a 4 d broad background and a sharp narrow central peak. This suggests an old comet producing a background over time and some event injecting a large quantity of meteoroids over a short time. The narrowness of the central peak led Jenniskens et al. (1997) to conclude that most of the meteoroids observed today are quite young (hundreds rather than thousands of orbits completed since formation). McIntosh (1990) suggested that comet 96P/Machholz was a possible candidate since the orbits were similar several millennia ago. The general characteristics of the orbital evolution of the comet and stream are also very similar, both showing changes with a 4000-yr period (Gonczi, Rickman & Froeschlè 1992). There is a difficulty in accepting 96P/Machholz as the parent. It requires the stream to have formed at least several thousand if not tens of thousands of years ago in contradiction of the results of Jenniskens et al. (1997). Hasegawa (1979) has suggested that comet C/1490 Y1 (1491 I) was the parent for the Quadrantid stream. The mean orbit of the present Quadrantid stream was numerically integrated back to the year 1491 by Williams & Wu (1993b) and these elements are in remarkably good agreement with those given by Hasegawa for C/1490 Y1 bearing in mind that the observing arc was not long enough to determine eccentricity. Williams & Wu (1993b) also showed that the comet could experience a close encounter with Jupiter in the middle of the seventeenth century.

The situation changed somewhat when (Jenniskens 2004) pointed out the remarkable similarity between the orbits of the Quadrantid meteoroid stream and asteroid 2003 EH1 (now 196256). He also suggested that the asteroid was a fragment from the break-up of C/1490 Y1. This was taken up by Williams et al. (2004) who claimed that the orbit of 2003 EH1 in 1490 could produce the path on the sky described by Hasegawa. A possible scenario here is that several millennia ago a large comet existed with normal activity. It fragmented into at least two parts one of which is 96P/Machholz and the other became C/1490 Y1. These produce the broad background in the Quadrantids observed today. The fragmentation of C/1490 Y1 a few hundred years ago produced 2003 EH1 and a large amount of dust that is now seen as the strong narrow peak.

4.3 The Taurids

It is universally accepted that the Taurid meteor shower can be observed over a long time (e.g. Cook 1973), giving the duration from September 15 to December 1. Early photographic observations of the Taurid shower identified two general radiants, located symmetrically relative to the ecliptic and Whipple (1940) proposed that these be called the Northern and Southern Taurid showers. With more data available, it has become accepted that the Southern Taurid shower last from September 17 to November 27 with the maximum in the interval October 30 to November 7, while the Northern Taurid shower lasts from October 12 to December 2 with the maximum occurring between November 4 and 7 (Levy 2008). The stream has inclination less than 5°, a perihelion distance of about 0.4 au and eccentricity about 0.85, implying an orbital period of around 4 yr. It is also accepted that the very low inclination of the parent stream is the reason for the long duration of these showers, causing the Earth to be within the stream for a long arc. The Earth will also pass through this ‘stream’ after perihelion between May 20 and July 6 (Sekanina 1971) and cause the χ Perseid and β Taurid daylight showers to be observed by radar.

Denning (1928) showed that the above picture was too simple, being in fact 13 different radiants detectable within the two visible showers located in both Taurus and Aries and by now, numerous authors (Olsson-Steel 1988; Babadzhanov, Obrubov & Makhmudov 1990; Stöhl & Porubčan 1990; Steel et al. 1991; Babadzhanov 2001) agree that the stream is in fact a complex of several smaller meteoroid streams and filaments. (It is not clear whether there is a real physical distinction between a small stream and a filament, here we only distinguish between the two on the basis of historic nomenclature, thus for example the α Orionids is deemed to be a sub-stream while filament 1 of the N Taurids is deemed to be a filament.) The most recent list of such sub-streams is given by Porubčan et al. (2006) who list 15 sub-streams together with their orbital elements. It is interesting to note that in this listing there are two sub-streams recognized within both the main Taurid showers, with significantly different orbital parameters. For example for the N Taurids we have

N Taurids (a) \( q = 0.358, e = 0.835, i = 2:7, \omega = 293:7, \Omega = 228:6 \)
N Taurids (b) \( q = 0.380, e = 0.841, i = 2:9, \omega = 290:1, \Omega = 255:7 \)

while

S Taurids (a) \( q = 0.365, e = 0.833, i = 5:3, \omega = 113:1, \Omega = 43:3 \)
S Taurids (b) \( q = 0.225, e = 0.854, i = 8:2, \omega = 132:9, \Omega = 36:3 \)
Unlike the other two meteor streams, the Taurid meteoroid complex presently has an active comet associated with it, 2P/Encke, whose orbital parameters are

\[
q = 0.336, \quad e = 0.848, \quad i = 11.8, \quad \omega = 186.6 \quad \text{and} \quad \Omega = 334.6.
\]

Whipple (1940) suggested that a giant comet gently disintegrated into a number of comets at some unspecified time in the past, one of them being 2P/Encke. By using secular perturbation methods Whipple & Hamidi (1950) determined the orbital evolution of the nine then known meteor orbits and showed that some of the meteors had to be ejected from 2P/Encke 4700 yr ago while others must originate from one of the other hypothetical fragments 1400 yr ago. Note that these times are based on the currently observed meteoroids. Other meteoroids that have since been lost could have been ejected earlier and it does not give any real constraint on the time of the giant comet fragmentation, other than more than 4700 yr ago.

