Long-period comet C/1963 A1 (Ikeya), the probable parent body of π -Hydrids, δ -Corvids, November α -Sextantids, and ϑ -Leonids

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ABSTRACT

Aims. We study the meteoroid stream of the long-period comet C/1963 A1 (Ikeya) to predict the meteor showers originating in this comet. We also aim to identify the predicted showers with their real counterparts.

Methods. We modeled 23 parts of a theoretical meteoroid stream of the parent comet considered. Each of our models is characterized by a single value of the evolutionary time and a single value of the strength of the Poynting–Robertson effect. The evolutionary time is defined as the time before the present when the stream is modeled and when we start to follow its dynamical evolution. This period ranges from 10 000 to 80 000 yr. In each model, we considered a stream consisting of 10 000 test particles that dynamically evolve, and their dynamics is followed via a numerical integration up to the present. At the end of the integration, we analyzed the mean orbital characteristics of particles in the orbits approaching Earth’s orbit, which thus enabled us to predict a shower related to the parent comet. We attempted to identify each predicted shower with a shower recorded in the International Astronomical Union Meteor Data Center list of all showers. In addition, we tried to separate, often successfully, a real counterpart of each predicted shower from the databases of real meteors.

Results. Many modeled parts of the stream of comet C/1963 A1 are identified with the corresponding real showers in three video-meteor databases. No real counterpart is found in the IAU MDC photographic or radio-meteor data. Specifically, we predict five showers related to C/1963 A1. Two predicted showers are identified with π -Hydrids #101 and δ -Corvids #729. The third predicted shower is only vaguely similar to November α -Sextantids #483, when its mean orbit is compared with the mean orbit of the November α -Sextantids in the IAU MDC list of all showers. However, the prediction is very consistent with the corresponding showers newly separated from three video databases. Another predicted shower has no counterpart in the IAU MDC list, but there is a good match of the prediction and a shower that we separated from the Cameras for Allsky Meteor Surveillance video data. We name this new shower ϑ -Leonids. The last of the predicted showers should be relatively low in number and, hence, no real counterparts were either found in the IAU MDC list or separated from any considered database.

Key words. comets: individual: C/1963 A1 – meteorites, meteors, meteoroids

1. Introduction

Several long-period comets are known to be the parent bodies of meteoroid streams. The corresponding meteor showers are detected in the Earth’s atmosphere. The aphelion distance may exceed 100 au. The examples of such comets are C/1861 G1 (Thatcher), the parent body of April Lyrids with the aphelion distance $Q = 110.4$ au, and the comets that we recently studied: i.e., C/1964 N1 (Ikeya), the parent of July ξ -Arietids with $Q = 106.2$ au (Neslušan & Hajduková 2018a,b); and C/1975 T2 (Suzuki–Saigusa–Mori), the parent of λ -Ursae Majorids with $Q = 116.0$ au (Hajduková & Neslušan 2019). The orbits of the meteoroids from these comets are influenced by the objects residing beyond the orbit of Neptune. Thus, these can provide us with information about the trans-Neptunian region. This is a benefit of studying the streams of the comets with a long aphelion distance.

In this paper, we aim to increase the list of the studied comets with a large aphelion distance. We model and study a dynamical evolution of the meteoroid stream assumed to originate in the surface of the nucleus of long-period comet C/1963 A1 (Ikeya). Its aphelion distance equals 190.3 au. Comet C/1963 A1 was discovered on January 2, 1963 by Japanese observer K. Ikeya and lastly seen on October 12, 1963. The comet was

closest to the Earth (0.3268 au) on February 15, 1963. Seventy-six positions for this comet measured during the entire period of visibility were used for the orbit calculation by Marsden (Kronk 1999), who determined the perihelion date for this comet of March 21.47 and the orbital period equal to about 932 yr.

The search for new parent bodies of known meteor showers, or predictions of new meteor showers from known parent body, has been performed by many authors. The relationship between meteoroid streams and comets has been studied, through stream modeling, as early as the 1980s by Fox et al. (1983), and more recently, for example, by Hajdukova et al. (2015), Ishiguro et al. (2015), Kornoš et al. (2015), Rudawska et al. (2016), Abedin et al. (2015, 2017, 2018), Babadzhanov et al. (2017), Jenniskens et al. (2017), and Šegon et al. (2017). The association of streams with asteroids have been studied, for example, by Porubčan et al. (2004), Jopek & Williams (2013, 2015), Babadzhanov et al. (2015a,b), Jopek (2015), Rudawska & Vaubaillon (2015), Olech et al. (2016), Wiegert et al. (2017), Dumitru et al. (2018), Sergienko et al. (2018a,b), Ye (2018), Guennoun et al. (2019), and Ryabova et al. (2019). Some authors have attempted to work out or improve a prediction method for a particular shower, often on the basis of known parent body (Koten & Vaubaillon 2015; Ryabova 2016; Sugar et al. 2017; Vaubaillon 2017; Ryabova & Rendtel 2018a,b). All this effort is highly desirable in the

current era when a number of new showers and a number of new members of known showers are reported every year (e.g., Jones 2018; Jenniskens et al. 2018; Koukal 2018; Molau et al. 2018c,a,b; Shiba et al. 2018; Toth et al. 2018; Vida et al. 2018b,a; Wisniewski et al. 2018, if we consider only the last year).

We use the term “stream” to refer to the whole structure of meteoroids released from the parent body. The stream often consists of several “filaments”, i.e., the groups of meteoroids orbiting the Sun in several common corridors. If the particles of a filament hit the Earth, they can cause a meteor “shower” corresponding to the filament.

2. Known orbit of comet C/1963 A1

In our study, we consider the orbit of comet C/1963 A1 with the orbital elements published in the Jet Propulsion Laboratory small-body browser (Giorgini et al. 1996)¹. This orbit, referring to epoch 1963 April 1.0 (JDT = 2 438 120.5), has the following elements: $q = 0.632139$ au, $e = 0.993377$, $a = 95.4460214$ au, $\omega = 336.3018^\circ$, $\Omega = 53.2187^\circ$, $i = 160.6487^\circ$, and $T = 2 438 109.9748$ (1963 March 21.4748). The uncertainty of the orbit determination is unknown. Hereinafter, this orbit is referred to as the nominal orbit. The orbital period of the comet in the nominal orbit is 932 yr and its aphelion is situated in the distance of 190 au from the Sun. The comet passed its aphelion last time on August 1553 in the heliocentric distance of 175 au (aphelion of gravitationally perturbed orbit).

The variation of the orbital elements of C/1963 A1 during the last 100 kyr is shown in Fig. 1. We integrated the orbit of the comet using the RA15 integrator (Everhart 1985), which is the option of the MERCURY software package (Chambers 1999; Chambers & Murison 2000). During the followed period, the perihelion distance (Fig. 1a) frequently varies from ~ 0.5 to ~ 0.7 au. The variations of the perihelion distance and eccentricity are reflected in a large-amplitude variation of semimajor axis (Fig. 1b). This orbital element acquires values from ~ 73 to ~ 167 au during the followed period. The values of argument of perihelion (Fig. 1d) and longitude of ascending node (Fig. 1e) steadily increase.

