

# The potential meteoroid streams crossing the orbits of terrestrial planets

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**Abstract.** Using recent databases of orbits of both comets and asteroids, we search for the parent bodies of potential meteoroid streams crossing the orbits of four terrestrial planets. A list of the parents approaching to the orbit of each planet is presented together with some basic parameters of the potential streams. We divide these parents by the relative velocity of the particular approach to the given planet, since only high-speed encounters of the meteoroids of a potential stream can be observed as the meteors in planetary atmospheres.

**Key words:** comets – asteroids – meteoroid streams – terrestrial planets

## 1. Introduction

During a year, an observer on the surface of the Earth can observe several regular meteor showers. It is well known that the particles striking the Earth's atmosphere and producing these showers originate in cometary or asteroidal parent bodies in orbits passing close to the orbit of the Earth. Similar conditions have to be satisfied at the other planets of the solar system, therefore stream meteoroids can impact every planet.

In this work, we search for the parent-body candidates of potential meteoroid streams at four terrestrial planets. The streams impacting the Earth are well-known from observations as well as from other than parent-body investigations. However, we also include the streams at the Earth in the search to check the efficiency of our procedure. The candidates are looked for among the known periodic comets and asteroids. As already indicated, a necessary condition for a stream at a given planet is the proximity of the mean orbit of the stream and the trajectory of the planet. Since the stream is undetectable in free space, its mean orbit can usually be identified, approximately, with the orbit of its parent body. If the orbit of an examined body closely passes the orbit of a considered planet, then this body can be regarded as a potential parent body of a stream of the meteoroids which impact the planet.

If, moreover, the velocity of stream meteoroids relative to the planet is high enough, and the planet has an atmosphere, the colliding meteoroids can produce

a corresponding meteor shower. So, the orbital geometry of found candidates is analysed as well.

## 2. Earlier studies

In course to reveal the meteor streams crossing the orbits of Mars and Venus, as well as other planets of the solar system, several papers have already been published.

Beech and Brown (1995) dealt with the question of a detectability of fireballs in the Venusian atmosphere from the Earth. They found that the observation of such events would not be unreasonable even with small, "amateur-sized" telescopes.

In 1998, Beech tried to determine the large-body meteoroid flux at the orbit of Venus. His analysis indicates that eight meteoroid streams potentially produce meteor showers on both the Earth and Venus. It was not clear at that stage, however, if these streams are likely to yield an associated fireball activity at Venus. Moreover, Beech found a large number of comets and near-Earth asteroids that had nodal points close to the orbit of Venus. Pending the detailed investigation of the orbital evolution of hypothetical stream meteoroids associated with these bodies, it was impossible to predict the potential for such streams to produce an enhanced meteoric activity at the orbit of Venus. However, he noted that two comets, 27P/Crommelin and 7P/Pons-Winnecke, and their presumed associated meteoroid streams, do appear to be worthy of further study. In an attempt of detection of bright fireballs at Venus, Beech suggested directing a particular attention towards the times at which Venus moves through the  $\chi$  Orionid stream, being potentially rich in large meteoroids.

In order to assess the possibility of meteoroid streams detectable from the surface of Mars as meteor showers, Christou and Beurle (1999) derived minimum distances and associated velocities for a large sample of small body orbits relative to the orbits of Mars and the Earth. The population ratio for objects approaching within 0.2 AU of these two planets was found to be approximately 2:1. The smaller relative velocities in the case of Mars appeared to be the main impediment to the detection of meteors in the upper atmosphere of this planet. They identified five bodies, including an unusual object 5335 Damocles and periodic comet 1P/Halley, with relative orbital parameters most suitable to produce prominent meteor showers. Moreover, they identified specific epochs at which showers related to these bodies were expected to occur. An overview of possible detection methods taking into account the unique characteristics of the Martian environment is presented in their paper as well.

To explore potential dangers to Mars-orbiting spacecraft from cometary dust, Treiman and Treiman (2000) screened known comets and meteor showers for those with orbits that closely approach the Mars' orbit. Out of the 135 periodic Mars-crossing comets, the orbits of 50 approach Mars within 0.1 AU and so they

are potential current sources of dust and meteor streams at Mars according to their result. Among these, 1P/Halley, 9P/Tempel 1, and 1991 D1 P/Hermann seem to be the most promising targets for further study. Among known meteor streams, the daytime Arietids and Geminids could produce significant numbers of meteors at Mars but have not produced (so far) meteor storms that could present significant dangers to spacecraft.

In 2001, Larson published a simple geometric method for determining the closest proximity between the orbital paths of two bodies (comet and planet) in the solar system from the known ephemerides of the objects. The method was used to determine whether meteor showers on other planets in the solar system could be associated with any of 250 comets known at that time. Applying criterion for the minimum distance,  $\Delta$ , between the cometary orbits and near Earth's trajectory  $\Delta \leq 5R_l$  ( $R_l$  is the Roche lobe radius), Larson detected 128 possible showers: three at Earth, one at Mars, 106 at Jupiter, 17 at Saturn, and one at Uranus. Only two of three showers predicted at Earth can be identified with the actually observed showers, Leonids and Perseids. Since there are about ten major and few tens of diffuse observed showers at our planet, Larson's method does not seem to be very efficient.