Three decades ago, Clube & Napier (1984) showed that some Apollo asteroids had orbits that were very similar to the Taurid stream while a decade later Asher, Clube & Steel (1993a) suggested that the family of meteoroid streams, comet 2P/Encke and the then known associated Apollo asteroids could all have formed by the fragmentation of a giant comet 20–30 Kyr ago.

Since that date, there have been several other searches for asteroids with orbits that are similar to the mean orbit of the Taurid stream. Asher et al. (1993b) found 15 NEO’s that could be associated with the mean Taurid stream. Babadzhanov (2001) found 17 asteroids satisfying the condition, many in common with the list of Asher et al. (1993b). Porubčan et al. (2004) found that NEO2003 UV11 was associated with the S Taurid sub-stream, 2201 Oljato with \(\chi\) Orionids S, 2002 XM35 with \(\chi\) Orionids N and 2003ST and 2002 HP11 with the Piscids. They also claimed that 4183 Cuno was associated with the December Aurigid, not part of the Taurids complex. Babadzhanov et al. (2006) found that 91 NEO’s could be part of the Taurids complex. They argued that this is far too large a number for the associations to be real and that, as already stated, orbital evolution is fairly rapid in this locality of the Solar system and most asteroids have low inclination, many of the supposed orbital similarities are just chance, with the orbits being similar at the present time, but implying no generic connections. They argued that in order to claim any generic relationships, the orbits of the NEO’s and those of the meteoroid streams need to have remained similar for a long time interval, which they chose to be 5000 yr. They state that using formula and calculations given by Arter & Williams (1997) meteors in this locality can survive against the effects of Poynting–Robertson drag for up to \(10^4\) yr, but claimed that integrating for 5000 yr gave a sufficiently strong indication of a relationship. This reduced the number of possible NEAs associated with Taurid filaments to nine (associated with seven separate sub-streams). All these NEO’s were small with diameters less than 2 km. Porubčan et al. (2006) also claim that all the associations were formed within the last 5000 yr. Possible associations between seven Taurid filaments and nine NEO’s were found. The most probable are for S Piscids (b) – 2003QC10, N Taurids (a) – 2004TG10, \(\alpha\) Orionids – 2003U3 and N Taurids (b) – 2002XM35. Close associations were also confirmed between comet 2P/Encke and three of the sub-streams, the earlier branch of the S Taurids, the main branch of the S Taurids and the main branch of the N Taurids, the richest three sub-streams in the complex.

Babadzhanov et al. (2008a) also identified several NEO’s that may be associated with various meteor streams. In particular, they applied their methodology to the Taurid complex and identified seven NEO’s associated with various sub-streams. Three of these were actually the same as those identified by Porubčan et al. (2006) (2003WP21, 2003UL3 and 2004TG10). Jopek (2011) also produced a list of 14 NEO’s belonging to the Taurid Complex. Six of these were common to previous lists, namely 2201 Oljato, 2003 UV11, 2003WP21, 2004TG1, 2005TF50, 2003 WP21, while further list can be found in Napier (2010).

All of the above arguments lead to a model where at around 20 Ky or so ago a comet fragmented leaving an other smaller comet (2P/Encke), several NEO’s and a complex of sub-streams forming the broad Taurid complex.

5 SPORADIC METEOROIDS AND THEIR ORIGIN

Out of all the meteors only 25–35 per cent are observed in meteor showers. The majority are observed as sporadic meteors which cannot be associated with any known meteoroid stream. They were presumably formed from comets or asteroids and once belonged to a meteoroid stream, but due to the effects of perturbations and collisions over a long interval of time their orbits have evolved and any similarity with the orbit of the parent body has been lost. Hence, it is not possible to determine the parent body of any given sporadic meteoroid. Instead, it is only possible to discriminate between the populations, cometary and asteroidal, to which a given meteoroid belongs.

As was the case for meteoroid streams, we have to use dynamical parameters to establish the origin of sporadic meteoroids, and the results may be biased by observational selection. Also, on average, sporadic meteoroids have evolved over longer time interval than observed present-day stream meteoroids so that a number of non-gravitational factors have influenced their dynamical evolution to a far greater degree than was the case for stream meteoroids.

As was mentioned in Section 2 comet or asteroid sporadic meteoroids will differ depending on the density of the particles: low density of the order 500 kg m\(^{-3}\) for cometary meteoroids and about 3000 kg m\(^{-3}\) for meteoroids of asteroidal origin. As was discussed in the first part of the paper, it is generally believed that most meteoroids originate from comets. Observational evidence from the process of atmospheric fragmentation as observed by Jacchia (1954) and McCrosky (1955) supported this belief. The notion that sporadic meteoroids could originate from asteroids was suggested by Piotrowski (1953) and Fesenkov (1958). Piotrowski showed that inter-asteroid collisions could produce sufficient mass to support the zodiacal cloud.