The positions of orbital nodes in the followed period of 100 kyr are shown in Fig. 2. The ascending node (red dots in Fig. 2) was permanently situated at a vicinity of the orbit of Venus (black circle in Fig. 2) and sometimes approached the orbit of Mercury (green circle). Since the absolute inclination of orbit of the comet to the ecliptic is low, the meteoroids can also collide with Earth, although no node is situated at its orbit. The descending node (blue dots) changed its position from the region in the interior of the orbit of Jupiter (brown arc) to the region beyond the orbit of Saturn (outer cyan arc). No collision with Earth at this node is therefore possible.

The minimum distance between the orbits of the comet and Earth was also investigated. The behavior of this distance is shown in Fig. 3 for the period of the last 100 kyr. The post-perihelion arc has been situated closer to Earth’s orbit than the pre-perihelion arc. However, the minimum distance has not decreased below ~ 0.15 au.

3. Stream modeling

3.1. Recalling the theory

We used the method of the stream modeling developed by Neslušan (1999) and later slightly modified by Tomko &

Neslušan (2012). In the following, we only briefly recall its main steps. At first, the orbit of the parent body is integrated in time backward to the moment of the perihelion passage of the body, which happened closest to an arbitrarily chosen time t_{ev} . We then model a stream. In reality, the formation process of meteoroid stream is a stochastic process. For the purposes of our investigation, we filled the appropriate orbital phase with test particles representing the meteoroids. Specifically, we assumed a cloud of 10 000 test particles to be released from the parent body in the moment of the perihelion passage. All these particles, as well as the parent body itself, are then integrated in time forward, up to the present. A more detailed description of this modeling can be found in papers, for example, by Jakubík & Neslušan (2015) or Tomko & Neslušan (2019).

At the end of the integration, we select the particles that move in the orbits that approach the Earth’s orbit within 0.05 au. Their characteristics correspond to those of the expected shower and, thus, they enable us to predict the mean characteristics of the expected shower.

In our modeling, the numerical integration was performed via the integrator RA15 (Everhart 1985) within the software package MERCURY² (Chambers 1999; Chambers & Murison 2000). We took the gravitational perturbations of eight planets, Mercury to Neptune, into account.

In the models, the dynamics of the particles is assumed to be influenced by the Poynting-Robertson (P-R, hereinafter) effect. The term P-R effect is used to refer to the action of direct solar radial electromagnetic radiation pressure and the velocity-dependent effects on the meteoroid particles. Specifically, we used the formulas published by Klačka (2014).

The strength of the P-R effect is given by parameter β , which is the ratio of the accelerations due to both the P-R effect and the gravity by the Sun. This parameter depends on the properties of particles, such as the size (geometrical cross section), density, light scattering efficiency (on albedo and light absorption ability), and mass. In the case of meteoroids, these properties are rather uncertain. Therefore, we regard β as a free parameter and search, as far as possible, for its value to achieve the best agreement between the predicted and observed characteristics of found filaments of the investigated stream related to the considered parent body.

We created a series of models for various combinations of specific values of evolutionary time t_{ev} and parameter β . In reality, parameter β ranges in a wider interval of values since the stream consists of the particles of various sizes and densities. In addition, the particles are released at various times, therefore their evolutionary time must be different and can also acquire the values from a wider interval. Hence, the particular model we created does not represent a whole stream. The model of a whole stream is a composition of partial models, which give a good prediction of the corresponding real showers.

In greater detail, we created the models for all combinations of values $t_{ev} = 10, 20, 40, 60$, and 80 kyr and $\beta = 10^{-11}$ (this value practically implies no P-R effect), $0.0001, 0.001, 0.003$, and 0.005 . For $\beta = 0.005$, no shower was predicted. Therefore, we also created models for $\beta = 0.004$ and all considered values of t_{ev} . No shower was predicted in two of these additional models.

3.2. Results

It appears that the stream of C/1963 A1 splits up to five filaments that cross the orbit of our planet. Hence, five showers are

¹ <http://ssd.jpl.nasa.gov/sbdb.cgi>

² <https://ascl.net/1201.008>

Fig. 1. Behavior of perihelion distance (*panel a*), semimajor axis (*panel b*), eccentricity (*panel c*), argument of perihelion (*panel d*), longitude of ascending node (*panel e*), and inclination to the ecliptic (*panel f*) of the initially nominal orbit of comet C/1963 A1 (Ikeya). The evolution is reconstructed backward for 100 000 yr. A nongravitational force is ignored.

Fig. 2. Positions of ascending (red points) and descending (blue points) nodes of the orbit of comet C/1963 A1 during the last 100 000 yr. The green, black, violet, cyan, brown, and cyan circles/arcs indicate the orbits of Mercury, Venus, Earth, Mars, Jupiter, and Saturn, respectively.

Fig. 3. Evolution of the minimum distance between the orbital arcs of comet C/1963 A1 and Earth's orbit from 100 000 yr ago to the present. The minimum distance of post-perihelion (pre-perihelion) arc is shown by the red (blue) curve.

predicted. The mean geophysical characteristics of these showers are given in Table 1 and the orbital elements of their mean orbits in Table 2. The distributions of the radiant of theoretical

particles in the individual filaments and the radiant of corresponding real showers are shown in Fig. 4. The overall positions of the radiant areas on sky can be seen in the Hammer projection of the celestial sphere in Fig. 5.

Table 1. Geophysical parameters of the parts of predicted showers.