Christou (2004) in his work addressed the question of meteor brightness and height in the Venus' atmosphere, the abundance of meteor showers at Venus relative to the Earth, and a potential observability of these phenomena. He showed that Venus' meteors would typically be as bright, or brighter, and ablate higher in its atmosphere (in 100 – 120 km) than at the Earth. A census of a three-dimensional minimum orbit-to-orbit distance was carried out on sets of known comet, asteroid, and meteor stream orbits. It revealed that (a) a similar number of Halley-type comets but a substantially lesser population of Jupiter family comets approach Venus than the Earth, (b) Venus is likely intercepted by several minor streams detectable at the Earth, possibly the Geminids related to the Asteroid 3200 Phaethon, and also by the orbits of several asteroids that are suspected of being extinct or dormant cometary nuclei. Christou further claimed that it is reasonable to expect a prominent meteor activity at Venus related to four Halley-type comets (1P/Halley, 12P/Pons-Brooks, 27P/Crommelin, and 122P/de Vico), at least one Jupiter-family comet (45P/Honda-Mrkos-Pajdušáková), and Asteroid 3200 Phaethon.

### 3. Cometary streams

From the Catalogue of Cometary Orbits, 15-th edition (Marsden, Williams, 2003) containing 155 short-period and 1516 single-apparition comets, we selected all comets in orbits with the orbital period,  $P$ , shorter than 1 000 years. It is well known that a cometary meteoroid stream can be created only around the orbit of a periodic comet. Apart from short-period comets, which are main candidates to be the parent body of a stream, some periodic comets with a longer orbital

period can be the parent as well. As an example, we can mention the stream of Lyrids associated with comet C/1861 G1 (Thatcher) with  $P \approx 415$  years. To respect this fact, we set the upper limit for the orbital period of the potential cometary parent to 1 000 years.

For some comets, only a parabolic orbit is known. Since a fraction of these bodies are probably the periodic comets with  $P$  shorter than the limit of 1 000 years, we also select these comets as a specific group.

The known parents of major meteoroid streams crossing the orbit of the Earth approach this orbit typically within 0.07 AU (astronomical unit). Specifically, comets 109P/Swift-Tuttle (associated with the Perseids), C/1861 G1 (Lyrids), 55P/Tempel-Tuttle (Leonids), 45P/Honda-Mrkos-Pajdušáková ( $\alpha$ -Capricornids), and 1P/Halley ( $\eta$ -Aquarids) approach the orbit of our planet to 0.00114, 0.00182, 0.00847, 0.0620, and 0.0658 AU, respectively. Asteroid 3200 Phaethon, the parent of Geminids, approaches the orbit of our planet to 0.0208 AU. Therefore, we adopt the distance of 0.07 AU as limiting value, within which the parent of a potential meteoroid stream approaches a given planet closely enough for the significant part of the stream collided with the planet.

It is well known that the stream associated with comet 1P/Halley collides with the Earth two times, whereby the 1P approaches the Earth's orbit second time (when the stream is observed as the meteor shower Orionids) to the distance slightly larger than 0.15 AU. With respect to this fact and to map a wider space around each planet, we look for the approaches of potential parents within the 0.15 AU, too.

The approach of every potential parent to the orbit of a given planet is calculated numerically, considering discrete points of orbit of both the parent and the planet separated by a difference of  $0.001^\circ$  in true anomaly. In the point of parent's orbit being nearest to the orbit of the planet, the velocity vector is recorded. At the same time, we record the velocity vector of the planet in the point of its orbit being nearest to the orbit of the parent. Using these two vectors, we calculate the relative velocity,  $v_r$ , of both the bodies as well as the ecliptical coordinates of the planet-centric radiant of a potential stream (i.e. we use Porter's method for the radiant determination). The ecliptic longitude of the planet-orbit point is also recorded to characterize the position of the planet, when it crosses the corridor of the potential stream.

The numbers of the cometary approaches to the orbit of each of the four considered planets within the limiting distance of 0.07 AU, as well as within the mentioned larger distance of 0.15 AU are given in Tab. 1, cols. 5 and 2, respectively. The approaches of comets with known  $P < 1\,000$  years and those of comets with a known parabolic orbit are presented separately in the first and second parts of the table, respectively. In the interval of visible wavelengths, a meteor shower can be observed only during the night. The best observational conditions are at large elongation,  $E$ . We can formally divide the showers to daily showers with  $E < 90^\circ$  and night showers with  $E \geq 90^\circ$ . (Though a shower with  $E < 90^\circ$  but  $E$  larger than the angular distance of the Sun below the horizon

**Table 1.** The numbers of the approaches of comets to the orbits of terrestrial planets within distances 0.15 ( $N_{15}$ ) and 0.07 AU ( $N_{07}$ ). The periodic comets with the orbital period  $P < 1000$  years and those for which only a parabolic orbit is known are included. The sungrazing comets are, however, not included. (These can be found in Tab. 5.) Apart from the numbers of approaches to a given planet with arbitrary relative velocity  $v_r$  (i.e.  $v_r > 0 \text{ km s}^{-1}$ ), we also give the numbers of the approaches with (i)  $v_r > 20 \text{ km s}^{-1}$  and (ii)  $v_r > 30 \text{ km s}^{-1}$ . The comets with such approaches could associate the streams detectable in the planetary atmosphere as meteor showers. In the visible part of spectrum, the showers are well observable during the night. The first figure in the  $v_r > 20$  and  $v_r > 30$  columns gives the number of the approaches, for which the angular distance of predicted radiant from the Sun is larger than  $90^\circ$  (formally night showers), while the second figure in these columns gives the number of the approaches for which the above angular distance is smaller than  $90^\circ$  (formally daily showers).

