A&A 622, A84 (2019)
https://doi.org/10.1051/0004-6361/201834593

Astronomy & Astrophysics

A robust method to identify meteor showers new parent bodies from the SonotaCo and EDMOND meteoroid orbit databases[⋆]

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Received 7 November 2018 / Accepted 7 December 2018

ABSTRACT

Context. Several new meteor showers are added to the International Astronomical Union (IAU) list of meteor showers every year. Given the multiplication of video meteor measurements new parent bodies are to be found in addition to new showers. Such an endeavor is usually performed by comparing orbital elements, using a high threshold single-linking $D_{\rm sh}$-criterion. However, questions remain about the accuracy of the method and the veracity of the newly associated parent bodies.

Aims. Our goal is to find the presence of new parent bodies in a statistical meaningful way.

Methods. A search for parent bodies was performed among SonotaCo and EDMOND databases. The association of asteroids with meteors was based on different methods, discussed and compared below. In addition, a thorough statistical test was performed in order to investigate the possible random associations.

Results. A list of potential new parent bodies associated with at least 50 meteors is found. A statistical test was used to show whether the group of meteor orbits and the asteroid is a random coincidence or not. Out of 54 potential new parent bodies, only three new parent bodies are not excluded by the statistical test: 2014 BN_{14}, 2015 TX_{24} and 2015 QT_3, with a probability of chance occurrence of 37, 10 and 13%, respectively. This shows the need for rigorous method when searching for the existence of meteor showers and parent bodies.

Conclusions. Ideally, such a test (or even better, tests) should be conducted in order to confirm (or not) the current IAU list of meteor showers. Similarly, all meteor orbit data in our databases should ideally be revisited using the latest methods providing a better estimate of the real uncertainty and accuracy of the derived orbits.

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

1. Introduction

The International Astronomical Union (IAU) keeps track of all known meteor showers and their parent bodies, including those in need of confirmation. New showers are regularly added from ongoing meteoroid orbit surveys (Jenniskens et al. 2009; Jopek & Kaňuchová 2017).

In early 2018, the IAU Meteor Data Center lists 957 meteor showers, including 112 established and others considered in the working list[1]. Recently, Kornoš et al. (2014); Rudawska et al. (2015a,b); Jenniskens & Nénon (2016); Rudawska & Jenniskens (2014); Jenniskens et al. (2016) have identified several new meteor showers that were added to the IAU list of Meteor Showers using a high threshold single-linking $D_{\rm sh}$-criterion (Southworth & Hawkins 1963).

Here we investigate the possible parent bodies of these new showers. Usually, such a search is performed by comparing the orbits of known asteroids and comets to the mean orbit of a given shower, by using for example one of the $D_{\rm sh}$-criterion defined by several authors (e.g. Jopek 1993; Rudawska & Jenniskens 2014; Rudawska et al. 2015b). However, in recent work, doubts have been raised regarding the veracity of such a method, as a dependency on the sample was unveiled (Jopek & Bronikowska 2017). Indeed, as already shown in the case of the Pribram and Neuschweinstein meteorites, orbit similarity does not necessarily imply a common origin and thorough statistical analysis is needed to draw robust conclusions (regardless of the composition of the meteorites Pauls & Gladman 2005; Koten et al. 2014). Thanks to the multiplication of video meteor networks, the number of publicly available meteor orbits is growing quickly, and so it is not surprising to find many meteors with orbits similar to known asteroids or comets. In addition, the uncertainties of meteoroid orbital elements are much higher than expected before, as showed by Egal et al. (2017); Vida et al. (2018). Nevertheless, the need for parenthood for meteor shower is crucial in order to better perform typical dynamic works such as the exploration of the age of a meteoroid stream or the forecasting of future meteor showers (Abedin et al. 2017; Vaubaillon 2017). The question thus remains whether or not a given association between a meteor (or set of meteors) and parent body is relevant.

[⋆] Tables of all the associations are only available at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr` (`130.79.128.5`) or via `http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/622/A84`

[1] `http://pallas.astro.amu.edu.pl/~jopek/MDC2007/index.php`, accessed in Feb 2018.

In this paper, we present a new method, based on statistical analysis, to compare the parent bodies and meteoroids orbits. The method is presented in Sect. 2 and the results in Sect. 3. A discussion regarding the veracity of the developed method and the comparison to other ones follows in Sects. 3 and 4.

2. Method

2.1. Data

We use the video meteor orbits of SonotaCo and Edmond Database to find associations with a list of 15129 asteroids taken from JPL Small body Database[2] that provides us with tables of orbital and/or physical parameters for all existing asteroids and comets. The SonotaCo video meteor network operates about 100 cameras at 25 sites. It has been in operation since 2007, with first results published in 2009 (SonotaCo 2009; Jenniskens et al. 2016). Every year, new orbits are published on the SonotaCo website[3] by Touru Kanamori, Tokyo, Japan. From 2007 to 2017, the SonotaCo database grew to 257104 orbits. The computation of meteor orbits is performed by the UFOOrbit software (SonotaCo 2009).

The European video Meteor Network Database (EDMOND) is a database of video meteor orbits resulting from a cooperation and data sharing between several European national networks as well as the International Meteor Organization Video Meteor Network IMO VMN (Rudawska et al. 2015a). In early 2018, the EDMOND database contains 317831 video meteor orbits, gathered from 2001 to 2016[4]. A comparison of both the EDMOND and the SonotaCo catalogue, in terms of orbital parameters, showed an equivalence of the data (Kornoš et al. 2014).