t_{ev} [kyr]	β	$\langle\lambda_{\odot}\rangle$ [deg]	$\lambda_{\odot,\text{min}} - \lambda_{\odot,\text{max}}$ [deg]	$\langle\alpha\rangle$ [deg]	$\langle\delta\rangle$ [deg]	$\langle V_{\text{g}}\rangle$ [km s ⁻¹]	$\langle V_{\text{h}}\rangle$ [km s ⁻¹]	$\langle\gamma\rangle$ [deg]	n	D_{lim}
Filament F1										
60	10^{-11}	220.9 ± 13.8	203.2–245.2	150.5 ± 11.1	17.5 ± 2.9	70.0 ± 0.7	42.0 ± 0.1	75	15	0.22
60	10^{-04}	220.8 ± 10.0	202.9–237.8	151.1 ± 7.9	17.1 ± 2.0	69.9 ± 0.6	42.0 ± 0.1	74	13	0.21
80	10^{-11}	230.3 ± 13.8	206.1–266.6	160.0 ± 10.5	14.8 ± 3.2	70.0 ± 0.7	42.1 ± 0.1	74	30	0.23
80	10^{-04}	229.9 ± 16.7	199.8–256.7	158.7 ± 12.9	15.1 ± 4.0	70.2 ± 0.9	42.0 ± 0.1	75	21	0.25
80	0.001	242.3 ± 17.4	218.9–267.0	169.0 ± 13.0	12.2 ± 3.8	70.5 ± 0.8	42.1 ± 0.1	77	10	0.22
Filament F2										
60	10^{-04}	323.0 ± 8.5	315.3–331.6	211.9 ± 4.0	-11.2 ± 1.7	69.4 ± 1.2	42.1 ± 0.1	109	4	0.21
80	10^{-04}	337.2 ± 11.4	325.9–356.4	229.0 ± 8.3	-15.4 ± 3.0	70.0 ± 0.9	42.0 ± 0.1	107	5	0.22
Filament F3										
10	10^{-11}	221.2 ± 2.9	215.9–228.4	141.4 ± 1.9	5.8 ± 0.4	70.9 ± 0.2	42.3 ± 0.0	80	137	0.07
10	10^{-04}	220.7 ± 2.7	216.1–228.9	141.0 ± 1.7	5.8 ± 0.4	70.9 ± 0.2	42.3 ± 0.0	79	209	0.08
10	0.001	221.8 ± 3.4	215.5–229.8	141.8 ± 2.2	5.7 ± 0.5	71.0 ± 0.2	42.3 ± 0.0	80	720	0.09
10	0.003	221.9 ± 3.2	215.7–229.5	141.8 ± 2.1	5.7 ± 0.4	71.0 ± 0.2	42.3 ± 0.0	80	675	0.08
10	0.004	221.9 ± 3.5	215.9–229.5	141.8 ± 2.3	5.7 ± 0.5	71.0 ± 0.2	42.3 ± 0.0	80	546	0.08
20	10^{-11}	218.0 ± 3.0	211.9–226.1	138.7 ± 2.0	6.0 ± 0.4	70.7 ± 0.2	42.2 ± 0.0	79	654	0.09
20	10^{-04}	218.0 ± 3.1	212.0–226.9	138.7 ± 2.1	6.0 ± 0.4	70.7 ± 0.2	42.2 ± 0.0	79	663	0.09
20	0.001	218.1 ± 3.2	211.5–225.1	138.8 ± 2.1	6.0 ± 0.4	70.7 ± 0.2	42.3 ± 0.0	79	614	0.08
20	0.003	218.3 ± 3.1	211.4–225.4	138.9 ± 2.1	6.0 ± 0.4	70.7 ± 0.2	42.3 ± 0.0	79	452	0.08
40	10^{-11}	215.0 ± 3.1	207.7–229.0	136.3 ± 2.1	6.2 ± 0.5	70.5 ± 0.3	42.2 ± 0.0	78	609	0.14
40	10^{-04}	215.1 ± 3.2	203.2–227.7	136.4 ± 2.1	6.1 ± 0.5	70.5 ± 0.3	42.2 ± 0.0	78	591	0.14
40	0.001	215.3 ± 3.2	207.9–228.1	136.5 ± 2.2	6.1 ± 0.5	70.5 ± 0.3	42.2 ± 0.0	78	589	0.14
40	0.003	214.2 ± 2.8	208.6–219.6	135.7 ± 1.9	6.3 ± 0.3	70.5 ± 0.3	42.2 ± 0.0	78	151	0.08
60	10^{-11}	211.4 ± 4.0	203.0–231.2	133.6 ± 2.8	7.2 ± 0.8	70.4 ± 0.3	42.2 ± 0.0	78	539	0.15
60	10^{-04}	211.5 ± 3.9	200.3–228.9	133.6 ± 2.8	7.1 ± 0.9	70.4 ± 0.4	42.2 ± 0.0	78	605	0.17
60	0.001	210.8 ± 3.8	202.1–223.2	133.1 ± 2.7	7.2 ± 0.7	70.3 ± 0.3	42.2 ± 0.0	77	555	0.12
60	0.003	210.1 ± 3.3	199.5–224.6	132.6 ± 2.4	7.4 ± 0.8	70.3 ± 0.3	42.2 ± 0.0	77	311	0.17
60	0.004	209.0 ± 3.3	204.2–215.0	131.8 ± 2.2	7.6 ± 0.4	70.2 ± 0.3	42.2 ± 0.0	77	52	0.07
80	10^{-11}	209.4 ± 4.6	197.8–226.4	132.0 ± 3.3	6.6 ± 1.3	70.1 ± 0.4	42.2 ± 0.0	77	584	0.16
80	10^{-04}	209.0 ± 4.8	200.3–230.8	131.7 ± 3.5	6.6 ± 1.3	70.0 ± 0.4	42.2 ± 0.0	77	660	0.17
80	0.001	208.2 ± 4.4	195.0–229.4	131.2 ± 3.2	6.7 ± 1.3	70.0 ± 0.4	42.2 ± 0.0	77	643	0.17
80	0.003	206.8 ± 4.1	197.3–221.4	130.2 ± 3.0	7.0 ± 1.0	69.9 ± 0.3	42.2 ± 0.0	76	346	0.13
80	0.004	205.2 ± 3.6	197.7–219.6	128.9 ± 2.5	7.4 ± 1.0	69.8 ± 0.3	42.2 ± 0.0	76	128	0.13
Filament F4										
60	10^{-11}	318.2 ± 10.1	296.5–337.0	209.3 ± 8.0	-20.0 ± 2.2	70.3 ± 0.5	42.1 ± 0.1	104	77	0.23
60	10^{-04}	318.1 ± 11.4	292.7–345.6	209.6 ± 8.8	-19.5 ± 2.8	70.4 ± 0.6	42.1 ± 0.1	104	77	0.22
60	0.001	316.2 ± 11.3	291.6–341.5	208.3 ± 8.9	-18.9 ± 2.3	70.5 ± 0.5	42.1 ± 0.1	103	29	0.22
80	10^{-11}	317.7 ± 12.4	289.3–344.1	210.0 ± 10.0	-21.3 ± 2.9	70.5 ± 0.5	42.1 ± 0.1	102	160	0.24
80	10^{-04}	317.0 ± 13.0	285.9–343.0	209.4 ± 10.2	-21.1 ± 3.1	70.5 ± 0.5	42.1 ± 0.0	102	141	0.22
80	0.001	317.8 ± 11.5	291.2–343.1	210.5 ± 9.2	-21.2 ± 2.8	70.6 ± 0.5	42.1 ± 0.1	102	70	0.25
80	0.003	313.2 ± 8.0	303.1–322.1	206.8 ± 6.3	-19.6 ± 2.4	70.9 ± 0.2	42.1 ± 0.1	101	4	0.08
Filament F5										
60	10^{-11}	290.6 ± 5.0	284.6–295.0	190.6 ± 2.7	-14.9 ± 1.7	71.5 ± 0.3	42.2 ± 0.1	95	4	0.16
80	10^{-11}	272.7 ± 5.7	264.4–278.2	179.2 ± 4.2	-11.5 ± 2.8	71.4 ± 0.2	42.2 ± 0.0	89	5	0.20