planet	$N_{15}$			$N_{07}$		
	$v_r > 0$	$v_r > 20$	$v_r > 30$	$v_r > 0$	$v_r > 20$	$v_r > 30$
comets with known orbital period $P < 1000$ years						
Mercury	10	8 + 2	6 + 1	6	5 + 1	3 + 0
Venus	33	18 + 11	13 + 8	15	6 + 5	2 + 2
Earth	50	12 + 17	9 + 11	24	6 + 8	4 + 5
Mars	91	13 + 9	7 + 7	52	7 + 4	3 + 4
comets with known parabolic orbit						
Mercury	78	38 + 40	34 + 37	33	15 + 18	14 + 16
Venus	129	55 + 64	54 + 61	55	28 + 24	27 + 22
Earth	159	71 + 75	62 + 67	83	38 + 37	32 + 33
Mars	88	38 + 48	28 + 38	39	15 + 24	9 + 21

corresponding to the astronomical twilight is also, in principle, observable in the visible region.) Tab. 1 does not feature the sungrazing comets, because of several reasons introduced in Sect. 5, where the group of the sungrazing comets is separately analyzed.

Seeing Tab. 1, we can state an increasing number of approaching comets with known  $P < 1000$  years from Mercury to Mars. Such an increase can be expected as the increasing length of planetary orbits provides a chance for more bodies to approach them. Further, we can see a relatively large number of comets with known parabolic orbits to approach the orbits of the planets. Though only a part of these comets is in the actual orbits with  $P < 1000$  years, their contribution to the group of potential parents seems to be quite significant. The non-sungrazing comets with known parabolic orbits were observed in past centuries, when people were able to discover them only in a vicinity of the Earth. An imprint of this circumstance is apparent from the maximum numbers of the 0.15 AU and 0.07 AU Earth's approachers.

A collision of meteoroid particle with the Earth's atmosphere is detectable if the impact velocity,  $v_i$ , is high enough. It has been found that the intensity of light from a meteor is proportional to  $\propto v_i^5$ . When we aim to find the candidates for the parents of observable meteor showers, we must therefore discriminate the bodies with a low relative velocity to a given planet at the encounter. We perform this discrimination with the help of the calculated relative velocity  $v_r$  of a considered body to a given planet. In the case of streams at the Earth, this velocity is frequently used and known as the *geocentric* velocity. Apart from Taurids and  $\alpha$ -Capricornids, its value for the major Earth-approaching streams typically exceeds  $30 \text{ km s}^{-1}$ . Only a few streams with mean  $v_r$  down to  $\approx 20 \text{ km s}^{-1}$  are observable as meteor showers. Below this value of  $v_r$ , no meteors appear (only the largest bodies in a stream can be a rare exception).

When we do not take into account the  $v_r$ , we map the potential streams, which can deliver a material onto a given planet. To find the streams which can be observed in the atmosphere of each considered planet as meteor showers, we select from the planet-approaching streams those having (i)  $v_r > 20 \text{ km s}^{-1}$  and (ii)  $v_r > 30 \text{ km s}^{-1}$ . For the sake of completeness and because of a comparison among the results, we do this selection also for Mercury, which has no atmosphere enabling a meteor effect. The atmosphere of Venus is much denser than that of Earth. According Christou (2004), meteors reach here the maximum luminosity in the altitude range of 120 to 100 km. On the contrary, the maximum luminosity of meteors in the Martian tinier atmosphere is reached in the altitude range of 90 to 50 km (Adolfsson *et al.*, 1996).

The numbers of comets approaching the orbits of considered planets with  $v_r > 20 \text{ km s}^{-1}$  as well as  $v_r > 30 \text{ km s}^{-1}$  are again given in Tab. 1. The relative velocity cannot well discriminate among the potential parents approaching the orbit of Mercury. Here, a relatively strong solar gravity causes that all bodies are fast moving. In contrast, the Mars approachers, moving much more slowly, are considerably discriminated by the  $v_r$ . There are generally even less comets approaching the orbit of this planet with  $v_r > 20 \text{ km s}^{-1}$  than those approaching the orbits of Earth and Venus. This deficit is even more pronounced when we realize that roughly two (three) times more comets approach Mars than Earth (Venus), when they are not discriminated by the  $v_r$ . There are almost four times more approaches within 0.07 AU with  $v_r < 20 \text{ km s}^{-1}$  than with  $v_r > 20 \text{ km s}^{-1}$ , for example.

The comets approaching the orbit of a given planet within 0.07 AU with  $v_r > 20 \text{ km s}^{-1}$  are the best candidates for the parent bodies of observable meteor showers. A list of these candidates, with the predicted radiant, relative velocity of encounter, ecliptic longitude of the planet at the moment of the closest approach, minimum distance of the body from the planetary orbits, and elongation of radiant, is given in Tab. 2. One body can approach the given planet one time, either on the pre-perihelion or post-perihelion arc of its orbit, or it can approach the planet two times on both arcs.