2.2. Searching for an appropriate method

Most modern research on the association between parent bodies and meteor showers uses the Dissimilarity Criterion or the D criterion, which was first proposed by Southworth & Hawkins (1963) and has been modified by others, for example, Drummond (1981); Jopek (1993); Rudawska et al. (2015b). A small D-value indicates a high degree of similarity between two orbits. A threshold value of $D_{\rm sh} < 0.25$ is often used (Lindblad 1971a,b; SonotaCo 2009; Andreić et al. 2013; Šegon et al. 2014). A lower threshold value of $D_{\rm sh} < 0.05$ was used by Rudawska & Jenniskens (2014); Kornoš et al. (2014); and Jenniskens & Nénon (2016). Rudawska et al. (2012, 2015b) have revised such methods but there is still room for improvements, since even the date of ejection of simulated meteoroid stream cannot be found by backward integrations. The main difficulty remains in the comparison of semi-major axis and eccentricity, which are poorly determined (Egal et al. 2017; Vida et al. 2018). In order to bypass this difficulty, Micheli (2013) compares parent bodies and meteor showers orbits based on the comparison of the velocity and location of the radiant rather than the $D_{\rm sh}$-criterion.

Presumably, as this method uses better-constrained parameters, we developed a method that compares the apparent radiant and geocentric velocity (α, δ, V_g) of meteors and known potential parent bodies. The radiant and velocities of NEOs (asteroids and comets) can be computed thanks to several method, all summed up by Neslusan et al. (1998). The program is available on request and was kindly provided to us by the author. This step is performed using six different methods (Neslusan et al. 1998):

- adjustment of the orbit by variation of the perihelion distance – the q-adjustment (Hasegawa 1990);
- adjustment of the orbit by variation of both the perihelion distance and eccentricity considering a minimum change (Svoren et al. 1993);
- adjustment of the orbit by variation of the argument of perihelion (Steel & Baggaley 1985);
- adjustment of the orbit by rotation around the line of apsides (Svoren et al. 1993);
- adjustment of the orbit by variation of the argument of perihelion and inclination (Hasegawa 1990);
- parallel shift of the velocity vector (Porter 1952).

Most of the time, we considered the Hasegawa (1990) method.

The next step is to compare both the meteors (α_m, δ_m, V^g_m) and the parent bodies ($\alpha_{\rm NEO}$, $\delta_{\rm NEO}$, $V^g_{\rm NEO}$). As a first implementation, one might consider several criteria in terms of difference of position of the radiant ($\Delta^{\rm rad}_c$) and difference in velocity (ΔV^g_c) are defined. To consider the parenthood to be possible, a meteor and an NEO must satisfy: $\Delta^{\rm rad} < \Delta^{\rm rad}_c$ and $\Delta V^g < \Delta V^g_c$. This method resulted in association of the 2009 WN25 asteroid and the November i-Draconids (NID) by Micheli et al. (2016).

In our quest for the most appropriate method, the comparison of methods based on orbital elements and methods based on (α, δ, V^g) was performed. As a first step, the $D_{\rm sh}$ (Southworth & Hawkins 1963) criterion is computed, coupled with a constrain on Solar longitude in order to take into account the apsidal precession of the orbit and to focus on young showers only. Trying different threshold values, we considered: 8° for the difference in solar longitude, and 0.05, 0.1 and 0.2 for $D_{\rm sh}$. Such a method is referred to as Method 1 in Tables 1 and 2.

As a second step, and inspired by Micheli (2013), we computed the angular distance between the radiants, and the difference in solar longitude and Velocity. We fixed the threshold values for the difference in the position of the radiant and in the solar longitude, respectively, at 8° (solar longitude). In order to explore and find the best compromise, several values of the thresholds for the difference of position of radiant and the difference of velocity are considered. In a first step, the distance to the radiant is taken as 6°. Then it is refined at 2°. Similarly, the difference in velocity is taken at 0.5, 3 and 5 km s^{-1}. This method is referred to as Method 2. Given these choices, six different combinations of the difference in radiant and velocity are possible.

In order to fully explore the influence of the velocity, in addition to the criteria in solar longitude and radiant position, we considered a variable velocity threshold, based on a percentage of the measured meteoroid velocity. It is worth mentioning that the UFOOrbit orbit computation sofwtare provides a so called dv12% parameter, characterizing the quality of the orbit, and was commented in, for example, Kornoš et al. (2014). In our work, we have considered that an NEO is a potential parent body if $Vg - Vg * v\% < V^g_{\rm NEO} < Vg + Vg * v\%$, with the thresholds $v\%$ taken as $v\% = 5, 10$ or 20% of the meteoroid velocity. In other words, the NEO geocentric velocity must be comprised within the uncertainty of the meteoroid geocentric velocity for the association to be considered possible. This last method is called Method 3 hereafter.

Last but not least, in order for a shower to be confirmed and a parent body to be possible, a minimum number of N_m meteors must satisfy all the criteria for a given method. Trying several values, we retain $N_m \geq 10$ or 50 for the parenthood to be further considered. The results of such a preliminary exploration are shown in Table 1 for $N_m \geq 10$ and Table 2 for $N_m \geq 50$.

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[2] `https://ssd.jpl.nasa.gov` accessed in Feb 2018.

[3] `http://sonotaco.com/e_index.html`

[4] Accessed in Feb 2018.

Table 1. Number of asteroids associated with at least ten meteors, for each method.

Methods	#	Criteria	Number of associations	
			SonotaCo Database	EDMOND Database
Method 1	1.1	$D_{\rm sh} < 0.05$, $\lambda_{\rm o} < 8°$	6	11
	1.2	$D_{\rm sh} < 0.1$, $\lambda_{\rm o} < 8°$	420	638
	1.3	$D_{\rm sh} < 0.2$, $\lambda_{\rm o} < 8°$	3230	3839
Method 2	2.1	$V < 0.5$ km s^{-1}, Dis $< 6°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	190	368
	2.2	$V < 1$ km s^{-1}, Dis $< 6°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	513	929
	2.3	$V < 3$ km s^{-1}, Dis $< 6°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	1519	2267
	2.4	$V < 0.5$ km s^{-1}, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	115	231
	2.5	$V < 1$ km s^{-1}, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	350	709
	2.6	$V < 3$ km s^{-1}, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	1256	1975
Method 3	3.1	dv = 5%, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	315	555
	3.2	dv = 10%, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	315	555
	3.3	dv = 20%, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	1452	2150

Table 2. Number of asteroids associated with at least 50 meteors, for each method.