Notes. The following denotation is used: t_{ev} is the evolutionary time (i.e., the time before the present when the part of the stream was modeled); β is the parameter, characterizing the strength of P-R effect; $\langle\lambda_{\odot}\rangle$ is mean solar longitude; $\lambda_{\odot,\text{min}}$ and $\lambda_{\odot,\text{max}}$ are the minimum and maximum solar longitudes of shower occurrence delimiting the shower activity; $\langle\alpha\rangle$ and $\langle\delta\rangle$ are the mean equatorial coordinates of geocentric radiant; $\langle V_{\text{g}}\rangle$ and $\langle V_{\text{h}}\rangle$ are the mean geocentric and heliocentric velocities; $\langle\gamma\rangle$ is the angular distance of mean radiant from the Sun in time corresponding to $\langle\lambda_{\odot}\rangle$; n is the number of particles in the predicted shower; and D_{lim} is the limiting value of the Southworth-Hawkins D_{SH} discriminant to select the shower.

In panels b and d of Fig. 4 and panel b of Fig. 5, the positions of radiants are shown in the ecliptical coordinate system centered on the apex of the motion of Earth around the Sun. This

coordinate system differs from the common ecliptical coordinate system by its longitude, λ_2 , which is related to the longitude of the common ecliptical coordinates, λ , as $\lambda_2 = \lambda - (\lambda_{\odot} + 270^\circ)$;

Table 2. Mean orbital elements of the parts of predicted showers.

t_{ev} [kyr]	β	$\langle q \rangle$ [au]	$\langle a \rangle$ [au]	$\langle e \rangle$	$\langle \omega \rangle$ [deg]	$\langle \Omega \rangle$ [deg]	$\langle i \rangle$ [deg]
Filament F1							
60	10^{-11}	0.796 ± 0.079	44.5 ± 36.9	0.976 ± 0.010	130.8 ± 12.6	224.1 ± 13.4	170.1 ± 4.6
60	10^{-04}	0.782 ± 0.067	37.6 ± 11.1	0.978 ± 0.006	123.1 ± 14.5	218.8 ± 15.3	170.3 ± 3.2
80	10^{-11}	0.794 ± 0.069	42.6 ± 14.7	0.979 ± 0.008	124.7 ± 17.1	227.6 ± 18.3	168.6 ± 3.8
80	10^{-04}	0.807 ± 0.082	50.5 ± 57.4	0.978 ± 0.009	130.1 ± 20.7	229.8 ± 21.8	168.8 ± 3.5
80	0.001	0.855 ± 0.093	35.5 ± 11.5	0.974 ± 0.008	133.1 ± 14.1	238.7 ± 16.8	166.9 ± 2.8
Filament F2							
60	10^{-04}	0.689 ± 0.112	51.6 ± 24.6	0.983 ± 0.011	222.1 ± 29.4	298.8 ± 28.2	176.6 ± 1.6
80	10^{-04}	0.766 ± 0.078	39.1 ± 15.1	0.978 ± 0.008	225.7 ± 17.0	326.5 ± 16.8	175.1 ± 2.7
Filament F3							
10	10^{-11}	0.892 ± 0.028	333.7 ± 47.4	0.997 ± 0.000	329.2 ± 1.0	44.6 ± 0.9	164.5 ± 0.3
10	10^{-04}	0.887 ± 0.025	318.1 ± 42.7	0.997 ± 0.000	329.2 ± 0.9	44.7 ± 0.9	164.4 ± 0.3
10	0.001	0.899 ± 0.033	379.0 ± 117.6	0.997 ± 0.001	328.5 ± 1.0	44.1 ± 1.1	164.5 ± 0.4
10	0.003	0.899 ± 0.031	381.8 ± 116.0	0.997 ± 0.001	328.4 ± 0.9	44.0 ± 1.0	164.5 ± 0.4
10	0.004	0.900 ± 0.034	389.7 ± 116.4	0.998 ± 0.001	328.3 ± 1.0	43.9 ± 1.1	164.5 ± 0.4
20	10^{-11}	0.889 ± 0.032	444.6 ± 317.8	0.998 ± 0.001	325.7 ± 1.3	39.9 ± 1.4	163.2 ± 0.5
20	10^{-04}	0.889 ± 0.033	439.0 ± 221.5	0.998 ± 0.001	325.6 ± 1.3	39.8 ± 1.3	163.2 ± 0.5
20	0.001	0.890 ± 0.034	478.4 ± 346.6	0.998 ± 0.001	325.6 ± 1.3	39.8 ± 1.3	163.2 ± 0.5
20	0.003	0.893 ± 0.032	465.1 ± 269.5	0.998 ± 0.001	325.2 ± 1.1	39.5 ± 1.2	163.2 ± 0.4
40	10^{-11}	0.880 ± 0.033	458.5 ± 241.9	0.998 ± 0.001	323.5 ± 1.9	36.6 ± 2.1	162.2 ± 0.8
40	10^{-04}	0.882 ± 0.033	457.2 ± 256.0	0.998 ± 0.001	323.4 ± 1.9	36.5 ± 2.0	162.2 ± 0.8
40	0.001	0.884 ± 0.034	457.8 ± 233.1	0.998 ± 0.001	323.2 ± 1.9	36.4 ± 2.0	162.2 ± 0.9
40	0.003	0.879 ± 0.032	512.7 ± 407.8	0.998 ± 0.001	322.3 ± 1.2	35.3 ± 1.4	162.0 ± 0.6
60	10^{-11}	0.870 ± 0.034	468.7 ± 264.6	0.998 ± 0.001	321.1 ± 2.7	32.9 ± 3.2	162.5 ± 1.3
60	10^{-04}	0.870 ± 0.035	463.2 ± 271.5	0.998 ± 0.001	321.0 ± 3.0	32.8 ± 3.4	162.3 ± 1.6
60	0.001	0.867 ± 0.035	476.7 ± 300.2	0.998 ± 0.001	320.5 ± 2.6	32.2 ± 2.9	162.3 ± 1.2
60	0.003	0.865 ± 0.033	505.9 ± 446.8	0.998 ± 0.001	319.2 ± 2.1	31.0 ± 2.7	162.2 ± 1.3
60	0.004	0.862 ± 0.037	527.6 ± 366.7	0.998 ± 0.001	318.7 ± 1.4	29.9 ± 1.5	162.1 ± 0.7
80	10^{-11}	0.860 ± 0.035	416.0 ± 273.4	0.998 ± 0.001	318.9 ± 3.5	30.5 ± 4.4	160.6 ± 1.9
80	10^{-04}	0.857 ± 0.036	413.6 ± 241.0	0.998 ± 0.001	318.5 ± 3.5	30.2 ± 4.4	160.5 ± 1.8
80	0.001	0.854 ± 0.034	425.2 ± 301.0	0.998 ± 0.001	317.7 ± 3.2	29.3 ± 4.2	160.3 ± 1.8
80	0.003	0.849 ± 0.035	443.1 ± 360.8	0.998 ± 0.001	316.4 ± 2.5	27.7 ± 3.6	160.3 ± 1.3
80	0.004	0.844 ± 0.035	518.5 ± 491.1	0.998 ± 0.001	315.3 ± 1.9	26.0 ± 2.6	160.3 ± 1.2
Filament F4							
60	10^{-11}	0.824 ± 0.057	35.2 ± 7.4	0.976 ± 0.005	46.6 ± 13.2	137.9 ± 13.8	166.2 ± 3.4
60	10^{-04}	0.823 ± 0.066	38.1 ± 18.5	0.976 ± 0.006	45.8 ± 13.5	137.3 ± 14.1	167.1 ± 3.3
60	0.001	0.838 ± 0.065	34.8 ± 8.5	0.975 ± 0.006	44.9 ± 13.1	136.2 ± 13.8	167.1 ± 3.4
80	10^{-11}	0.854 ± 0.058	37.1 ± 7.7	0.976 ± 0.005	40.7 ± 12.5	137.0 ± 14.4	164.4 ± 3.3
80	10^{-04}	0.854 ± 0.062	38.1 ± 8.7	0.976 ± 0.006	40.8 ± 13.1	136.6 ± 14.5	164.3 ± 3.2
80	0.001	0.861 ± 0.058	37.4 ± 7.9	0.976 ± 0.005	39.9 ± 12.5	137.2 ± 13.7	164.9 ± 3.3
80	0.003	0.873 ± 0.035	37.6 ± 9.5	0.975 ± 0.007	33.9 ± 4.2	129.4 ± 5.9	165.8 ± 2.8
Filament F5							
60	10^{-11}	0.953 ± 0.046	34.4 ± 7.1	0.971 ± 0.006	15.7 ± 7.8	109.1 ± 2.3	163.6 ± 2.6
80	10^{-11}	0.950 ± 0.020	34.0 ± 4.3	0.972 ± 0.003	356.0 ± 8.0	92.5 ± 5.3	161.3 ± 2.3

