Research in Astronomy and Astrophysics, 24:125002 (13pp), 2024 December https://doi.org/10.1088/1674-4527/ad8c87

Near-Earth Asteroids as the Parents of the δ-Cancrid Meteoroid Stream

G. I. Kokhirova[1,6], M. Zhang[2,3,4,6], X. -G. Li[2,5], A. I. Zhonmuhammadi[1], and X. Liu[2,3,4]
[1] Institute of Astrophysics, National Academy of Sciences of Tajikistan, Ayni 299/5, Dushanbe, 734067, Tajikistan
[2] Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi 830011, China; zhangm@xao.ac.cn
[3] Key Laboratory for Radio Astronomy, Chinese Academy of Sciences, Nanjing 210008, China
[4] Xinjiang Key Laboratory of Radio Astrophysics, Urumqi 830011, China
[5] University of Chinese Academy of Sciences, Beijing 100049, China
Received 2024 April 11; revised 2024 October 9; accepted 2024 October 28; published 2024 November 28

Abstract

The δ-Cancrid meteoroid stream forms four active meteor showers which are observable on the Earth annually during January–February and August–September. The stream's definite parent comet has not been established. We performed a search for near-Earth asteroids (NEAs) associated with this stream. We have followed the backward evolution of the orbital elements of a sample of NEAs and found their orbits at the Earth-crossing positions. Using these orbits, we calculated the theoretical parameters of meteor showers associated with the considered NEAs. We carried out our search for observable active showers that match theoretically predicted ones with published data, and the result turned out that the predicted meteor showers of 13 NEAs were identified with the active showers produced by the δ-Cancrid meteoroid stream. The comet-like orbits of NEAs and established association with active meteor showers indicate their common cometary origin. The NEAs considered are moving within the stream and likely represent the dormant remnants of a parent comet of the δ-Cancrid asteroid-meteoroid complex that disintegrated more than 12 thousand years ago.

Key words: comets: general – minor planets – asteroids – δ-Cancrids – meteorites – meteors – meteoroids

1. Introduction

Small bodies in the solar system have archived the state of the proto-solar disk throughout the solar system's formation. Therefore, studying small bodies in our solar system will help us deeply understand the formation and evolution of this unique planetary system. There are a lot of minor bodies along with major planets moving in our solar system. The family of small bodies in our solar system includes comets, asteroids and meteoroids. In this hierarchy, meteoroids are fragmental outputs of the disintegration of comets and asteroids. A meteoroid component is divided into two main groups: sporadic background and stream meteoroids. In the context of our paper, a meteoroid stream will be considered so we give it a definition as follows. A meteoroid stream is formed by a great number of meteoroids generated by one parent body. The meteoroids belonging to the same stream move in interplanetary orbits close to the parent body's orbit. It has been proven that the formation of meteoroid streams can only be caused by the activity or destruction of comets. As was shown by Bredikhin (1954), only periodic normal gas- and dust-producing activity of a comet can form a stable and long-lived meteoroid stream. This normal activity is observed when a comet passes its orbital perihelion. In addition, a meteoroid stream may result from the catastrophic disintegration of a comet as a result of impact or other processes. The formation of a long-lived and developed meteoroid stream cannot be ensured by a break-up or so-called decay of an asteroid, such as a collision, since the ejection of dust and debris will be one-time off and insufficient for the formation of a stable stream in this case. The theory of a meteoroid stream's formation due to cometary activity, and the circumstances of its evolution and structure are defined in a series of papers (see e.g., Whipple 1950, 1951; Hughes 1986; Babadzhanov & Obrubov 1992; Babadzhanov et al. 2008b, 2015b).

Of course, there are exceptions to this concept, the most famous and well-studied of which is the connection between near-Earth asteroid (NEA) (3200) Phaethon and the Geminid meteor shower based on the similarity of orbits (Whipple 1983), which is observed on Earth annually in the period of December 10–15. There are a lot of papers showing that with a very high probability Phaethon can be the parent body of the Geminid meteor shower, on the basis of which the cometary nature of the asteroid is assumed (see, for example, Williams & Wu 1993; Ryabova et al. 2019). Moreover, in 2009, Phaethon was recorded for the first time to have short-term cometary activity in the perihelion region (Jewitt & Li 2010) and then this phenomenon was observed in 2012 and 2016 (Jewitt et al. 2013; Hui & Li 2017), and for this reason the object was classified as an active asteroid (Jewitt 2012). Phaethon's geometric albedo estimate of 0.107 ±0.011 (https://ssd.jpl.nasa.gov) corresponds to dark asteroids and is consistent with an albedo range of 0.02–0.12 for extinct cometary nuclei (Jewitt 1991). On the other hand, exploring the relationship

[6] The equal contributors and co-first authors of this paper.

between NEAs and showers, Wiegert & Brown (2004) found that the link between the Geminids and Phaethon is extremely unlikely and a mere chance alignment. Therefore, for a convincing statement of the association between the primordial asteroid and the meteor shower, both the connection with the shower and the nature of Phaethon require further research.