Methods	#	Criteria	Number of associations	
			SonotaCo Database	EDMOND Database
Method 1	1.1	$D_{\rm sh} < 0.05$, $\lambda_{\rm o} < 8°$	2	3
	1.2	$D_{\rm sh} < 0.1$, $\lambda_{\rm o} < 8°$	17	28
	1.3	$D_{\rm sh} < 0.2$, $\lambda_{\rm o} < 8°$	850	1424
Method 2	2.1	$V < 0.5$ km s^{-1}, Dis $< 6°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	16	25
	2.2	$V < 1$ km s^{-1}, Dis $< 6°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	35	64
	2.3	$V < 3$ km s^{-1}, Dis $< 6°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	207	389
	2.4	$V < 0.5$ km s^{-1}, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	13	20
	2.5	$V < 1$ km s^{-1}, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	23	42
	2.6	$V < 3$ km s^{-1}, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	128	240
Method 3	3.1	dv = 5%, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	36	55
	3.2	dv = 10%, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	84	131
	3.3	dv = 20%, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$	251	367

From Tables 1 and 2, we concluded that considering associations of asteroids with at least ten meteors is not enough to clearly identify new parent bodies. One can easily get a very large number of possible parent asteroids by slightly chasing the N_m criterion. We decided to consider $N_m \geq 50$ to obtain a smaller number of possible associations (Table 2).

Using the first method (Table 2), and in the case of $D_{\rm sh} < 0.05$, the number of associations is small, knowing that normally we should obtain names of asteroids already known as parent bodies of some major meteor showers. Increasing the threshold value of the criterion to 0.1 or 0.2 did not solve the problem, and we obtained a very large number of possible associations with asteroids. The value of the chosen $D_{\rm sh}$ criterion drastically changes the number of possible parent asteroids, thus preventing us from concluding with confidence regarding a potential parenthood.

On the other hand, using Methods 2 and 3 (Table 2) allowed us to obtain better constrain the potential parent bodies. Considering the preliminary results shown in Table 2 and the associations we obtained, we decided to consider the first case of the third method since the results are more robust (dv = 5%, Dis $< 2°$, $\lambda_{\rm o} < 8°$, $\alpha < 8°$, $\delta < 8°$).

Once this preliminary analysis is performed, the question remains: how can we test if the found associations are not simply resulting from a high number of meteoroid orbits? Such question was pertinently asked by Pauls & Gladman (2005) regarding the Pribram and Neuschweinstein meteorites, and later used by Koten et al. (2014) to examine the possible associated meteor showers. The results were negative: the found possible associations between the two meteorites, as well as between each individual meteorite and meteors having similar orbital elements are simply the result of statistical fluctuations in a high set of orbits. As a consequence, we conduct a similar analysis for the 36 and 55 showers found with Method 3.1 (Table 2).

2.3. Statistical test

We use a slightly modified statistical test of Koten et al. (2014) to determine whether a given group of meteoroid orbits associated with a new parent body is a random coincidence or not. Let us assume that $N_{\rm tot}$ is an amount of all recorded meteors within the corresponding interval of solar longitudes (excluding the shower meteors). $N_{\rm asoc}$ is the number of meteors which were chosen as possible stream connected with a parent asteroid and $D_{\rm sh}^{1,\ldots,N_{\rm asoc}}$ are their D-criteria (Southworth & Hawkins 1963). The statistical test itself is the following:

1. Artificial set of $N_{\rm tot}$ orbits is created. The semimajor axes, eccentricities and inclinations have the same distribution as

Table 3. Number of meteors associated with already known parent bodies.

Parent body	N_S	N_E
2011 X_{A3}	75	64
2009 WN_{25}	199	–
2004 TG_{10}	70	93
2010 TU_{149}	195	178
2015 DU_{180}	–	55
(196256) 2003 EH_1	2480	1976
(3200) Phaethon 1983 TB	14685	11778

Notes. N_S: number of meteors in the SonotaCo database. N_E: number of meteors in the EDMOND Database.

small NEAs (absolute magnitude $H > 24$, see Koten et al. 2014). Arguments of perihelion, longitudes of ascending node and mean anomalies are randomly chosen so that the simulated collisions with Earth occur in the same interval of solar longitudes as the observed meteor group.

2. For each artificial orbit the D_{sh}-criterion (with respect to the possible parent body) is computed and these values are sorted so that

$$\widetilde{D_{sh}}^1 < \widetilde{D_{sh}}^2 < \cdots < \widetilde{D_{sh}}^{N_{tot}}. \tag{1}$$

3. An occurence of a random subset which is “closer” to parent body than observed possible stream (and it is only random association) is tested by following the conditions:

$$\widetilde{D_{sh}}^1 < D^1_{sh},\ \widetilde{D_{sh}}^2 < D^2_{sh},\ \ldots,\ \widetilde{D_{sh}}^{N_{asoc}} < D^{N_{asoc}}_{sh}. \tag{2}$$

If all of these conditions are fulfilled, then a “false stream” is detected.

Steps 1–3 are repeated $N = 10\,000$ times. If N_f is a number of false streams, then probability of chance occurrence is

$$PCO = N_f/N. \tag{3}$$

3. Results

As a first step to validate the method, we searched for already known associations between meteor showers and asteroids, for example, 3200 Phaethon and the Geminids. Table 3 presents the lists of such parent asteroids and the number of meteors found to be associated with each of them.

As a second step, we present in Table 4 two asteroids that have never been associated with meteor showers before, and for which the statistical tests is positive (the statistical significance of the association is high). Table 5 lists all unconfirmed cases, in order to illustrate the difficulty of the task, and the absolute necessity to perform statistical analysis in order to highlight potential parent bodies. Twenty six asteroids are potentially associated with meteors from both databases. Similarly, 28 asteroids are potentially associated with meteors either from SonotaCo or EDMOND Database only. This does not mean they were not associated with the other database at all, but the members of associations is less than 50.

Examples of which meteor is potentially associated with which asteroid are provided in Tables A.1–A.5. By providing the community with such data, we hope to encourage future studies to complement and improve this work.