Notes. The parameter t_{ev} is the evolutionary time (the time before the present when the part of the stream was modeled) and β is the parameter characterizing the strength of P-R effect.

$\lambda_{\odot}$ is the solar longitude of meteor. The latitude of the apex-centered system is the same as that in the common system.

We note that some authors prefer to use the Sun-centered ecliptical coordinate system with the longitude $\lambda' = \lambda - \lambda_{\odot}$. We see that there is the constant difference of 270° between λ_2 and λ' ; therefore the relative positions of radiants and sizes of the radiant areas are exactly the same in both Sun-centered and

apex-centered coordinate systems. We prefer to use the apex-centered system since the symmetry of radiant areas can better be seen in this frame.

In Figs. 4b,d and 5b, we see a grouping of the radiants around the apex of Earth's motion around the Sun. This grouping is obviously a consequence of low-inclined, but retrograde orbits of meteoroids and suitable geometry leading to the collision

Fig. 4. Positions of predicted radiants in the constructed models (*panels a and b*) and radiants of corresponding real meteors (*panels c and d*). The positions are shown in the equatorial (*panels a and c*) and the Earth apex centered ecliptical coordinate (*panels b and d*) frames. *Panels a and c*: the sinusoid-like curve is the ecliptic. The positions of the radiants of various filaments and showers are distinguished by various symbols and colors. *Panels c and d*: positions of meteor radiants separated from the C, S, and E catalogs are also distinguished by black, blue, and yellow, respectively.

Fig. 5. Overall positions on sky of predicted radiants in the constructed models and radiants of corresponding real meteors. The positions are shown in the Hammer projection of the celestial sphere. *Panel a*: equatorial coordinate system is used. The sinusoid-like curve is the ecliptic. *Panel b*: Earth apex centered ecliptical coordinate frame is used. The positions of the radiants of theoretical particles are shown with black full circles. The position of the radiants of real meteors separated from the C, S, and E catalogs are shown with blue asterisks, red crosses, and green empty squares, respectively.

of meteoroids with our planet just when their velocity vector is almost opposite from the velocity vector of Earth. As

a consequence of this circumstance, the geocentric velocity of meteoroids is close to the maximum collisional velocity of two solar system objects ($\sim 72 \text{ km s}^{-1}$). We note that the grouping of the radiants around Earth's apex and high geocentric velocity were also observed for the filaments and corresponding showers of long-period comet C/1964 N1 (Ikeya) (Neslušan & Hajduková 2018a,b). The showers of C/1964 N1 are active in other periods of year than the showers of C/1963 A1.

In the case of the showers of comet C/1963 A1, there is also a symmetry of the radiant areas of filaments (of corresponding showers) with respect to the Earth apex: the area of filament F1 is symmetrical with that of filament F4 (Figs. 4b,d). An analogous symmetry between the areas of filaments F2 and F3 is not as clear. Nevertheless, we can state a symmetry in the sense that the area of F2 is situated in the upper left quarter of the celestial sphere (when the apex-centered coordinate frame is considered) and area of F3 in the lower right quarter.

Comets C/1964 N1 and C/1963 A1, as the parent bodies, are also similar in that in both cases, after a long time ($>50 \text{ kyr}$), the fifth filament of their streams emerged. This filament has the radiant area situated below the ecliptic and between the radiant areas of filaments F3 and F4. We can speculate that filament F5 occurs, in both comets, owing to a secular resonance. Proving this hypothesis, however, exceeds the scope of this work.

4. Identification of the predicted showers with real showers

The mean dynamical characteristics of the predicted shower were used to search for the corresponding real shower. We searched for the real shower in the International Astronomical Union Meteor Data Center (IAU MDC) list of all showers and in the databases of meteor orbits.

4.1. Identification with the showers in the IAU MDC list

The real counterparts of the predicted showers can be expected to be recorded in the IAU MDC list of all showers³ (Jopek & Kaňuchová 2014). Since only the mean characteristics of the showers are available in the list, we identified our predictions, by the individual models, to the shower in the list using the Southworth-Hawkins discriminant, D_{SH} (Southworth & Hawkins 1963). We calculated the value of D_{SH} for every pair of orbits, where the first component of the pair was the mean orbit of predicted shower and the second component was the orbit in the list.

In our experience, the dispersion of the meteors in the major showers, characterized by the limiting value of the D_{SH} , ranges from 0.07 to 0.20 (see, e.g., Neslušan et al. 1995). The extraordinary numerous Perseids had $D_{lim} = 0.32$ when separated from the photographic IAU MDC database. Hence, we accepted the upper limit for the identification of predicted shower to its real counterpart equal ~ 0.20 . This value is, of course, not strict.