6 METHODS FOR DETERMINING THE PARENT POPULATION OF A METEOROID

In order to discriminate between the orbits of comets and asteroids (the C–A classification) Whipple (1954) proposed using an empirically found, ‘K-criterion’:

\[
K = \log [a(1 + e)/(1 - e)] - 1
\]

where \(a\) is the semi-major axis in au, \(e\) the eccentricity of the orbit and the logarithm is to base 10. When \(K \geq 0\) the orbit is of a cometary type, while negative values indicate an asteroid orbit. Using this K-criterion Whipple (1954) found that 96 per cent of known comets and 99.8 per cent of known asteroids were correctly classified. The criterion can also be applied to meteoroids, and Whipple classified 90 per cent of 144 bright photographic meteors as cometary.
The $K$-criterion is an empirical one; it has no fundamental physical basis, and for short-period, low eccentricity orbits it gives inconclusive results. For example, for the Pribram and Neuschwanstein meteorites $K \approx 0.08$, whereas most authors would agree that meteorites either have originated in the main asteroid belt and perturbed on to Earth-crossing orbits or are pieces of near-Earth asteroids. In order to classify sporadic meteoroids 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 $a_{J}$ and $a$ are the semi-major axis of Jupiter’s orbit and the meteoroid orbit, both in au, $e$ is the eccentricity and $I$ is 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.

Kresak (1967, 1969) also proposed two additional discriminants, the $P$- and $Q$-criterion defined by

$$P = k^{2}a_{J}^{-2}e,$$

(5)

where $k$ is the Gauss gravity constant. For a cometary orbit the condition $P > 2.5$ is used.

$$Q = a(1 + e)$$

(6)

with $Q > 4.6$ au for a Cometary orbit. $Q$ is aphelion distance and so this condition simply requires that the orbit does not go beyond the asteroidal belt.

In this paper we use one additional discriminant, the $E$-criterion (the orbital energy $E$) given by

$$E = -\frac{k^{2}}{2a},$$

(7)

with $a > 2.8$ au for cometary orbits.

Except for the Tisserand invariant, all the above criteria have been derived on an empirical basis, that is to determine a quantity where in general the known comets generate a different value from the known asteroids.

Assuming that comets and asteroids form disjoint populations, Starczewski & Jopek (2004) estimated the reliability of the $K$-, $P$-, $Q$-, $T$-criteria. 2656 NEAs and 582 comets were classified for several epochs spanning the time interval of 40 thousands years, and the authors found the $Q$-criterion to be the most reliable; it produced the smallest number of exceptions and has shown the best stability. In this paper we have repeated the reliability test, applying all the criteria (3)–(7) to the orbits of 780 comets (Marsden & Williams 2008) and 7830 near-Earth asteroids available in 2012 July (NEO Dynamic Site 2012). The results are given in Table 1. As one can see, the $Q$- and $E$-criterion proves to be the most reliable; the $K$-criterion produced the most exceptions.

In Fig. 1 five lines are plotted corresponding to the threshold values of all C–A criteria. The points representing individual comets and NEAs are also shown. It can be seen that the curve which represents the $K$-criterion passes through the different region of the $(1/a) – e$ plane. On such a plot, the points representing meteoroids have to lie between the two black lines corresponding to the boundaries $Q = 1$ and $q = 1$ of the meteoroid observation selections effects.

### Table 1. The number of exceptions (in per cent) not obeying the cometary – asteroidal orbital criteria amongst 7830 NEAs and 780 periodic comets.

<table>
<thead>
<tr>
<th>$Q$ (per cent)</th>
<th>$E$ (per cent)</th>
<th>$T$ (per cent)</th>
<th>$P_{c}$ (per cent)</th>
<th>$K$ (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9</td>
<td>3.8</td>
<td>7.2</td>
<td>10.7</td>
<td>16.4 NEAs</td>
</tr>
<tr>
<td>1.0</td>
<td>1.5</td>
<td>2.2</td>
<td>5.8</td>
<td>13.8 Comets</td>
</tr>
</tbody>
</table>

![Figure 1. Distribution of comets (orange points) and NEAs (green points) in the $(1/a) – e$ plane. They are well separated, but not perfectly. The continuous black lines represent a boundary condition for crossing the Earth’s orbit, the remaining lines represent: $K$-criterion (red), $P$-criterion (grey), $T$-criterion (magenta), $Q$-criterion (blue), $E$-criterion (pastel green) given by equations (3)–(7). Depending on the inclination $I$ of the meteoroid orbit relative to Jupiter’s orbital plane, the curves for the $T$-criterion occupy different positions. In this figure the T-curve corresponds to $I = 0$, which occupies the lowest position of all the T-lines.](https://academic.oup.com/mnras/article-abstract/430/3/2377/2908441/)