Table 4. Statistically not excluded new parent bodies and number of associated meteors in each database.

Parent body	α	δ	N_S	N_E
2016 BN_{14}	306.6169	−5.3973	247	462
2015 TX_{24}	49.3551	14.0942	179	278

Notes. α and δ are the location of the radiant (right ascension and declination, in deg. N_S: number of meteors in the SonotaCo database. N_E: number of meteors in the EDMOND Database.

We also computed the probability of chance occurrence (PCO) for each potential parent body associated with SonotaCo and EDMOND databases meteor orbits, using the method described in Sect. 2.3. The results are provided in Table 6. For the vast majority of potential parents, the statistical significance test prove the association to be the result of pure random process. Only for the first four asteroids (namely 2015 TX_{24}, 2016 BN_{14}, 2015 QT_3 and 2009 HE_{21}), the PCO is significantly lower than all other potential parents. However, even the PCO value for 2009 HE_{21} is of 60% only, we decided not to consider it as a potential parent candidate. The 2015 QT_3 asteroid was only associated with 15 meteors from SonotaCo Database, which does not satisfy our condition in considering a potential parent body ($N_m \geq 50$). However, considering the EDMOND data, we find 68 meteors possibly associated with this asteroid, which triggered the computation of PCO. Eventually, we found that PCO$_s$ is very high, precisely because of the small number of meteors taken into account. Nevertheless, the PCO$_E$ value 13% is quite low and statistically meaning that there are 87% of chances that the association is real. Overall, and as a consequence of this analysis, we decide that asteroids 2016 BN_{14}, 2015 TX_{24}, 2015 QT_3 are significant candidates to retain them, but ideally additional data would benefit from such a study to definitely confirm or infirm such conclusion. We should note that our work did not take into account the asteroids orbit uncertainties. In the case of poorly observed asteroid such as 2016 BN_{14} (observed for one day only) further observations leading to a new orbit determination might possibly change our results.

4. Conclusion

In this work, we searched in available databases (SonotaCo and EDMOND) for new meteor showers, with at least 50 members, identifying their parent bodies. Fifty four new asteroids were associated with meteor streams from both used databases. This is done by comparing their orbits basing on threshold values of the difference in geocentric velocity, distance to the radiant, right ascension, declination and solar longitude. We performed a statistical test to show whether or not the new meteor showers are only a chance occurrence. Our method ended up leading to much less confirmed associations than in absence of statistical test: from 26 asteroids potentially associated with at least 50 meteor orbits from SonotaCo and Edmond database, only three were not excluded. But at least they are identified using a reliable test. The two streams are associated with 2014 BN_{14}, 2015 TX_{24} and 2015 QT_3 asteroids that were never linked to a meteor shower before.

Egal et al. (2017) and Vida et al. (2018) highlight the difficulty of computing an accurate meteoroid orbit from the observation of a meteor. In the light of such works, we understand today that our databases might contain lots of data in which accuracy are not as we previously thought they were. From these data, several new meteor showers are added regularly to the IAU.

Table 5. Statistically excluded potential parent bodies.

Parent body	α	δ	N_S	N_E
2011 UE_{256}	54.35	10.01	594	793
2003 WP_{21}	53.14	15.40	451	568
1999 VK_{12}	56.52	9.28	303	373
2007 RU_{17}	36.79	7.82	262	381
2016 UZ_{25}	43.14	12.83	244	410
2003 UV_{11}	8.25	12.56	168	258
2008 XM_1	82.77	29.16	133	109
2014 NK_{52}	75.19	19.73	126	95
2007 UL_{12}	69.70	17.24	106	73
2002 XM_{35}	68.70	24.05	88	58
2016 VK	50.35	23.16	86	210
(251722) 1997 US2	70.82	17.90	82	70
1997 VM_4	63.84	10.33	82	112
2014 UQ_{114}	62.21	27.80	80	132
2005 UR	42.93	12.6	75	84
2015 XL_1	78.22	9.64	67	–
2001 XX_{103}	78.09	13.17	67	–
(312942) 1995 EK1	189.81	4.23	61	60
2016 PZ_{39}	94.05	19.63	61	57
2014 YQ_{34}	104.10	25.89	59	53
2014 WD_7	55.42	21.69	59	–
2006 SO_{198}	27.99	4.36	58	159
2010 XZ	73.76	7.41	55	–
2009 HE_{21}	226.65	−12.44	53	79
(452302) 1995 YR1	118.26	17.58	52	–
2016 BV_{14}	313.06	−4.75	51	121
(4197) Morpheus 1982 TA	26.17	−0.79	50	111
2013 BP_{45}	282.19	50.88	50	278
2014 NF_{64}	299.04	−5.90	–	143
2010 RV_3	9.56	−1.92	–	55
2015 TD_{144}	31.27	10.71	–	58
2015 FP_{33}	188.17	1.41	–	58
2014 BD_{33}	333.93	51.97	–	51
(139359) 2001 ME1	280.70	−18.86	–	55
2014 HK_{197}	205.72	0.01	–	50
2016 DF_1	316.67	−14.21	–	107
2013 RL_{43}	13.16	10.10	–	91
2016 TA	24.17	5.22	–	85
(144861) 2004 LA12	291.92	59.50	–	99
2011 GS_{60}	335.54	1.56	–	74
1999 VR_6	40.31	24.44	–	70
2015 QO_3	355.42	5.38	–	68
2007 PR_{25}	344.96	−3.11	–	59
2014 OX_{299}	341.43	−0.82	–	51
2012 LL_9	281.99	49.15	–	59
2005 CM_7	316.75	−8.41	–	56
2015 PM_{307}	344.92	−1.46	–	58
(434677) 2006 BZ7	209.97	57.73	–	60
2016 QB_{11}	342.15	−4.32	–	50
2015 QT_3	341.91	−2.31	–	50
(297274) 1996 SK	21.94	11.43	–	54

Notes. α and δ are the location of the radiant (right ascension and declination, in deg. N_S: number of meteors in the SonotaCo database. N_E: number of meteors in the EDMOND Database.