We found an excellent agreement between the predicted mean orbit of filament F4 in the model for $(t_{ev}, \beta) = (80 \text{ kyr}, 0.001)$ and π -Hydrids #101, as determined by (Jenniskens 2006). In this case, $D_{SH} = 0.083$. The identification of the F4 with this shower was also successful for several other models for $t_{ev} = 60$ and 80 kyr ; the value of D_{SH} varied up to 0.115. π -Hydrids is a minor shower, which was reported for the first time in (Jenniskens 2006). This shower was confirmed by Molau & Rendtel (2009) and Molau et al. (2017).

In the IAU MDC list, the π -Hydrid shower is given in three variants. Aside from the above-mentioned mean orbits by Jenniskens (2006) and Molau & Rendtel (2009), who provided only the geophysical parameters (orbital elements are missing), the mean parameters of this shower were also determined by Jenniskens et al. (2018). This last variant is largely different from the two previous variants and does not practically match any predicted shower; we give its mean parameters in Tables 3 and 4 in the parentheses to demonstrate the large differences. Most likely, this variant of π -Hydrids is contaminated by meteors of other showers.

Our prediction of filament F5 in the model for $(t_{ev}, \beta) = (80 \text{ kyr}, 10^{-11})$ could be identified with δ -Corvids #729, as derived by Jenniskens et al. (2016c). These authors already stated that the parent body is probably a long-period comet. The difference between both mean orbits predicted and given by Jenniskens et al. was characterized by $D_{SH} = 0.169$. However, this was the single successful identification of filament F5. For the other models the value of D_{SH} was larger than 0.4. The same is valid for all predicted models and the variant of the shower in the IAU MDC list presented by Jenniskens et al. (2018).

Finally, we discuss a vague similarity between filament F3 and November α -Sextantids #483. When calculating D_{SH} between each of 1185 variants of 792 showers in the IAU MDC list of all showers and each of the predicted variants of filament F3, the value of D_{SH} is lower than 0.4 only for November α -Sextantids. For a few predicted variants, $D_{SH} = 0.310$ or D_{SH} is higher but also lower than 0.4 for α -Sextantids #439. Comparing the mean characteristics of both showers #483 and #439, it seems that #439 is a substructure of #483 detected at the end of activity of the latter. It is, thus, a duplicate naming of the same shower and should likely be deleted from the list. This is why we suspect that there could be a relationship between

the filament and shower #483, even though this shower has a large D_{SH} , which significantly exceeds the adopted upper limit of ~ 0.20 .

Specifically, in the IAU MDC list, the real shower is given in two variants with the mean characteristics derived by Rudawska & Jenniskens (2014), who found the shower in both Cameras for Allsky Meteor Surveillance (CAMS) and SonotaCo databases. The value of D_{SH} between the mean orbit of the shower and that in every model for $t_{ev} = 10 \text{ kyr}$ listed in Tables 1 and 2 equals 0.279. If we consider the models for $t_{ev} = 20 \text{ kyr}$ (40, 60, and 80 kyr), then $D_{SH} = 0.285$ or 0.283 in a single case (0.292 to 0.295, 0.317 to 0.329, and 0.313 to 0.336). The value of D_{SH} for any predicted mean orbit of filament F3 and that of the November α -Sextantids, as determined by Jenniskens et al. (2016a), varies from 0.303 to 0.356. Such the high values cannot be an evidence of relationship between the shower and its parent body. However, we newly separated the variants of the November α -Sextantids from three video databases that are much more similar to filament F3 (see Sect. 4.2); therefore the relationship still seems to be real.

Filament F3 was predicted to be the most numerous of all five predicted filaments (see the second last column, labeled as n , in Table 1). The fact that a shower that would match the prediction well is missing in the observational data can be caused by worse observational conditions. The angular distance, $\langle \gamma \rangle$, of mean radiant of filament F4 from the Sun (see the third last column in Table 1) is $\langle \gamma \rangle \geq 101^\circ$ (and of filament F5 $\langle \gamma \rangle \geq 89^\circ$), therefore a prevailing part of π -Hydrids (and δ -Corvids) can be seen on the January night sky; the angular distance of mean radiant of filament F3 from the Sun is $\langle \gamma \rangle \leq 80^\circ$. Therefore, a relatively large portion of meteors corresponding to F3 can be seen on the daily November sky.

The predicted filaments F1 and F2 were not identified with any IAU MDC shower. The values of D_{SH} were larger than 0.377 for F1 and larger than 0.4 for F2. A shower corresponding to F1, if it exists, is predicted to be an order of magnitude less numerous than the showers corresponding to filaments F3 and F4. The observational conditions to observe F1 meteors are similarly bad as those of F3. In the case of F1, $\langle \gamma \rangle = 74^\circ - 77^\circ$ (Table 1, the second last column).

On the contrary, the best conditions in the discussed context are those at observations of meteors related to F2, where $\langle \gamma \rangle \sim 109^\circ$ in the first half of February. However, the shower corresponding to filament F2 is predicted to be low in numbers. This shower is “indicated” rather than “predicted” because it was predicted only in two models, i.e., for $(t_{ev}, \beta) = (60 \text{ kyr}, 10^{-4})$ and $(t_{ev}, \beta) = (80 \text{ kyr}, 10^{-4})$, and only with the help of four and five particles, respectively. This is obviously the reason of why no observational counterpart of F2 was found. We note that none of the identified showers at filaments F3–F5 were classified as established.

4.2. Separation of real showers from databases

We searched for a corresponding shower in the following meteor databases: (1) the IAU MDC photographic database, version-2013 (Porubčan et al. 2011; Neslušan et al. 2014); (2) the IAU MDC CAMS video database (Gural 2011; Jenniskens et al. 2011, 2016a,b,c; Jenniskens & Nénon 2016); (3) the 2007–2015 SonotaCo video (SonotaCo 2009, 2016); the European viDeo MeteOr Network Database (EDMOND) video (Kornoš et al. 2014a,b); and (5) the radio-meteor database (Hawkins 1963; Sekanina & Southworth 1975; Lindblad, priv. comm.). These databases contain 4873, 110 521, 208 826, 145 830, and 62 907

³ http://www.ta3.sk/IAUC22DB/MDC2007/Roje/roje_lista.php?corobic_roje=1&sort_roje=0

records on meteor orbits and geophysical data, respectively. We briefly refer to these databases with the capital letters F, C, S, E, and R, respectively.

To select the meteors of searched shower from the given database, we used the “break-point method” (Neslušan et al. 1995, 2013). We briefly describe the main steps of this method, which is based on an analysis of the dependence of the number of selected shower meteors on the limiting value of the Southworth-Hawkins (Southworth & Hawkins 1963) D_{SH} discriminant, D_{lim} .