### 7 PREVIOUS STUDY: C–A CLASSIFICATIONS AMONGST METEOROID ORBITS

To classify meteoroid orbits the $K$-, $P$-, $Q$-, $T$- criteria have been used by several authors. Whipple (1954) studied 144 orbits and found that 90 per cent were of cometary type. However his data sample (small camera meteoroids) contained many stream meteoroids. Using the Super Schmidt photographic meteors Jacchia et al. (1967) classified 99.8 per cent orbits as cometary. Using the $K$-criterion Jones & Sarma (1985) found that the video meteors were about equally divided into the cometary and asteroidal classes. Steel (1996) found more cometary orbits within photographic data. Also, amongst the Canadian video meteors, he found approximately the same number of cometary and asteroidal orbits. In the Adelaide radio meteors Steel found more than 50 per cent were cometary orbits, whereas in the Kharkov radio meteor streams he found more asteroidal orbits. Voloshchuk, Vogul’ & Kashcheev (1997) found that 63 per cent of the Kharkov sporadic radio meteors were on cometary orbits. Starczewski & Jopek (2004), using the $Q$-criterion, found that for sporadic meteors 78 per cent of radio meteors, 48 per cent of photographic meteors and 53 per cent of video meteors moved on asteroidal type orbits. Concerning the photographic and video meteor samples, the estimates of Starczewski and Jopek are consistent with those given by Steel (1996). However, in the case of sporadic radio meteors they obtained significantly different result to Voloshchuk et al. (1997).

In this paper we have carried out a similar classification exercise using ~78 000 orbits of sporadic meteoroids.
8 PRESENT STUDY: C–A CLASSIFICATION AMONGST ORBITS OF SPORADIC METEOROIDS

8.1 Data sample of the sporadic meteoroids

The meteor data were collected from several sources, namely:

(i) the IAU MDC photographic and radio data (Lindblad & Steel 1993; Lindblad et al. 2003; Svoren, Porubcan & Neslusan 2008; Porubcan et al. 2011);

(ii) Canadian video orbits (Hawkes, Jones & Ceplecha 1984; Jones & Sarma 1985);

(iii) photographic and video meteors observed by members of Dutch Meteor Society (DMS) (Betlem et al. 1998, 2000);

(iv) video meteors published by Koten et al. (2003), and those used in Jopek, Koten & Pecina (2011);

(v) video meteors observed by Japanese amateur astronomers – SonotaCo group (SonotaCo 2009, 2011).

The C–A criteria listed in Section 6 were applied to the sample of the ~78 000 sporadic meteoroids obtained. We have used only elliptical orbits with quality flags ≥1, and data which passed the internal consistency check (see Jopek, Valsecchi & Froeschlé 2003). The resulting set of ~118 000 meteors was tested for stream membership using a single linkage cluster analysis, the orbital distance function \( D_v \) (Jopek et al. 2008) and the orbital similarity thresholds listed in Table 2. We detected 71 streams with 10 or more members, which represents 33.4 per cent of the meteor sample. After removing these stream meteoroids, there were ~78 000 orbits of sporadic meteoroids that were studied further. As can be seen in Fig. 2, these meteoroids occupy almost all of the region across the boundary conditions for crossing the Earth’s orbit: \( q = 1 \) au, \( Q = 1 \) au.

8.2 Results of the C–A classification: discussion

The C–A criteria given by formulae (3)–(7) were applied to ~78 000 sporadic meteoroids and the results obtained are listed in Table 3. The values of the percentages can change slightly because of uncertainties in the meteoroid orbital elements. However, as was shown in Starczewski & Jopek (2004) the percentages given in Table 3 can differ at most by ±2 due to such uncertainties.

The \( E \)-criterion always gave the smallest fractions of sporadic meteoroids moving on cometary orbits. The larger values, in increasing order, were obtained with the \( Q \), \( P \) and \( T \)-criterion, respectively. The greatest fractions were obtained with the \( K \)-criterion. The differences between the results obtained by the respective criteria are in the range 10–15 per cent.

The smallest fractions of cometary orbits was obtained using the \( E \)-criterion as can be seen from looking at Fig. 2; the \( E \)-curve occupies the lowest position in the region occupied by the meteoroids. This means that all the meteoroids classed by the \( E \)-criterion as cometary were also classed as cometary by all the other C–A criteria. In the bottom part of Table 3 we have listed the results obtained by Starczewski & Jopek (2004). They used a similar classification method and partly used the same meteor data. Despite that, two discrepancies between their results and ours are clearly seen in Table 3. First, the present study resulted in a higher fractions of cometary meteoroids noticeable in Table 3. However, as was shown in Starczewski & Jopek (2004) the percentages given in Table 3 can differ at most by ±2 due to such uncertainties.