Table 6. Probability of chance occurrence (PCO) computed for each potential parent body associated with meteor orbits.

Parent body	PCO_S (%)	PCO_E (%)
2015 TX_{24}	24	10
2015 QT_3	97	13
2016 BN_{14}	31	37
2009 HE_{21}	57	62
(139359) 2001 ME1	–	77
(251722) 1997 US_2	96	82
2016 BV_{14}	87	83
1999 VK_{12}	90	84
2003 UV_{11}	91	84
2014 YQ_{34}	96	84
2015 FP_{33}	–	84
2007 RU_{17}	79	86
2008 XM_1	92	88
2003 WP_{21}	93	91
2016 TA	–	92
2006 SO_{198}	96	92
2013 RL_{43}	–	93
2011 UE_{256}	96	94
2010 RV_3	–	95
2016 UZ_{25}	97	95
2014 HK_{197}	–	96
(297274) 1996 SK	–	96
2016 QB_{11}	–	97
2001 XX_{103}	97	97
2007 UL_{12}	98	97
2005 UR	97	98
2014 NK_{52}	98	98
2016 VK	98	98
(312942) 1995 EK_1	98	98
2015 TD_{144}	–	98
2015 QO_3	–	98
2007 PR_{25}	–	98
2014 UQ_{114}	97	99
2002 XM_{35}	99	99
1997 VM_4	99	99
2016 PZ_{39}	99	99
(4197) Morpheus 1982 TA	99	99
2013 BP_{45}	99	99
2014 NF_{64}	–	99
2014 BD_{33}	–	99
2016 DF_1	–	99
(144861) 2004 LA_{12}	–	99
2011 GS_{60}	–	99
1999 VR_6	–	99
2014 OX_{299}	–	99
2012 LL_9	–	99
2005 CM_7	–	99
2014 WD_7	–	99
2015 PM_{307}	–	99
(434677) 2006 BZ_7	–	99
2015 XL_1	98	–
2010 XZ	99	–
(452302) 1995 YR_1	98	–

Notes. The first three potential parent bodies have low values. PCO_S: PCO for meteors from the SonotaCo database; PCO_E: PCO for meteors from the EDMOND database. See text for further explanation.

A meteor shower might sometimes be identified if only four to six meteors orbits are similar. Knowing the orbit real uncertainty (and inaccuracy...), and in absence of robust statistical test as the one shortly presented here, it is legitimate to question the veracity of the very existence of some meteor showers. It is worth mentioning that to revisit the list of meteor showers in the IAU database is a continuous ongoing work, and the reason for the very existence of several lists of meteor showers, including the "working list" and the "removed list". Even the statistical test performed in the present work might be improved in itself. We looked in the list of all meteor showers given by the IAU database, for streams associated with 2016 BN_{14}, 2015 TX_{24} and 2015 QT_3 asteroids. Neither of the three asteroids were associated with a stream from the list. This could be interpreted by the fact that these streams have never been observed before.

The present approach is actually pretty simple in its principle, and more experienced professional statisticians might come up with more robust ways to decide whether or not a possible parent body association is statistically significant or not. For example, Pauls & Gladman (2005) revisited the possible association between the Neuschwanstein and Pribram meteorites and concluded by the negative.

In both SonotaCo and EDMOND databases, many orbits (all for SonotaCo) are obtained using the UFOOrbit software. Recently, SonotaCo (2016) provided the users with improved way to estimate the orbit accuracy. Ideally it would be worth revisiting all meteoroid orbit and to (re-)compute all of them using the latest methods (Vida et al. 2018). This would greatly help to revise, for example, the present work, but also will greatly help future works searching for meteor showers parent bodies.

Acknowledgements. We are thankful to L. Neslusan for providing us with the Neslusan et al. (1998) program.

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Appendix A: Additional tables

Table A.1. Orbital elements of the confirmed parent bodies.

α_{pb}	δ_{pb}	$V_{g\,\mathrm{pb}}$	λ_{pb}	q_{pb}	e_{pb}	ω_{pb}	i_{pb}	a_{pb}	Desig
306.6169	−5.3973	22.5479	127.5492	0.5814	0.7543	268.9198	10.1019	2.3664	(2016 BN14)
49.3551	14.0942	31.2848	33.0070	0.2896	0.8724	127.0160	6.0442	2.2689	(2015 TX24)

Notes. α_{pb}, δ_{pb}, $V_{g\,\mathrm{pb}}$, q_{pb}, e_{pb}, a_{pb}, ω_{pb}, Ω_{pb}, i_{pb} and λ_{pb} refer, respectively, to right ascension (°) and declination (°) of the radiant, geocentric velocity (km s^{-1}), perihelion distance (au), eccentricity, semi-major axis (°), argument of perihelion (°), longitude of the ascending node (°), inclination (°) and solar longitude (°). "Desig" is the designation of the parent body.

Table A.2. Associations of meteors from SonotaCo Database with the 2003 WP_{21} asteroid.