In the first step, we calculate the values D_{SH} between the mean orbit of predicted shower and every meteor in the database considered. If D_{SH} is smaller than a chosen limiting value, D_{lim} , then the meteor is regarded as the member of the shower. Then, we calculate the mean orbit of the separated group of shower meteors and, in the second step, calculate D_{SH} between this new mean orbit and every meteor in the database. And, considering the meteors separated in this step, we again calculate their mean orbit, which is again the reference orbit for the new selection, etc. We terminate this iteration procedure, when the difference between two successive mean orbits is negligible. In the final separation, we obtain N shower meteors.

The above sketched iteration procedure is performed for a series of limiting values D_{lim} , usually 0.01, 0.02, 0.03, ..., 0.50. Having the corresponding numbers of separated meteors, we can construct the dependence $N = N(D_{lim})$. If the corresponding real shower was recorded in the database, the dependence exhibits a convex behavior followed by a constant or only moderately increasing behavior, known as a plateau. The value of D_{lim} corresponding to the beginning of the plateau is the most appropriate to separate the densest core of the shower from the database. In other words, the actual members of the shower in our search are the meteors separated within the iteration procedure using this critical D_{lim} .

The iteration procedure might sometimes significantly change the mean orbit of the separated shower from its prediction. After the separation, it is therefore necessary to evaluate a measure of relationship between the theoretically predicted and separated real shower. We did this evaluation suggesting and performing the following empirical procedure. We calculated the mean value of the Southworth-Hawkins D-discriminant, $\langle D_{mj} \rangle$, between the mean orbit of real shower and each orbit of its members and its statistical uncertainty, σ_D . We suppose that, when the diversity is evaluated with the help of the D_{SH} criterion, the orbit of any member of the predicted shower should not differ from the orbit of at least one meteor of real shower more than about $\langle D_{mj} \rangle + \sigma_D$. We added σ_D , since some meteors of the shower itself at the border of its orbital phase space would not differ within $\langle D_{mj} \rangle$ alone.

Subsequently, we calculated D_{SH} between every pair of the orbits of both theoretical particle and meteor of real shower. If $D_{SH} \leq (\langle D_{mj} \rangle + \sigma_D)$ at least once, then the particle of predicted shower is regarded as matching the real shower. The values of $\langle D_{mj} \rangle$ with their sigmas for the separated real showers are given in the last column of Table 3.

Let us denote the number of the matching particles as n_{yes} and the number of the other particles as n_{no} , where the sum $n_{yes} + n_{no}$ equals the total number of the particles of predicted shower. The measure of the agreement of corresponding predicted and real showers is then defined as

$$\eta = \frac{n_{yes}}{n_{yes} + n_{no}}. \quad (1)$$

The mean characteristics of the successfully separated real showers, corresponding with the filaments F1, F3, F4, and F5,

are given in Tables 3 and 4 together with the measure of the best agreement, η_b . We speak about the best agreement since the agreement is different for the real shower and shower predicted in various models.

As seen in Tables 3 and 4, the real counterpart of predicted filament F1 was separated only from S catalog. The shower related to F3 was separated from C, S, and E catalogs; that related to F4 from S and E catalogs; and F5-related shower only from S catalog.

The minimum and often also maximum values of D_{SH} between the mean predicted and separated-shower orbits (see the second column in Table 3) are lower than such values between the mean predicted and IAU MDC shower orbits. Likely, the quality of the separation of a shower from the database can be better if the shower is predicted and, hence, its approximate mean orbit (entering the iteration procedure as initial orbit) is known.

When we compare the mean parameters of the separated showers with those of corresponding showers in the IAU MDC list (Tables 3 and 4), both groups are consistent and, hence, the showers separated by us can be regarded as further variants of π -Hydrids #101 and δ -Corvids #729. It also seems that our separations from C, S, and E catalogs of the shower corresponding to filament F3 can be regarded as variants of November α -Sextantids #483. Especially in the case of separations from S and C catalogs, the agreement between the prediction and these variants of a real shower is ordinarily good enough to identify the predicted filament F3 with November α -Sextantids.

It is well-known that the SonotaCo team often performs the observations of meteors during daytime as well. It is therefore not surprising that a shower, corresponding to filament F1 with the predicted daytime prevailing activity, was separated just from the SonotaCo catalog. The separated shower is again in good agreement with the corresponding prediction. No relevant shower was found in the IAU MDC list, therefore it is a new shower. Its mean radiant is situated in the constellation of Leo, close to stars ρ Leonis and θ Leonis. Since the shower named ρ -Leonids already exists and it is a different shower, we suggest the new shower, originating in comet C/1963 A1 and corresponding to the predicted filament F1, be named θ -Leonids.

5. Summary

We modeled the theoretical stream originating from the long-period comet C/1963 A1 (Ikeya). It appears that the stream has a filamentary structure; we determined five filaments intersecting the orbit of the Earth.

Since the comet moves around the Sun in a low-inclined, but retrograde orbit, its geocentric velocity and the geocentric velocity of its meteoroid stream in a trajectory near the Earth's orbit is high, i.e., $\sim 70 \text{ km s}^{-1}$. Consequently, the radiant areas of all filaments are situated near the apex of the Earth's heliocentric motion. The radiant areas of the filament that we refer to as F1 is symmetrical to that of the filament referred to as F4 with respect to the apex of the Earth's motion around the Sun. A certain symmetry of the radiant areas of filaments F2 and F3 can also be stated.

Two mostly night-time filaments, F4 and F5, were identified with the real showers in the IAU MDC list of showers and also separated from one or two considered video catalogs. Specifically, the filament F4 corresponds well to π -Hydrids #101 and F5 corresponds to δ -Corvids #729. We successfully separated π -Hydrids from S and E catalogs and δ -Corvids from the S catalog.