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There are two reasons of these discrepancies. First, in this study we have used a different sample of the video meteoroids. We used 30 899 orbits, mainly obtained by SonotaCo group which included a significant number, 1221, of the video data also used by Starczewski & Jopek. These meteoroids were observed by cameras used in searching for streams amongst orbits of sporadic meteoroids in the (1/a)–e plane (green points). Continuous black lines represent a boundary condition for crossing the Earth's orbit; the remaining lines represent: \( K \)-criterion (red), \( P \)-criterion (grey), \( T \)-criterion (magenta) for \( I = 0 \), \( Q \)-criterion (blue), \( E \)-criterion (pastel green). On the right, the \( K \)-criterion by (Whipple 1954) clearly runs above the remaining criteria. It is undoubtedly related to the significant differences between the proportion of the cometary meteoroids noticeable in Table 3.

### Table 2. The values of thresholds \( D_v \) and their uncertainties \( \sigma_{D_v,M} \) used in searching for streams amongst ~118 000 meteoroids. For each group of \( M \) members the thresholds and their uncertainties correspond to \( D_v \)-function and the reliability level 99 per cent.

<table>
<thead>
<tr>
<th>( M )</th>
<th>( D_v \pm \sigma_{D_v,M} )</th>
<th>( M )</th>
<th>( D_v \pm \sigma_{D_v,M} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.58 ± 0.03</td>
<td>17</td>
<td>2.85 ± 0.01</td>
</tr>
<tr>
<td>3</td>
<td>0.90 ± 0.02</td>
<td>18</td>
<td>2.87 ± 0.01</td>
</tr>
<tr>
<td>4</td>
<td>1.18 ± 0.02</td>
<td>19</td>
<td>2.89 ± 0.01</td>
</tr>
<tr>
<td>5</td>
<td>1.44 ± 0.02</td>
<td>20</td>
<td>2.91 ± 0.01</td>
</tr>
<tr>
<td>6</td>
<td>1.67 ± 0.02</td>
<td>21</td>
<td>2.91 ± 0.01</td>
</tr>
<tr>
<td>7</td>
<td>1.87 ± 0.02</td>
<td>22</td>
<td>2.92 ± 0.01</td>
</tr>
<tr>
<td>8</td>
<td>2.05 ± 0.02</td>
<td>23</td>
<td>2.93 ± 0.01</td>
</tr>
<tr>
<td>9</td>
<td>2.21 ± 0.02</td>
<td>24</td>
<td>2.93 ± 0.01</td>
</tr>
<tr>
<td>10</td>
<td>2.35 ± 0.02</td>
<td>25</td>
<td>2.94 ± 0.01</td>
</tr>
<tr>
<td>11</td>
<td>2.47 ± 0.02</td>
<td>26</td>
<td>2.95 ± 0.01</td>
</tr>
<tr>
<td>12</td>
<td>2.56 ± 0.02</td>
<td>27</td>
<td>2.97 ± 0.02</td>
</tr>
<tr>
<td>13</td>
<td>2.65 ± 0.02</td>
<td>28</td>
<td>2.99 ± 0.02</td>
</tr>
<tr>
<td>14</td>
<td>2.72 ± 0.02</td>
<td>29</td>
<td>3.03 ± 0.02</td>
</tr>
<tr>
<td>15</td>
<td>2.77 ± 0.02</td>
<td>30</td>
<td>3.07 ± 0.02</td>
</tr>
<tr>
<td>16</td>
<td>2.82 ± 0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3. C–A one-parameter classification. The proportion of cometary orbits among the sporadic meteors. In the separate rows we give the percentages of meteors among the whole sporadic component, the radar, video and photographic meteors, respectively. For comparison, in the bottom part of table, we have listed the results of the C–A classification by Starczewski & Jopek (2004).

<table>
<thead>
<tr>
<th>Q (per cent)</th>
<th>E (per cent)</th>
<th>T (per cent)</th>
<th>P (per cent)</th>
<th>K (per cent)</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>44.0</td>
<td>41.8</td>
<td>56.8</td>
<td>49.0</td>
<td>61.8</td>
<td>77 869 (all meteoroids)</td>
</tr>
<tr>
<td>23.4</td>
<td>21.4</td>
<td>36.1</td>
<td>28.1</td>
<td>44.8</td>
<td>45 539 radio meteors</td>
</tr>
<tr>
<td>73.4</td>
<td>71.0</td>
<td>86.6</td>
<td>78.9</td>
<td>86.1</td>
<td>30 899 video meteors</td>
</tr>
<tr>
<td>65.5</td>
<td>59.6</td>
<td>70.6</td>
<td>68.4</td>
<td>76.5</td>
<td>1431 photographic meteors</td>
</tr>
<tr>
<td>23.6</td>
<td>–</td>
<td>35.5</td>
<td>28.7</td>
<td>42.8</td>
<td>55 891 (all meteoroids)</td>
</tr>
<tr>
<td>22.2</td>
<td>–</td>
<td>34.0</td>
<td>27.1</td>
<td>41.4</td>
<td>52 993 radio meteors</td>
</tr>
<tr>
<td>46.9</td>
<td>–</td>
<td>64.9</td>
<td>54.2</td>
<td>63.6</td>
<td>1221 video meteors</td>
</tr>
<tr>
<td>51.7</td>
<td>–</td>
<td>60.2</td>
<td>62.4</td>
<td>71.7</td>
<td>1677 photographic meteors</td>
</tr>
</tbody>
</table>