α	δ	V_g	λ	q	e	ω	i	a	Dis	D_{sh}	Desig	meteor_localtime
301.8032	−11.1678	21.8474	121.0263	0.5777	0.7299	271.2687	6.5898	2.1390	1.4535	0.0863	(2016 BN14)	20080724_004307
304.7979	−10.2344	22.8693	124.7734	0.5747	0.7711	269.8237	7.0335	2.5104	1.7967	0.0620	(2016 BN14)	20080727_225158
305.5989	−8.8113	22.8116	125.7056	0.5759	0.7662	269.8716	7.9378	2.4628	1.0110	0.0419	(2016 BN14)	20080728_221536
308.5972	−9.3211	23.3884	123.6191	0.5074	0.7431	280.0117	7.7095	1.9751	1.9562	0.1277	(2016 BN14)	20090726_234851
300.0231	−11.5859	21.6901	123.6341	0.6294	0.7706	262.7484	6.1592	2.7432	0.3255	0.1588	(2016 BN14)	20090727_001121
308.0497	−8.9481	22.8925	128.7472	0.5813	0.7776	268.6774	7.3525	2.6141	1.4203	0.0549	(2016 BN14)	20110801_205050
306.3273	−8.4300	22.2989	128.9342	0.6091	0.7751	265.1738	7.6654	2.7081	0.2923	0.0635	(2016 BN14)	20110802_013219
308.0395	−7.3520	22.6145	130.7534	0.6058	0.7852	265.1935	8.2345	2.8209	1.4123	0.0524	(2016 BN14)	20110803_230926
312.9036	−7.9640	22.5183	134.5652	0.5938	0.7758	267.0712	6.9250	2.6478	0.0449	0.0929	(2016 BN14)	20110807_224209
302.3354	−10.7849	23.4034	121.8936	0.5653	0.7844	270.5116	7.2361	2.6216	1.9724	0.0823	(2016 BN14)	20120724_225701
304.8714	−6.8828	23.2188	123.8952	0.5589	0.7622	272.2711	9.8327	2.3499	1.7320	0.0269	(2016 BN14)	20120727_011504
304.8480	−9.1857	23.0314	125.6978	0.5827	0.7827	268.3110	7.7841	2.6820	1.7502	0.0595	(2016 BN14)	20120728_223211
305.3420	−9.2830	23.2914	125.7596	0.5750	0.7873	269.1105	7.7530	2.7037	1.2643	0.0573	(2016 BN14)	20120729_000522
308.2440	−9.1507	21.8910	129.5640	0.5986	0.7506	267.5131	6.8021	2.4000	1.6112	0.0609	(2016 BN14)	20120801_233730
306.4201	−8.1821	22.8519	129.5846	0.6098	0.8008	264.1124	7.9555	3.0616	0.2013	0.0764	(2016 BN14)	20120802_000814
305.5402	−7.8979	22.8785	129.5847	0.6196	0.8112	262.5076	8.2315	3.2810	1.0695	0.0970	(2016 BN14)	20120802_000815
308.2933	−8.2444	22.8551	129.5964	0.5879	0.7811	267.6736	7.7606	2.6852	1.6613	0.0507	(2016 BN14)	20120802_002601
306.9762	−8.1993	22.2909	129.6281	0.6091	0.7753	265.1475	7.7109	2.7106	0.3600	0.0592	(2016 BN14)	20120802_011342
307.4418	−8.5479	22.1994	129.6286	0.6049	0.7683	265.9672	7.3942	2.6113	0.8202	0.0562	(2016 BN14)	20120802_011432
307.1376	−10.4606	23.5177	129.6583	0.5978	0.8264	264.7393	6.3970	3.4432	0.5230	0.1025	(2016 BN14)	20120802_015939
308.0323	−8.7808	21.6655	129.6739	0.6042	0.7447	267.0128	7.0043	2.3670	1.4034	0.0597	(2016 BN14)	20120802_022253
307.5287	−8.8114	22.2418	129.6927	0.6045	0.7702	265.9410	7.2055	2.6308	0.9061	0.0592	(2016 BN14)	20120802_025108
306.8643	−9.7344	21.5444	129.7227	0.6202	0.7557	264.4636	6.4045	2.5384	0.2566	0.0814	(2016 BN14)	20120802_033632
305.9524	−9.3681	22.2413	126.5737	0.5879	0.7541	268.8032	7.2221	2.3911	0.6623	0.0527	(2016 BN14)	20160729_211752
306.5570	−9.5212	22.0857	126.5853	0.5825	0.7442	269.9464	7.0094	2.2775	0.0933	0.0550	(2016 BN14)	20160729_213521
308.4269	−8.4027	22.2346	130.2011	0.5995	0.7652	266.7912	7.3720	2.5533	1.7922	0.0530	(2016 BN14)	20170802_222208
312.1605	−9.0231	21.7218	132.1856	0.5847	0.7344	270.0231	6.2150	2.2017	0.7361	0.1030	(2016 BN14)	20170805_000819
308.1434	−7.6994	22.7353	132.1978	0.6197	0.8075	262.5938	7.8700	3.2196	1.5145	0.0808	(2016 BN14)	20170805_002600

Notes. α, δ, V_g, q, e, a, ω, Ω, i and λ refer, respectively, to right ascension (°) and declination (°) of the radiant, geocentric velocity (km s^{-1}), perihelion distance (au), eccentricity, semi-major axis (°), argument of perihelion (°), longitude of the ascending node (°), inclination (°) and solar longitude (°) of the meteors orbits. "Dis" is the distance to the radiant. We kept displaying the D_{sh} criterion although we did not use it as a condition for associations. And over all, the criterion is less than 0.25. For few associations with asteroids orbits, which have a large semi-major axis a, it exceeds this value up to 1.5. The larger the semi-major axis of the orbits the larger the value of D_{sh}. For few associations with asteroids orbits, which have a large semi-major axis a, it exceeds this value up to 1.5. The larger the semi-major axis of the orbits the larger the value of D_{sh}. The same quantities are represented in Tables A.3–A.5.

Table A.3. Associations examples of meteors from EDMOND database with the 2016 BN14 asteroid.