**Table 2.** The predicted parameters of streams associated with periodic comets having the orbital period  $P < 1000$  years and approaching the orbits of terrestrial planets within the distance of 0.07 AU with the relative velocity  $v_r > 20 \text{ km s}^{-1}$ . The sun-grazing comets and comets with a known parabolic orbit are not included. The listed comets are the best candidates for the parent bodies of the observed meteor streams. (The candidates for Mercury with no atmosphere appropriate for any meteor phenomenon are listed, too, for the sake of completeness and possibility of a comparison.) The presented parameters are:  $\lambda, \beta$  – ecliptical coordinates of predicted radiant,  $v_r$  – the relative velocity of the body and planet at the closest possible encounter,  $\lambda_p$  – ecliptic longitude of the planet at the moment of the closest encounter,  $r_{\min.}$  – the minimum distance of the comet from the planetary orbit at the closest approach,  $E$  – elongation of the radiant, i.e. the angular distance of the radiant from the Sun. The last column provides information whether the comet approaches the planetary orbit at the pre-perihelion (1) or post-perihelion (2) arc of its orbit.

comet	$\lambda$ [deg.]	$\beta$ [deg.]	$v_r$ [km s <sup>-1</sup> ]	$\lambda_p$ [deg.]	$r_{\min.}$ [AU]	$E$ [deg.]	arc
Mercury							
2P	107.5	32.3	27.7	139.0	0.0257	136	1
D/1766 G1	182.9	5.9	28.8	219.3	0.0284	143	1
D/1766 G1	148.0	12.5	29.0	291.9	0.0133	38	2
C/1886 H1	97.8	59.2	98.1	16.5	0.0617	94	1
C/1987 B2	205.5	74.6	42.3	286.8	0.0591	92	1
C/1989 A3	275.2	57.5	69.4	208.2	0.0006	102	1
Venus							
1P/1982 U1	356.7	6.7	79.3	249.7	0.0490	73	2
27P	24.8	71.0	26.5	72.1	0.0260	103	1
45P	335.2	-2.6	23.5	348.5	0.0100	166	1
45P	314.0	-4.8	23.5	120.7	0.0018	14	2
122P/1995 S1	159.8	-57.0	57.8	79.6	0.0525	95	1
D/1766 G1	166.6	8.0	29.3	168.1	0.0559	172	1
D/1766 G1	164.1	8.2	29.4	342.7	0.0566	8	2
C/1857 O1	290.3	78.0	28.2	26.8	0.0237	89	2
C/1917 F1	109.0	-13.4	45.8	91.0	0.0084	158	1
C/1937 D1	24.9	-49.1	26.1	51.4	0.0349	126	1
C/1963 A1	148.3	-10.2	84.4	50.2	0.0623	82	2
Earth							
1P/1982 U1	340.7	9.8	66.7	228.0	0.0658	68	2
8P	135.4	69.8	33.3	91.2	0.0628	104	1
21P	240.9	79.8	20.4	15.0	0.0385	83	2
45P	323.1	-0.4	24.7	321.8	0.0599	179	1
45P	325.5	-6.4	24.6	146.5	0.0619	6	2
55P/1997 E1	147.4	10.1	70.8	55.0	0.0085	88	2
109P/1992 S2	61.6	38.5	59.4	319.5	0.0011	81	2
D/1770 L1	275.3	2.8	20.9	283.2	0.0143	172	1
D/1770 L1	261.1	0.2	20.9	73.0	0.0234	8	2

C/1846 J1	202.0	13.2	66.4	88.0	0.0490	67	2
C/1861 G1	273.0	56.9	47.1	211.9	0.0018	105	1
C/1917 F1	104.3	-17.4	41.7	83.3	0.0614	153	1
C/1964 N1	31.3	-3.6	68.7	285.5	0.0408	74	2
C/1979 Y1	353.0	16.1	65.0	288.6	0.0674	115	1
Mars							
1P/1982 U1	108.7	-4.8	53.6	51.0	0.0667	122	1
13P/1956 A1	97.5	-44.4	26.8	88.0	0.0265	135	1
45P	316.5	0.3	22.6	303.0	0.0159	166	1
D/1783 W1	124.0	-81.5	21.2	58.6	0.0320	94	2
C/1846 J1	324.9	-12.7	51.9	263.0	0.0414	117	1
C/1889 M1	271.5	-47.1	21.9	272.1	0.0346	133	1
C/1932 G1	352.3	-51.3	36.8	213.6	0.0254	62	2
C/1940 O1	342.2	55.3	31.3	315.9	0.0288	121	1
C/1952 H1	48.2	37.6	50.9	301.6	0.0229	77	2
C/1974 O1	69.3	4.1	61.8	335.6	0.0166	86	2
C/1979 Y1	219.4	-13.4	48.0	98.1	0.0515	60	2

From Tab. 2, one can see that some parents approach the orbits of two or three terrestrial planets. Comets 1P/Halley and 45P/Honda-Mrkos-Pajdušáková in their most recent osculation orbits approach Venus, Earth, and Mars closer than 0.07 AU. The disappeared comet D/1766 G1 approached the orbits of Mercury and Venus in both pre-perihelion and post-perihelion arcs of its orbit. Comet C/1917 F1 approaches the orbits of Venus and Earth, while comets C/1846 J1 and C/1979 Y1 approach the orbits of Earth and Mars within the 0.07 AU distance. Comet 2P/Encke, approaching the orbit of Mercury in a distance shorter than 0.03 AU, is a known parent body of Taurids on the Earth.

A complete list of the parameters of potential cometary streams crossing the orbits of terrestrial planets with the parent approaching the orbit of given planet within 0.15 AU can be found in:

<http://www.astro.sk/caosp/Eedition/FullTexts/vol35no3/pp163-179.dat/>

Concerning an efficiency of the method used in the case of cometary streams, we can state that it predicts all major meteoroid streams with a well-known parent at the Earth, except for a largely dispersed Taurid complex. Moreover, it predicts a quite large number of other streams, which are hardly identified with the known diffuse meteor showers as the characteristics of these showers are quite uncertain. This is the reason of why the efficiency of the method to predict the cometary streams can only roughly be evaluated.