Figure 3. Left-hand panel: the distribution of stellar magnitudes of 29 651 video meteors observed by the SonotaCo group. The limiting magnitude of these meteors is close to $+4^m$; the mean magnitude is $\approx -1^m$. Right-hand panel: the brightness of 322 video meteors observed in Canada. The mean value of the magnitude is close to $4.5^m$.

with different photo-sensitivity. Most of the 1221 video meteoroids were observed using equipment for which the limiting magnitude was $6^m–8^m$ (Hawkes et al. 1984; Jones & Sarma 1985; Koten et al. 2003). In contrast, the faintest meteors observed by SonotaCo group only reached $4^m$ (see Fig. 3). The mean magnitude of $\sim 30,000$ sporadic meteors observed by the SonotaCo group was $-1^m$ so that the sample of video meteoroids used in this study should probably be regarded as ‘photographic’ rather than video.

The second discrepancy between our results and those obtained by Starczewski & Jopek (2004) seen in Table 3 concerns the small but clear differences between the percentages of cometary orbits found amongst both the radio meteors and the photographic meteors. In both studies the same sources of radio and photographic data were used. However in this study, the sporadic radio and photographic samples had smaller sizes. The reason is because different cluster analysis methods were applied for detecting the sporadic component in the studies. Starczewski & Jopek (2004) made limited search for streams; they used only one orbital similarity threshold, and they found that 15 per cent of the sample belongs to the stream component. In the present study, individual thresholds were used (see Table 2), and 33.4 per cent of meteoroids were found to be in streams. Voloshchuk et al. (1997) and Starczewski & Jopek (2004) have found that $17–25$ per cent of meteoroid streams have mean orbits of a cometary type. Since in this study 33.4 per cent of the sample were a part of a stream, in comparison with 15 per cent used by Starczewski & Jopek, our sporadic samples of radio and photo meteoroids contained more Cometary type orbits and thus proportionally less orbits of asteroidal type. This, in turn, means that in our sporadic samples, using the same C–A criteria as Starczewski & Jopek, we would expect to find a greater proportion of cometary orbits.

In summary, the results of the C–A classification among the sporadic meteoroids depends critically on the method used for the separation of the stream and sporadic component. In Table 3 we can see that in case of the radio and photographic samples, taken from the same data sources, the percentages of the cometary meteoroids differ by $2–14$ per cent. The greatest differences between our results and those by Starczewski & Jopek (2004) occurred for the $Q$-criterion.

8.3 Limitation of the one-parameter C–A classification

We also found that the result of the one-parameter C–A classification listed in Table 3 may contain a serious bias. This can be seen in Figs 4 and 5.

According to the definition (6), using the one-parameter classification based on the $Q$-criterion and the threshold value $Q_t = 4.6$ [au], all meteoroids for which $\log (Q/Q_t) < 0$ should be
regarded as moving on asteroidal type orbits. However, as can be seen in Fig. 4, there are many ‘asteroidal’ meteoroids for which \( i > 75^\circ \). However, at the time of writing (2012 August), we know of only one NEA, 2009 HC82, for which \( Q < 4.6 \text{ au} \) and \( i > 75^\circ \). Further, there is no single comet in this region. Therefore, determining the source of all sporadic meteoroids plotted in magenta in Fig. 4 is an interesting question. These meteoroids represent 22.4 per cent of the whole sporadic sample. The highest fraction of such orbits, 28 per cent were found among the radio meteor data, 15 per cent among the video data and only 5 per cent among the photographic orbits.

In the case of the \( E \)-criterion (see Fig. 5), we found a similar percentage (23.2 per cent) of ‘asteroidal’ meteoroids moving on the orbits for which \( i > 75^\circ \). For the remaining criteria the percentages of such ‘asteroidal’ meteoroids can be found in Table 4. Using the \( E \)-criterion led to the classification of the greatest fractions of ‘asteroidal’ meteoroids. The reason is the same as mentioned previously, in case of the results listed in Table 3 – from the triangle containing all meteoroids, the \( E \)-curve cuts the smallest fraction containing cometary orbits (see Fig. 6).

To find the source of the sporadic meteoroids for which \( Q < 4.6 \text{ au} \) and \( i > 75^\circ \) we have used another graphical representation, namely the Hammer–Aitoff equal-area diagrams. For sporadic meteoroids such plots of geocentric meteor radiants were applied for the first time by Hawkins (1956), and then by Elford & Hawkins (1964), Sekanina (1973), Jones & Brown (1993, 1994), Steel (1997), Galligan & Baggaley (2005), Chau et al. (2007) and Campbell-Brown (2008). For our purpose the most suitable variant of the Hammer–Aitoff diagram is that made in the Earth apex rotating reference frame. For the sporadic meteoroids, such diagram clearly exposes six concentrations: the helion and antihelion, the north and south apex concentrations, and the north and south toroidal ones [see e.g. Elford & Hawkins (1964) or Campbell-Brown (2008)].