α	δ	V_g	λ	q	e	ω	i	a	Dis	D_{sh}	Desig	meteor_localtime
304.6471	−9.6390	21.7765	126.0663	0.6022	0.7465	267.2454	7.0270	2.3759	1.9450	0.0713	(2016 BN14)	2008_7_28_22_19_9
306.9226	−8.6326	21.6780	126.0854	0.5762	0.7197	271.9232	7.5380	2.0555	0.3086	0.0604	(2016 BN14)	2008_7_28_22_47_38
305.1463	−9.3519	22.1343	126.1221	0.5933	0.7536	268.1283	7.3041	2.4075	1.4570	0.0581	(2016 BN14)	2008_7_28_23_43_1
301.9407	−12.2313	22.7363	119.7906	0.5525	0.7493	273.7175	6.1372	2.2040	1.5861	0.0862	(2016 BN14)	2010_7_22_20_47_28
301.5560	−12.0931	23.4388	119.9826	0.5520	0.7771	272.5310	6.4530	2.4771	1.2109	0.0920	(2016 BN14)	2010_7_23_1_37_20
302.0199	−11.3923	23.6481	120.8906	0.5548	0.7871	271.7480	6.9511	2.6053	1.6647	0.0875	(2016 BN14)	2010_7_24_0_27_23
301.9251	−4.1936	23.0282	123.7269	0.5969	0.7729	266.8808	11.8764	2.6281	1.5844	0.0875	(2016 BN14)	2010_7_26_23_45_8
305.3061	−10.8479	22.8213	121.6723	0.5321	0.7384	276.9582	6.7932	2.0340	1.2984	0.0841	(2016 BN14)	2011_7_25_2_17_1
304.6568	−11.8925	22.1821	123.4884	0.5698	0.7419	271.7630	5.7138	2.2076	1.9288	0.0805	(2016 BN14)	2011_7_26_23_53_37
304.9435	−10.8656	22.8710	123.4947	0.5581	0.7592	272.5134	6.6570	2.3175	1.6533	0.0657	(2016 BN14)	2011_7_27_0_3_5
311.2097	−7.3692	23.0029	131.8742	0.5773	0.7780	269.1385	7.9630	2.6002	1.6767	0.0756	(2016 BN14)	2012_8_4_0_34_46
302.2420	−12.0989	22.9652	120.0277	0.5491	0.7564	273.8444	6.2592	2.2537	1.8782	0.0836	(2016 BN14)	2013_7_22_21_22_37
301.3202	−9.6764	22.7085	121.0348	0.5741	0.7586	270.4616	8.0102	2.3780	0.9798	0.0767	(2016 BN14)	2013_7_23_22_41_31
301.2027	−10.7145	21.6324	121.0999	0.5877	0.7273	270.0485	6.8867	2.1552	0.8645	0.0938	(2016 BN14)	2013_7_24_0_19_58
302.1542	−10.4230	21.9271	122.8951	0.5940	0.7454	268.4035	6.9699	2.3327	1.7977	0.0886	(2016 BN14)	2013_7_25_21_27_12
301.3405	−13.1056	22.6894	122.9449	0.5981	0.7890	266.1126	5.2735	2.8348	1.0007	0.1361	(2016 BN14)	2013_7_25_22_42_51
306.5231	−7.9279	21.8171	129.2869	0.6151	0.7580	265.0399	7.8102	2.5419	0.1031	0.0599	(2016 BN14)	2014_8_1_19_51_41
307.0045	−8.3326	22.1704	129.3866	0.6075	0.7680	265.6423	7.5971	2.6192	0.3881	0.0564	(2016 BN14)	2014_8_1_22_21_51
306.9827	−8.8554	22.1779	129.4041	0.6081	0.7710	265.4487	7.2268	2.6552	0.3679	0.0633	(2016 BN14)	2014_8_1_22_48_11
313.7518	−12.1171	22.3427	134.9534	0.5971	0.7808	266.4309	3.7380	2.7242	0.8488	0.1331	(2016 BN14)	2015_8_8_0_11_5
299.7755	−10.2410	22.9124	120.3936	0.5833	0.7756	268.5656	7.7976	2.5988	0.5591	0.1107	(2016 BN14)	2016_7_23_1_4_24
312.3218	2.2022	23.4941	134.7662	0.5929	0.7735	267.2748	14.8805	2.6173	0.5927	0.1156	(2016 BN14)	2016_8_7_1_41_20

Notes. Same as Table A.2.

Table A.4. Associations examples of meteors from SonotaCo database with the 2015 TX24 asteroid.

α	δ	V_g	λ	q	e	ω	i	a	Dis	D_{sh}	Desig	meteor_localtime
43.1818	11.0696	30.5240	28.5036	0.2884	0.8649	122.1032	7.2689	2.1351	0.1195	0.1442	(2015 TX24)	20081022_005605
49.8472	12.8092	30.2422	34.3635	0.2803	0.8553	123.8683	7.4797	1.9374	0.4788	0.0418	(2015 TX24)	20081027_220440
49.7198	17.0200	32.3685	34.3753	0.2420	0.8933	127.1055	1.9753	2.2672	0.3548	0.0908	(2015 TX24)	20081027_222253
49.8208	13.9842	30.3591	34.5622	0.2758	0.8583	124.3409	5.9421	1.9460	0.4515	0.0263	(2015 TX24)	20081028_025123
48.0741	13.8526	30.4594	35.2887	0.3049	0.8703	119.3035	5.2224	2.3507	1.2372	0.0855	(2015 TX24)	20091029_021245
50.5474	13.3462	30.4179	35.3834	0.2806	0.8597	123.5157	7.0217	1.9995	1.1539	0.0292	(2015 TX24)	20091029_043020
53.8185	8.0276	31.6086	40.8277	0.3365	0.8981	113.3620	14.4765	3.3021	1.7749	0.1827	(2015 TX24)	20101103_212640
55.9759	15.9776	31.2782	40.9638	0.2682	0.8753	124.2707	5.4260	2.1516	0.3276	0.0836	(2015 TX24)	20101104_004155
42.0675	9.7891	29.8091	29.7871	0.3324	0.8633	115.9308	7.7530	2.4309	0.9833	0.2223	(2015 TX24)	20111024_021850
47.9268	11.2606	30.1309	33.6409	0.3028	0.8579	120.3826	8.5104	2.1317	1.3871	0.1022	(2015 TX24)	20111027_230421
49.0795	14.8858	30.1149	33.6596	0.2710	0.8534	125.4240	4.4537	1.8481	0.2671	0.0410	(2015 TX24)	20111027_233035
50.9554	13.5110	30.6485	37.3398	0.2978	0.8704	120.2903	6.7619	2.2975	1.5417	0.0407	(2015 TX24)	20131031_041839
44.0599	13.0214	32.7855	30.0719	0.2665	0.9094	122.4934	5.5288	2.9406	0.9583	0.1240	(2015 TX24)	20141024_033122
48.5841	15.0229	32.1075	31.9911	0.2359	0.8859	128.5865	4.6334	2.0681	0.7452	0.0612	(2015 TX24)	20141026_014302
47.6989	14.9591	31.3634	32.0261	0.2536	0.8756	126.5754	4.1252	2.0379	1.5879	0.0538	(2015 TX24)	20141026_023259
50.4043	14.2206	30.3051	37.7589	0.3094	0.8675	118.8034	5.4681	2.3351	1.0142	0.0582	(2015 TX24)	20151101_023821
54.1877	14.0211	30.9422	40.5586	0.2963	0.8755	120.1528	7.1993	2.3803	1.3981	0.0280	(2015 TX24)	20151103_214740
54.0047	14.7095	30.3156	40.6506	0.3022	0.8638	120.0167	6.0458	2.2196	1.5678	0.0226	(2015 TX24)	20151103_235948
54.5832	17.9022	31.5241	37.4374	0.2303	0.8741	130.2885	2.4221	1.8293	1.0122	0.1458	(2015 TX24)	20161031_005644
49.5322	13.5175	30.7711	37.4697	0.3151	0.8809	117.2354	6.1003	2.6452	0.1723	0.0864	(2015 TX24)	20161031_014823
55.6745	8.7791	30.7262	30.1024	0.1939	0.8489	138.8985	18.4465	1.2830	0.0993	0.2735	(2015 TX24)	20171023_223950
48.5366	11.3304	32.7920	32.2095	0.2527	0.8994	125.1014	10.1918	2.5131	0.7987	0.0953	(2015 TX24)	20171026_012337