#### 4. Asteroidal streams

From the web-site of the Minor Planet Center of the International Astronomical Union (<ftp://cfa-ftp.harvard.edu/pub/MPCORB/>), we downloaded the data-



base of the orbits of all asteroids known till October 4-th, 2004. The database contained the total of 221,974 osculation orbits. We reduced this huge record by the perihelion distance: no asteroid with the perihelion of 0.15 AU larger than the aphelion of a given planet can approach the orbit of the planet within 0.15 AU. Thus, we obtained four files for each considered terrestrial planet.

Having the data on the asteroidal orbit, we can again calculate the closest approach of every asteroid to the orbit of each of considered planets. Subsequently, it is possible to calculate the parameters of approaches within a limiting distance. In course of a comparison between cometary and asteroidal streams, we look for the numbers of approaches within 0.07 AU. In contrast to the cometary streams, the asteroidal streams do not seem to consist of so large number of meteoroids. The results of past research indicate that an asteroidal stream can be detected if it is not very dispersed. The single well-known asteroidal stream, Geminids, is much more concentrated than the major cometary streams due to its resonance with the planets (Emel'yanenko, 2001). Therefore for asteroids it is reasonable to adopt a shorter limiting approaching distance than for comets. Specifically, we adopt the value equal to the distance of the closest approach of a Geminids' parent, 3200 Phaethon, to the Earth, which is about 0.021 AU.

**Table 3.** The numbers approaches of asteroids to the orbits of terrestrial planets within distances 0.07 ( $N_{07}$ ) and 0.021 AU ( $N_{02}$ ). Apart from the numbers of approaches to a given planet with arbitrary relative velocity  $v_r$  (i.e.  $v_r > 0 \text{ km s}^{-1}$ ), we also give the numbers of approaches with (i)  $v_r > 20 \text{ km s}^{-1}$  and (ii)  $v_r > 30 \text{ km s}^{-1}$ . Similarly to Tab. 1, the first figure in the  $v_r > 20$  and  $v_r > 30$  columns gives the number of the approaches for which the angular distance of predicted radiant from the Sun is larger than  $90^\circ$  (formally night showers), while the second figure in these columns gives the number of the approaches for which the above angular distance is lower than  $90^\circ$  (formally daily showers).

planet	$N_{07}$			$N_{02}$		
	$v_r > 0$	$v_r > 20$	$v_r > 30$	$v_r > 0$	$v_r > 20$	$v_r > 30$
Mercury	180	63 + 66	42 + 45	69	26 + 33	17 + 20
Venus	631	109 + 114	23 + 28	207	29 + 34	5 + 9
Earth	1575	125 + 137	11 + 15	620	47 + 48	5 + 6
Mars	1819	54 + 58	1 + 2	535	15 + 12	0 + 0

The numbers of approaches of asteroids within 0.07 and 0.021 AU to the orbits of terrestrial planets are given in Tab. 3. Again, we present all approaches within these distances as well as the approaches with the relative velocity  $v_r > 20 \text{ km s}^{-1}$  and  $v_r > 30 \text{ km s}^{-1}$ , at which the potential night and daily showers are distinguished. Similarly to the cometary potential parents, a relatively low number of the approaches to the Mars are obviously the consequence of the observational selection effects at asteroid discoveries.

Comparing the cometary and asteroidal approaches within the 0.07 AU distance in Tabs. 1 and 3, respectively, it is clear that many more asteroids than comets pass closely the orbits of the terrestrial planets. Oppositely, we observe, at least in the case of the Earth, significantly more cometary than asteroidal meteor showers. This indicates a different structure of cometary and asteroidal surfaces. The asteroids likely do not produce as rich meteoroid streams as comets. This conclusion is also supported by the fact that the only well-proved asteroidal stream, Geminids, seems to be observable because of a relatively small dispersion of its meteoroids around the mean orbit. Emel'yanenko (2001) showed that the particles of Geminids move in a resonance phase space allowing the dispersion of the semi-major axes two to three orders lower than that of such major streams as Perseids, Orionids/ $\eta$ -Aquadrids, or Lyrids.

When we know all approaches of periodic comets ( $P < 1000$  years) and asteroids to the orbit of a given terrestrial planet within, e.g., 0.15 AU, we can calculate the statistical probabilities of collisions of these minor bodies with the given planet over its entire orbital revolution. Subsequently, we can find the minimum total frequency of the collision of a periodic comet or asteroid with the planet. These minimum frequencies are, on average, one collision per  $4.7 \times 10^8$ ,  $2.7 \times 10^8$ ,  $1.1 \times 10^8$ , and  $1.7 \times 10^8$  years for comets and  $1.3 \times 10^7$ ,  $7.3 \times 10^5$ ,  $3.6 \times 10^5$ , and  $1.2 \times 10^6$  years for asteroids for Mercury, Venus, Earth, and Mars, respectively. The actual frequencies are higher, especially in the case of Mars, because of yet undiscovered bodies. Comparing the frequencies for comets and asteroids, the collisions with the asteroids are currently one to three orders more frequent than those with the periodic comets.