In Fig. 7 we have used such variant of the Hammer–Aitoff diagram on which 60 412 and 17 457 radiants of the sporadic meteoroids have been plotted. The top diagram in Fig. 7 illustrates the radiant points of meteoroids moving on either cometary or asteroidal orbits. On the top panel, one can distinguish the regions corresponding to the helion, antihelion, north and south apex and north toroidal concentrations. It can be seen that sporadic meteoroids for which \( Q > 4.6 \text{ au} \) or \( i < 75^\circ \) are not connected with any particular concentration. On the bottom panel, in case of the meteoroids for which \( Q < 4.6 \text{ au} \) and \( i > 75^\circ \) we see opposite property – these meteoroids are connected with the apex concentrations. As one can see in Fig. 8, these meteoroids entered the Earth atmosphere with a speed \( V_g > 30 \text{ km s}^{-1} \). Similar diagrams can be produced for remaining C–A criteria.

### 8.4 The origin of meteoroids with \( Q < 4.6 \text{ au} \) and \( i > 75^\circ \)

To explain the origin of the six concentrations of the sporadic meteoroids [see fig. 7 in Elford & Hawkins (1964)] it is necessary...
to carry out a numerical integration of motion of the meteoroid particles under both gravitational and non-gravitational forces. Dycus & Bradford (1964) using quasi-invariant of the motion due to Poynting–Robertson drag [equations (7) and (8) in their paper] has shown that P–R drag can rapidly decrease the aphelion of the comet orbits, ultimately changing the trajectories to asteroidal-class orbits. Such mechanism was earlier proposed by Davies (1957) for small meteoroids moving on high-inclined and small-sized orbits of ‘asteroidal’ type. In a more extended study Jones, Campbell-Brown & Nikolova (2001), Wiegert, Vaubaillon & Campbell-Brown (2009) and Nesvorny et al. (2011) have shown that the apex and toroidal meteoroids may originate from disruption of long-period comets or Oort Cloud comets. Therefore the observed meteoroids (at least those observed by radar technique) moving on the highly inclined ‘asteroidal’ orbits can have cometary origin. This result means that the one-parameter C–A criteria may not be sufficient to classify correctly sporadic meteoroids to the appropriate parent-body population.

### 9 TWO-PARAMETER C–A CLASSIFICATION

Hence, to classify sporadic meteoroids as cometary or asteroidal origin, we propose using a two-parameter approach $Q - i$, $E - i$, $T - i$, $P - i$, $K - i$. For cometary meteoroids one can use the following two-parameter criteria:

$$ Q = a(1+e) > 4.6 \text{ [au]}, \quad \text{or } i > 75^\circ $$

$$ E = -\frac{k^2}{2a} > -5.28 \times 10^{-5} \left( \frac{\text{au}^2}{M_\odot \text{D}^2} \right), \quad \text{or } i > 75^\circ $$

$$ T = a^{-1} + 2a_{i1.5} \sqrt{a(1-e^2)\cos I} < 0.58, \quad \text{or } i > 75^\circ $$

$$ P = a^{1.5} e > 2.5 \text{ [yr]}, \quad \text{or } i > 75^\circ $$

$$ K = \log \left[ a(1+e)/(1-e) \right] - 1 > 0, \quad \text{or } i > 75^\circ $$
Meteoroids associated with asteroids

Accordingly to the $Q - i$ and $E - i$ criteria, out of the whole sporadic sample available for this study, 66–67 per cent of them were on cometary orbits.

The smallest fraction on cometary orbits, 50–51 per cent, was found among the radio meteors using the $Q - i$ and $E - i$ criteria. For the video and photographic sub-samples, and using the same criteria, the fractions on cometary orbits were 87–89 and 64–68 per cent, respectively.

In the study by Starczewski & Jopek (2004), cometary orbits were found to be less numerous, especially for the video meteors. As explained in Section 8.2 the video observations sample almost the same population of meteors as in the photographic technique. To determine how the fraction of orbits classified as cometary change with the brightness of the meteors we have scrutinized the sporadic meteoroid sample.

In the ‘video’ section in Table 5 we list the results for each video sub-sample used in this study. In the first part of the ‘video’ section we see that fraction meteoroids on cometary orbits observed in Canada is about 30 per cent 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 group was $-1^m$, but for meteors observed in Canadian the mean magnitude was close to $4.5^m$.

We now proceed to classify only the faint meteors observed in Ondrejov and SonotaCo. Bright meteors for which the absolute magnitudes $M_g < 3^m$ and $M_g < 2^m$, respectively, were removed from the analysis. As can be seen in Table 5, among the faint meteors observed in Ondrejov the fraction of meteors on cometary orbits is 14 per cent less when using the $Q - i$ and $E - i$ criteria. In case of the SonotaCo data number classified as cometary orbits decreased by 14–20 per cent. Hence, the fraction of meteoroids...
classified as cometary depends significantly on the magnitude of the observed meteors.