Notes. Same as Table A.2.

Table A.5. Associations examples of meteors from EDMOND database with the 2015 TX24 asteroid.

α	δ	V_g	λ	q	e	ω	i	a	Dis	D_{sh}	Desig	meteor_localtime
48.2506	14.0420	30.9687	39.8319	0.3576	0.9124	109.9187	4.6711	4.0804	1.0677	0.1805	(2015 TX24)	2008_11_2_0_20_18
53.9371	16.7275	30.0311	40.7715	0.2985	0.8578	120.9388	3.3776	2.0990	1.6215	0.0566	(2015 TX24)	2008_11_2_22_51_13
44.1887	13.3976	30.7643	26.5270	0.2379	0.8618	130.1036	5.0636	1.7222	1.0813	0.0761	(2015 TX24)	2009_10_19_22_12_6
47.7460	6.8587	30.2135	31.6536	0.3089	0.8522	119.8947	14.1054	2.0892	1.5786	0.1916	(2015 TX24)	2009_10_25_1_48_21
47.8875	14.3154	31.4230	32.7650	0.2631	0.8785	124.9123	5.0535	2.1656	1.4131	0.0482	(2015 TX24)	2009_10_26_4_31_25
49.3374	13.2856	31.3718	35.3261	0.2849	0.8827	121.4079	6.7937	2.4293	0.0222	0.0537	(2015 TX24)	2010_10_29_0_23_32
48.5038	10.5610	30.2000	35.3581	0.3219	0.8655	117.1919	9.3289	2.3926	0.8326	0.1315	(2015 TX24)	2010_10_29_1_10_9
47.7847	6.7019	30.7538	35.3982	0.3528	0.8866	111.8572	13.4878	3.1109	1.5420	0.2440	(2015 TX24)	2010_10_29_2_8_29
50.5975	13.5060	30.2199	36.2809	0.2926	0.8588	121.7942	6.6364	2.0718	1.2014	0.0350	(2015 TX24)	2010_10_29_23_20_29
50.9000	15.2240	32.1090	38.0083	0.2849	0.9013	120.2664	4.7472	2.8874	1.4825	0.0468	(2015 TX24)	2011_10_31_22_55_15
41.9312	11.8952	30.7472	25.7064	0.2603	0.8645	126.3876	6.0130	1.9202	1.1086	0.1240	(2015 TX24)	2012_10_18_20_51_3
43.9726	8.9654	31.1165	25.7226	0.2526	0.8647	127.5547	11.3504	1.8677	0.8854	0.1433	(2015 TX24)	2012_10_18_21_15_44
42.6148	12.6891	32.0239	27.9681	0.2647	0.8924	123.8197	5.3085	2.4605	0.4451	0.1312	(2015 TX24)	2012_10_21_3_25_32.0
50.1872	15.5907	29.8819	34.3787	0.2668	0.8481	126.4485	3.8832	1.7559	0.8031	0.0518	(2015 TX24)	2013_10_27_20_11_58
47.5799	12.5121	31.6604	35.3031	0.3068	0.8991	117.3822	6.9833	3.0402	1.7107	0.1192	(2015 TX24)	2013_10_28_18_24_15
42.1903	13.9092	31.9910	25.0594	0.2276	0.8836	130.1528	3.6302	1.9549	0.8537	0.1060	(2015 TX24)	2014_10_18_17_36_28
42.9334	15.4598	30.9782	26.2692	0.2373	0.8668	129.8217	1.4757	1.7821	0.1360	0.1127	(2015 TX24)	2014_10_19_22_48_55
50.1856	16.1529	31.4041	34.8809	0.2556	0.8768	126.1403	3.3129	2.0750	0.8008	0.0607	(2015 TX24)	2015_10_28_20_27_38
49.5082	13.0255	32.4401	34.8802	0.2688	0.9000	122.6797	7.6498	2.6873	0.1500	0.0588	(2015 TX24)	2015_10_28_20_27_39
50.6606	14.0875	30.4394	36.1266	0.2847	0.8621	122.7330	6.0049	2.0646	1.2599	0.0220	(2015 TX24)	2015_10_30_2_25_42.0
47.5397	12.5696	30.7491	35.7207	0.3210	0.8828	116.3365	6.5697	2.7382	1.7480	0.1270	(2015 TX24)	2016_10_28_22_49_46
50.1987	7.1204	30.2040	35.7426	0.3315	0.8591	116.2207	14.0720	2.3531	0.8366	0.1911	(2015 TX24)	2016_10_28_23_22_48

Notes. Same as Table A.2.