Table 3. Mean geophysical parameters of the real meteor showers related to the predicted filaments of comet C/1963 A1.

cat.; ref.	$D_{\min} - D_{\max}$	$\langle \lambda_{\odot} \rangle$ [deg]	$\lambda_{\odot, \min} - \lambda_{\odot, \max}$ [deg]	$\langle \alpha \rangle$ [deg]	$\langle \delta \rangle$ [deg]	$\langle V_g \rangle$ [km s ⁻¹]	$\langle V_h \rangle$ [km s ⁻¹]	$\langle D_{mj} \rangle$
Shower corresponding to Filament F1; ϑ -Leonids								
S	0.086–0.137	235.3 ± 9.0	224.2–251.8	161.4 ± 7.0	13.0 ± 3.3	70.2 ± 0.7	41.4 ± 0.5	0.092 ± 0.032
Shower corresponding to filament F3; November α -Sextantids, #483								
C	0.115–0.166	222.9 ± 18.3	190.5–249.8	142.4 ± 13.4	1.4 ± 4.7	70.4 ± 1.1	42.6 ± 0.7	0.194 ± 0.059
S	0.085–0.145	221.9 ± 5.9	211.1–232.3	140.6 ± 4.2	4.0 ± 2.0	69.9 ± 0.8	41.5 ± 0.7	0.098 ± 0.016
E	0.185–0.227	215.3 ± 10.0	200.0–239.0	136.8 ± 7.4	1.2 ± 3.2	68.4 ± 1.5	41.5 ± 0.6	0.161 ± 0.069
[1]	0.279–0.336	231.4		149.9	–3.4	71.1		
[2]	0.303–0.356	232.0		148.8 ± 0.91	–3.9 ± 0.34	69.0		
Shower corresponding to filament F4; π -Hydrids, #101								
S	0.036–0.078	314.2 ± 5.2	303.3–324.3	207.2 ± 4.1	–20.0 ± 1.7	70.6 ± 0.6	42.0 ± 0.5	0.090 ± 0.028
E	0.115–0.138	315.6 ± 8.1	297.9–330.4	209.5 ± 6.2	–20.3 ± 2.6	69.5 ± 0.8	40.7 ± 0.6	0.101 ± 0.032
[3]	0.083–0.115	317.1		210.3 ± 1.3	–23. ± 0.4	70.7		
[4]	>0.4	319		215.2 ± 1.0	–26.2 ± 1.9	69.7		
[5]	>0.4	271.0		179.0	–13.7	70.8)		
Shower corresponding to filament F5; δ -Corvids, #729								
S	0.040–0.094	287.8 ± 6.1	278.5–297.7	189.0 ± 4.3	–14.8 ± 1.7	71.5 ± 0.4	42.1 ± 0.3	0.066 ± 0.014
[6]	0.169	282.0		186.8 ± 0.93	–16.4 ± 0.39	71.8		
[5]	>0.4	275.2		185.9	–10.7	72.0		

Notes. The showers were separated from C, S, and E catalogs. In addition, we also give the mean parameters of the related showers in the IAU MDC list as published by various authors. Further symbols are used as follows: $D_{\min}$ and $D_{\max}$ are the minimum and maximum values of the Southworth-Hawkins D-discriminant, characterizing the similarity of the mean orbits of the given separated real shower (or shower in the IAU MDC list) and the predicted shower of a given filament (all predicted showers are considered, therefore there is a set of the D-discriminant values); $\langle \lambda_{\odot} \rangle$ is mean solar longitude; $\lambda_{\odot, \min}$ and $\lambda_{\odot, \max}$ are the minimum and maximum solar longitudes of shower occurrence delimiting the shower activity; $\langle \alpha \rangle$ and $\langle \delta \rangle$ are the mean equatorial coordinates of geocentric radiant; $\langle V_g \rangle$ and $\langle V_h \rangle$ are the mean geocentric and heliocentric velocities; and $\langle D_{mj} \rangle$ is the mean value of the Southworth-Hawkins D-discriminant, characterizing the dispersion of meteor orbits in a given variant (see Sect. 4.2).

References. [1] Rudawska & Jenniskens 2014; [2] Jenniskens et al. 2016a; [3] Jenniskens 2006; [4] Molau & Rendtel 2009; [5] Jenniskens et al. 2018; [6] Jenniskens et al. 2016c.

Table 4. Mean orbital elements of the real meteor showers related to the stream of comet C/1963 A1.

cat.; ref.	$\langle q \rangle$ [au]	$\langle a \rangle$ [au]	$\langle e \rangle$	$\langle \omega \rangle$ [deg]	$\langle \Omega \rangle$ [deg]	$\langle i \rangle$ [deg]	η_b	N
Shower corresponding to filament F1; ϑ -Leonids								
S	0.854 ± 0.037	19.8 ± 21.9	0.925 ± 0.039	136.1 ± 6.9	235.3 ± 9.0	171.2 ± 2.2	0.769	17
Shower corresponding to filament F3; November α -Sextantids, #483								
C	0.889 ± 0.063	599 ± 484	1.024 ± 0.060	324.7 ± 12.9	42.9 ± 18.3	158.0 ± 5.5	1.000	24
S	0.913 ± 0.029	16.4 ± 22.6	0.928 ± 0.056	327.0 ± 6.2	41.9 ± 5.9	160.8 ± 2.6	1.000	17
E	0.855 ± 0.049	16.7 ± 20.0	0.936 ± 0.051	316.3 ± 9.5	35.3 ± 10.0	153.3 ± 7.4	1.000	31
[1]	0.898		1.103	325.5	51.9	154.2		8
[2]	0.896	29.40	0.970	323.3	51.9	152.6		6
Shower corresponding to filament F4; π -Hydrids, #101								
S	0.871 ± 0.030	26.1 ± 31.6	0.963 ± 0.037	40.0 ± 5.9	134.2 ± 5.2	165.1 ± 2.1	1.000	28
E	0.873 ± 0.039	8.0 ± 6.0	0.864 ± 0.049	40.5 ± 8.2	135.6 ± 8.1	165.8 ± 3.8	1.000	16
[3]	0.892	32.8		36.2	137.1	162.2		8
[5]	0.931	999.	1.014	349.8	91.0	157.3		493)
Shower corresponding to filament F5; δ -Corvids, #729								
S	0.969 ± 0.012	37.0 ± 36.0	0.970 ± 0.029	12.6 ± 6.5	107.8 ± 6.1	162.7 ± 2.0	0.750	15
[6]	0.983	–6.27	1.024	356.9	102.1	159.0		7
[5]	0.966	59.4	0.984	344.9	95.2	167.1		10

Notes. The measure of the best agreement between the predicted and corresponding real shower, η_b , and the number of shower meteors, N , are also given. The showers were separated from C, S, and E catalogs. In addition, we also give the mean elements of the corresponding orbits in the IAU MDC list. The numbers of references, in brackets, are the same as in Table 3.

The characteristics of filament F3 are vaguely similar to those of the shower November α -Sextantids #483 in the IAU MDC list. The corresponding real shower was also separated from the C, S, and E catalogs. Interestingly, the separated variants of the shower match the predicted shower better than the shower in the IAU MDC list. We guess that at least a rough knowledge of the mean orbit of shower, which is going to be separated from a data set, results in a more perfect separation. This circumstance will deserve special attention in future research.

The real counterpart of filament F1 was not found in the IAU MDC list, but a shower that agreed well was separated from the S catalog. We named this new shower, originating from C/1963 A1, θ -Leonids.

Filament F2 was predicted to be low numerous. Hence, it is not surprising that no similar shower can be found in the IAU MDC list of all shower or separated from any considered catalog.

None of the identified real showers are classified as established.

In conclusion, comet C/1963 A1 is the parent body of several, probably four, meteor showers observable in the Earth's atmosphere.

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