**Table 4.** The predicted parameters of streams associated with the asteroids approaching the orbits of terrestrial planets within the distance of 0.021 AU with the relative velocity  $v_r > 30 \text{ km s}^{-1}$ . (The candidates for Mercury with no atmosphere appropriate for any meteor phenomenon are listed, too, for the sake of completeness and possibility of a comparison.) The same parameters as in Tab. 2 are presented.

asteroid	$\lambda$ [deg.]	$\beta$ [deg.]	$v_r$ [km s <sup>-1</sup> ]	$\lambda_p$ [deg.]	$r_{\text{min.}}$ [AU]	$E$ [deg.]	arc
Mercury							
2212	169.1	15.2	33.7	194.0	0.0070	151	1
1991 VE	175.9	4.8	36.2	187.3	0.0092	168	1
1991 VE	156.2	9.3	36.4	324.6	0.0023	15	2
1995 CR	221.7	2.5	57.4	55.0	0.0164	14	2
1996 FS1	7.6	74.2	43.1	357.1	0.0170	105	1
1999 GR6	193.0	54.1	45.6	6.8	0.0123	54	2
2000 JG5	39.8	62.6	44.6	36.1	0.0044	117	1
2000 WO107	186.6	4.8	48.2	185.4	0.0156	175	1
2000 WO107	189.3	8.0	48.1	10.3	0.0144	8	2

2001 KR1	296.7	18.2	37.5	292.5	0.0198	161	1
2001 KR1	284.8	-32.3	39.9	113.9	0.0112	33	2
2001 SK9	174.2	-48.7	40.5	199.4	0.0190	127	1
2001 SF286	193.9	-65.7	35.5	231.6	0.0047	109	1
2001 UY4	187.6	-9.1	39.4	201.7	0.0032	163	1
2001 VB	102.0	21.4	42.6	108.2	0.0190	158	1
2001 VB	87.9	-6.2	41.7	262.9	0.0204	8	2
2001 WN15	264.9	-62.1	56.8	243.3	0.0013	116	1
2001 YO2	76.3	-63.5	47.8	263.4	0.0127	64	2
2001 YB5	154.8	-4.2	37.5	175.4	0.0037	159	1
2002 AX1	228.3	-78.0	33.1	285.1	0.0198	97	1
2002 AY1	123.6	-62.1	31.3	278.9	0.0079	65	2
2002 AD9	244.4	-75.1	31.6	353.9	0.0144	85	1
2002 BN	139.5	51.4	32.5	306.0	0.0162	53	2
2002 EZ11	262.2	5.4	35.5	77.9	0.0134	7	2
2002 FB3	219.4	52.0	36.8	29.2	0.0029	53	2
2002 FV5	206.3	-41.5	40.1	31.7	0.0206	42	2
2003 FJ1	188.2	50.4	30.9	325.1	0.0079	62	2
2003 WM7	128.0	9.8	35.6	148.8	0.0195	157	1
2003 WM7	101.6	10.9	36.4	266.9	0.0153	18	2
2003 XF11	177.9	19.1	36.9	336.2	0.0074	29	2
2004 BL11	202.0	27.2	34.1	0.3	0.0060	34	2
2004 BD68	264.7	61.6	31.5	8.6	0.0208	83	1
2004 EV9	10.3	72.9	46.2	358.8	0.0008	107	1
2004 HC	212.3	66.0	41.8	27.2	0.0011	66	2
2004 QX2	110.2	-5.4	56.5	300.5	0.0032	12	2
2004 RU10	128.6	-23.7	32.2	143.4	0.0019	152	1
2004 RX109	186.5	-52.6	40.7	207.9	0.0161	124	1
Venus							
36284	113.7	-67.3	33.6	320.7	0.0123	70	2
1995 YR1	136.3	3.4	32.2	324.7	0.0130	9	2
1997 MS	116.5	-52.7	39.1	86.2	0.0183	122	1
1998 UO1	159.4	-21.7	31.6	349.2	0.0179	24	2
2000 WO107	214.1	-0.3	31.8	53.7	0.0104	20	2
2001 ME1	293.7	0.1	31.6	291.0	0.0056	177	1
2001 ME1	298.7	-5.7	31.6	121.7	0.0113	6	2
2001 UY4	187.5	9.4	30.7	15.7	0.0026	12	2
2001 YB5	128.3	-1.5	32.7	122.7	0.0148	174	1
2001 YB5	139.5	6.2	32.8	325.2	0.0030	8	2
2002 EZ11	261.2	-2.2	32.8	245.4	0.0151	164	1
2002 EZ11	297.4	-0.5	32.8	133.7	0.0070	16	2
2002 PM6	98.4	-12.6	37.1	298.1	0.0057	23	2
2002 TZ59	172.4	23.1	30.6	171.7	0.0159	157	1

Earth							
3200	110.9	11.1	33.8	82.5	0.0208	150	1
16960	68.0	-13.3	31.0	263.5	0.0133	20	2
23187	312.0	-57.2	31.2	165.0	0.0159	63	2
89958	345.4	-5.3	32.4	188.0	0.0050	23	2
2001 FO32	205.8	-24.2	34.1	181.6	0.0057	146	1
2001 SN289	219.6	64.7	31.1	176.9	0.0157	108	1
2001 VB	101.1	-4.5	33.0	298.5	0.0208	18	2
2001 YB5	120.0	-4.5	30.5	106.9	0.0042	166	1
2002 AJ129	288.6	-5.9	34.9	136.5	0.0113	28	2
2003 QQ47	287.9	58.8	31.5	181.0	0.0032	81	2
2003 YH136	143.1	10.2	33.9	125.1	0.0081	159	1
Mars							
no asteroid approaching within 0.021 AU with $v_r > 30 \text{ km s}^{-1}$							

The most probable candidates for the parent bodies of asteroidal meteor showers are those approaching the planets within 0.021 AU with  $v_r > 20 \text{ km s}^{-1}$ . In the following, we however constrain our discussion only to the less numerous best part of them, which is characterized with  $v_r > 30 \text{ km s}^{-1}$ . The list of these bodies with various parameters is given in Tab. 4. We can see that there is no asteroid passing the orbit of the Mars with such a high relative velocity. Though we can expect a relatively large amount of meteoroid material falling on this planet, meteor phenomena are obviously rare in its atmosphere. The same conclusion was drawn by Christou and Beurle (1999). Perhaps, it is useful to note that asteroid 3200 Phaethon approaches the orbit of Mars to the relatively short minimum distance of 0.14 AU. But because of the strong concentration of Geminids at the Earth's orbit, it is questionable if at least a small fraction of the stream can cross the orbit of Mars and impact the planet.