Similar significantly different results were found amongst the radio data. The lowest value 40–42 per cent of meteors on cometary orbits occurred among the Harvard2 ‘synoptic year’ sample using $Q - i$ and $E - i$ criteria. For Harvard1 sample using the same criteria the results were 4 per cent higher. The data from the Kharkov radar (similar sensitivity as the Harvard equipment) – cometary orbit accounted for 55–56 per cent of the Kharkov sample. On the other hand, where a significantly less sensitive radar was used in Mogadishu the percentage of meteors on cometary orbits is smaller than detected with the Kharkov radar, 50–52 per cent. The radar equipments used in Australia (Adelaide1, Adelaide2) and in the USSR (Obninsk) all have a sensitivity comparable to that used in Mogadishu. In the Australian data we found many more meteoroids moving on cometary type orbits. Unfortunately, we do not have sufficient information available to us to allow us to offer an explanation of such diversity in the results. They are probably partly caused by different observation selection effects, for example the Obninsk radio meteor data consist solely of orbits observed at their descending nodes, and hence all observed radiants have ecliptic latitude $\beta \geq 0$.

Application of the $Q - i$ and $E - i$ criteria to the photographic meteors resulted in 79–81 per cent of meteors being on cometary orbits. As expected, in the case of meteors observed with the more sensitive Super Schmidt cameras, the fraction classified as cometary meteoroids was smaller, 63–68 per cent. Also as expected, among the photographic meteoroids, the fraction on cometary orbits was low, 43–48 per cent, when the $Q - i$ and $E - i$ criteria were used.

**10 CONCLUSIONS**

In the first section, we concluded that the meteoroid associated with the three major streams, the Geminids, the Taurids and the Quadrantis, were mostly of cometary origin. We have shown that to classify the sporadic meteoroids into comet or asteroid populations one needs to use two-parameter criteria. Using only one-parameter criteria can result in the fractions of meteoroids on cometary orbits being understated by up to 29 per cent. For the photographic meteorites, the underestimate is much less, 2–5 per cent. In case of radio data, depending on the C–A criterion used, the underestimate can reach 15–29 per cent. This bias is a consequence of the fact that among the sporadic meteoroids there are many asteroidal orbits ($Q < 4.6$ au) with high inclinations ($i > 75^\circ$).

Assuming that the comet and NEA populations are disjoint, the Q-i and E-i are the most reliable tool for dynamical discrimination of the NEOs population. Using these criteria we have found that among all ~78 000 sporadic meteoroids studied, those on orbits of cometary type predominate, the fraction of such orbits equals 66–67 per cent. Amongst ~45 000 radio meteors studied, 50–51 per cent were on cometary orbits, and among ~31 000 video orbits 87–89 are cometary type. Finally, 64–68 per cent of 1431 sporadic meteoroids moved on cometary orbits. These fractions can differ significantly from one orbital sub-sample to the other. A general trend was observed – the fraction of cometary orbits decreases with decreasing magnitude (increasing size) of the observed meteors.

Due to insufficient information, we were not able to make any inferences regarding the real fractions of the cometary and asteroidal sporadic meteoroids. Our results are concerned only with the observed samples.

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**REFERENCES**

Battams K., Watson A., 2009, IAU Circ. 9054
Betlem H. et al., 1998, DMS Photographic Meteor Data base, Leiden
Betlem H. et al., 2000, DMS Video Meteor data base, Leiden
Campbell-Brown M. D., 2008, Icarus, 196, 144
Drummond J. D., 1981, Icarus, 45, 453
Drummond J. D., 1982, Icarus, 49, 143
Fesenkov V. G., 1958, SVA, 2, 303
Hasegawa I., 1979, PASJ, 31, 257
Hawkes G. S., 1956, AJ, 61, 386
Hoffmeister C., 1937, Die Meteore, Akademische Berlaggesellschaft, Leipzig

Downloaded from https://academic.oup.com/mnras/article-abstract/430/3/2377/2908441 by guest on 22 February 2019
Meteors associated with asteroids

Jewitt D., Mathews J. D., Meisel D., Zhou Q., 2001, Icarus, 150, 706
Jopek T., 1993, Icarus, 106, 603
Jopek T. J., Valsecchi G. B., Froeschl
Jopek T. J., Valsecchi G. B., Froeschl
Jopek T. J., Valsecchi G. B., Froeschl
Jopek T. J., Valsecchi G. B., Froeschl
Langbroek M., 2003, JIMO, 31, 177
McIntosh B. A., 1990, Icarus, 86, 299
Olivier C. P., 1925, Meteors. The Williams & Willkins Company, Baltimore
Olsson-Steel D. I., 1988, Icarus, 75, 64
Sekanina Z., 1971, BAAS, 3, 271
Sekanina Z., 1972, Icarus, 18, 253
Sekanina Z., 1976, Icarus, 27, 265
SonotaCo, 2009, JIMO, 37, 55
Starczewski S., Jopek T. J., 2004, Earth Moon Planets, 95, 41
Terentjeva A., Barabanov S., 2004, JIMO, 32, 60
Whipple F. L., 1983, IAU Circ. 3881

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