Similarly to the cometary parents, some asteroidal parents also approach more than one orbit of the terrestrial planets. Within the distance of 0.021 AU with the relative velocity larger than  $30 \text{ km s}^{-1}$ , the asteroids approaching the orbits of Mercury and Venus are 2000 WO107, 2001 UY4, and 2002 EZ11, that approaching the orbits of Venus and Earth is 2001 YB5, and that approaching the orbits of Mercury and Earth is 2001 VB.

A complete list of the parameters of potential asteroidal streams crossing the orbits of terrestrial planets with the parent approaching the orbit of given planet within 0.15 AU can be found in:  
<http://www.astro.sk/caosp/Eedition/FullTexts/vol35no3/pp163-179.dat/>

Concerning the efficiency of the method used in the case of asteroidal streams, we can say that it predicts, at the Earth, 14 of 17 streams, which are represented in the IAU MDC photographic database by at least five meteors (Kostolanský, 1999, Tab. 1). On the other hand, it predicts a lot of potential streams, at which there is no indication of their existence. In both cometary and asteroidal

streams, the method seems to be maximalistic: it predicts the potential streams of which only a subset does actually exist.

## 5. Comparison with the results of other authors

Several results of our study can be confronted with the corresponding previous results by other authors. We find 43 comets approaching the Earth's orbit and 30 comets approaching the orbit of Venus within 0.15 AU. The ratio of less than 1.5 is significantly smaller than the corresponding ratio of about 3 found by Christou (2004) for the minimum distance of 0.2 AU. However, we confirmed 7 cometary candidates (1P, 12P, 27P, 45P, 72P, 122P, and 141P) for the parent of a potential Venus-intercepting stream suggested by this author.

Our search does not confirm the periodic comet 26P/Grigg-Skjellerup found by Beech (1998) as a parent of potential stream at Venus. Instead, we found several more periodic comets (1P, 2P, 23P, 45P, 141P, 153P, and D/1766 G1) approaching the orbit of this planet.

Christou and Beurle (1999) found only two periodic comets, 1P and 13P, approaching the orbit of Mars with  $v_r > 25 \text{ km s}^{-1}$ . The difference with our result of 8 such comets (Tab. 2) obviously occurs due to the different approach: while Christou and Beurle considered only the short-period comets with  $P < 200$  years, we included the periodic comets with  $P < 1000$  years.

Concerning asteroidal streams, our search does not confirm the suggestion by Beech (1998) that the near-Earth asteroids 5025 P-L, 1990 UA, 2062 Aten, and 1982 TA, having nodal points within 0.1 AU of the Venusian orbit and being associated with the meteoroid streams observed on the Earth, could be appropriate parents of Venus-intercepting meteoroid streams. On the contrary, we confirm the candidates 2101 Adonis, 2201 Oljato, 2212 Hephaistos, and 3200 Phaethon mentioned by Christou (2004) as the parents of the streams passing the orbits of both Venus and Earth.

Christou and Beurle (1999) found three asteroidal candidates of potential meteor showers on Mars, asteroids 2102, 5335, and 5660. They selected these candidates from the database of numbered minor planets requiring an approach to the orbit of Mars within 0.1 AU with  $v_r > 25 \text{ km s}^{-1}$ . That time, the database contained 9246 numbered bodies. Although this number has considerably increased to 90671 numbered bodies in the data set used by us, we find only two more candidates, asteroids 88959 and 89958, using Christou and Beurle's criterion. When the non-numbered bodies in less precise orbits are included, the total number of the candidates is 35.

## 6. Approaches of sungrazing comets

In the past few years, the Solar Heliophysical Observatory (SOHO) spacecraft has discovered several hundreds of comets approaching close to the surface of the

Sun. As they are relatively very small, with sizes of not much exceeding  $\approx 3.5$  m (Iseli *et al.*, 2002), and do not survive their approach to the Sun (Biesecker *et al.*, 2002), no single body of them can create an associated meteoroid stream. If we considered them as ordinary parent bodies, they would only blur the result on regular comets (Sect. 3). It is more reasonable to study this case separately. Eight large sungrazing comets discovered from the Earth's surface (Marsden, 1989) can be omitted in the study as none of them approaches close to the orbit of any terrestrial planet.

A prevailing part of the sungrazing comets belongs to the so-called Kreutz group. The members of the group move within a common corridor, similarly to the meteoroids of a stream. It evokes an idea that the members of this as well as any other sungrazing-comet group could, perhaps, be considered as the largest members of meteoroid stream. Actually, let us study the sungrazing comets discovered from space (mostly *SOHO comets*) from this point of view. Before starting such a study, it is, however, necessary to mention the following three essential differences from an ordinary meteoroid stream. First, small SOHO comets do not survive their approach to the Sun as already mentioned. Therefore, they actually do not approach any planetary orbit in the post-perihelion arc of their orbit. Second, while we know only a very small fraction of orbits of an ordinary cometary stream, we know the orbits of almost all members in the SOHO-comet stream which have approached the Sun in the period of the spacecraft operation. Third, the orbits of the SOHO comets are determined only from a low number of positions gained during a short time of the approach to the Sun. Therefore, the precision of their orbit determination is much lower than that of other comets, and even lower than that of photographic-meteor orbits. We know only the parabolic approximation of the orbit with an assumed perihelion distance and a very uncertain value of the argument of perihelion. Given this circumstance, the result presented in this section is only statistical. Perhaps, it is worthy to note that the SOHO-comet stream is less numerous. Its numerosity can be compared to a diffuse stream (Werner, 2004).

**Table 5.** The numbers of orbital arcs of the sungrazing comets passing the orbits of terrestrial planets within the minimum distances of 0.15 ( $N_{15}$ ) and 0.07 AU ( $N_{07}$ ). The numbers are given separately for the pre-perihelion (pre.) and post-perihelion (post.) arcs of cometary orbit.

planet	$N_{15}$		$N_{07}$	
	pre.	post.	pre.	post.
Mercury	39	89	18	27
Venus	17	35	0	23
Earth	1	33	0	18
Mars	1	21	0	14

There is no exact definition of what is the critical perihelion distance,  $q$ , separating the sungrazing comets from other comets. A prevailing part of the sungrazing comets has  $q < 0.05$  AU. In this work, we however include also several comets with  $0.05 \leq q < 0.075$  AU in the category of the sungrazers to not infiltrate the sample of ordinary comets with those having less accurately determined orbits. So, our sample of the sungrazing comets is chosen by  $q < 0.075$  AU.

The numbers of pre-perihelion approaches of sungrazing comets to the orbits of terrestrial planets are given in Tab. 5. To demonstrate what the situation would be if these bodies survived their approach to the Sun, we also present the numbers of the post-perihelion arcs of sungrazer orbits to the planetary orbits. The relative velocity of every calculated approach exceeds  $\approx 55$ ,  $\approx 50$ ,  $\approx 40$ , or  $\approx 38$  km s<sup>-1</sup> for Mercury, Venus, Earth, or Mars, respectively.

Comparing the sum of pre-perihelion and theoretical post-perihelion approaches of sungrazers in Tab. 5 with the corresponding approaches of the comets with known orbital period  $P < 1000$  years in Tab. 1, we can see that more orbital arcs of the sungrazing comets than those of the periodic comets are situated at a close vicinity of the orbits of Mercury and Venus. At Venus, much more bodies would pass closely to its orbits in the post-perihelion arc if they survived the perihelion passage at the solar surface. In the case of Mercury, even real, pre-perihelion approaches of sungrazers exceed the approaches of periodic comets. The surfaces of Earth and Mars are not threatened by small sungrazing comets as they are completely disintegrated at their perihelion. Otherwise, the frequency of the approaches of these bodies to the orbits of both planets would be quite significant.

## 7. Summary

(i) The number of comets with known  $P < 1000$  years approaching to the orbits of terrestrial planets increases from Mercury to Mars. Specifically, there is 6, 15, 24, and 52 cometary nuclei approaching the orbit of Mercury, Venus, Earth, and Mars, respectively, within 0.07 AU.

(ii) A relatively large number of comets with known parabolic orbits approach the orbits of terrestrial planets (33, 55, 83, and 39 within 0.07 AU for Mercury, Venus, Earth, and Mars, respectively). Though, only a part of these comets are in the actual orbits with  $P < 1000$  years, their contribution to the group of potential parents seems to be quite significant.

(iii) There has been found a relatively low number of asteroids approaching to the orbit of Mars. This is obviously a consequence of the observational selection effects at asteroid discoveries.

(iv) No asteroid approaching the orbit of the Mars within 0.021 AU with the relative velocity larger than 30 km s<sup>-1</sup> is known. Though we can expect

a relatively large amount of meteoroid material falling on this planet, meteor phenomena are obviously rare in its atmosphere.

(v) Comparing the cometary and asteroidal approaches within the 0.07 AU distance, it is clear that many more asteroids than comets pass closely the orbits of the terrestrial planets. On the contrary, we observe, at least in the case of the Earth, significantly more cometary than asteroidal meteor showers. This indicates a different structure of cometary and asteroidal surfaces. The asteroids obviously do not associate as rich meteoroid streams as comets.

(vi) Comparing the sum of pre-perihelion and post-perihelion approaches of sungrazing comets with the corresponding approaches of comets with known orbital period  $P < 1000$  years, we can say that more orbital arcs of the sungrazing comets (altogether 68 within 0.07 AU) than those of the periodic comets (altogether 21 within 0.07 AU) are situated at a close vicinity of the orbits of Mercury and Venus. At Venus, much more bodies would closely pass its orbit in the post-perihelion arc if they survived the perihelion passage at the solar surface. In the case of Mercury, even the real, pre-perihelion approaches of sungrazers exceed the approaches of periodic comets. The surfaces of Earth and Mars are not threatened by small sungrazing comets as these are completely disintegrated at their perihelion. Otherwise, a frequency of the approaches of these bodies to the orbits of both planets would be quite significant.

(vii) Summing the statistical probabilities of collisions of the minor bodies with a given terrestrial planet over its entire orbital revolution, one can find that the minimum total frequency of the collision of periodic comet ( $P < 1000$  years) or asteroid with the planet. These minimum frequencies are, on average, one collision per  $4.7 \times 10^8$ ,  $2.7 \times 10^8$ ,  $1.1 \times 10^8$ , and  $1.7 \times 10^8$  years for comets and  $1.3 \times 10^7$ ,  $7.3 \times 10^5$ ,  $3.6 \times 10^5$ , and  $1.2 \times 10^6$  years for asteroids for Mercury, Venus, Earth, and Mars, respectively.

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