As the orbit of the meteoroid stream intersects the Earth's orbit, meteor showers are generated, which we can observe and record using various techniques. As Babadzhanov & Obrubov (1992) showed, meteor streams, depending on the number of intersections between their orbits and the Earth's orbit, can generate from four to eight observable annual meteor showers on the Earth during the corresponding periods. However, quadruple crossings are the most common case for meteoroid streams and therefore the most typical production of a stream is four showers. To demonstrate this, we use the example of the Taurid meteoroid stream, which produces four meteor showers in a period. When the stream's orbit intersects the Earth's orbit at pre-perihelion, these are the Northern and Southern Taurids, observed on the Earth annually from September to November. At the post-perihelion crossing, these are the Daytime β-Taurids and ζ-Perseids, observed annually from June to July. The parent body of the Taurid stream is the comet 2P/Encke; nevertheless, it turns out that more than 40 other NEAs belong to this family. A dynamic affinity of these objects was established, and the family was named the Taurid asteroid-meteoroid complex. There is a very high probability that the asteroids in the Taurid complex are in fact extinct comet nuclei or dead fragments of a larger progenitor comet (see e.g., Asher et al. 1993; Porubčan et al. 2006; Babadzhanov et al. 2008b). The presence of a certain number of extinct or dormant comet nuclei among the NEAs is beyond doubt; according to some estimates, they may account for up to 6% of the total discovered NEAs currently (Öpik 1963; Weissman et al. 1989; Babadzhanov & Kokhirova 2012).

According to Weissman et al. (1989), the term "dormant" or "extinct" comet refers to a comet nucleus that was active in the past and currently loses its ability to generate a visible coma in any section of its orbit. Throughout their evolution, such comet nuclei are gradually covered with a thick and refractory mantle that prevents the ejection of gas and dust; consequently, normal cometary activity ceases (Whipple 1950, 1951; Öpik 1963). Meanwhile, an extinct comet can be reactivated by a non-catastrophic collision with another body or by bombardment of its surface by small meteoroids (Weissman et al. 1989). Such events have been confirmed by observations (Babadzhanov et al. 2017). According to ground-based observations, the nuclei of extinct comets are indistinguishable from asteroids in appearance. However, they can be distinguished by their dynamic properties, i.e., their orbital elements. The typical cometary orbit implies the cometary origin. The established connection between such objects and the observable active meteor showers will significantly strengthen this assumption. Several asteroid-meteoroid complexes have already been identified by using this approach, such as the Piscids complex (Babadzhanov et al. 2008a), the ι-Aquariids complex (Babadzhanov et al. 2009), the δ-Scorpiids (Babadzhanov et al. 2013), the σ-Capricornids (Babadzhanov et al. 2015a), the Virginids (Babadzhanov et al. 2012, 2015c; Kokhirova et al. 2024), etc. In addition to the meteoroid stream, each of these complexes contains several NEAs of cometary origin, which may be the parents of relevant streams. However, the parent bodies of all known meteoroid streams have not yet been identified. Considering that finding the parents of meteoroid streams is a critical step in understanding the genetic connections between small solar system objects, we continue to study their relationships and discover new extinct comets in NEAs. This paper presents the results of the discovery of relevant objects in the δ-Cancrid meteoroid stream.

2. δ-Cancrid Asteroid-Meteoroid Complex

2.1. Meteor Showers of the δ-Cancrid Meteoroid Stream

In the meteor shower database of IAU MODC (www.ta3.sk, 2023), the confirmed showers of the δ-Cancrid stream are the nighttime Northern and Southern δ-Cancrids, 00096 NCC and SCC, respectively, with a period of maximum activity at the end of January, and the daytime southern shower Daytime χ-Leonids being in the database with code 00204 DXL, with active period at the end of August. The daytime northern shower has not been established. NEAs 1991 AQ and 2001 YB5 are indicated as possible parent bodies of the stream in the IAU MODC database.

We searched for objects associated with this stream among NEAs discovered before 2018, and identified 13 asteroids related to the δ-Cancrid stream, and also established the northern branch of the daytime shower and our results are presented hereinafter.

2.2. Research Approach and Methodology

The research approaches and methods are based on the theory of formation and evolution of meteoroid streams (Babadzhanov & Obrubov 1992) and the fact that there are a certain number of extinct comet nuclei among NEAs (Öpik 1963; Weissman et al. 1989; Babadzhanov & Kokhirova 2012). It turns out that among the large number of meteoroids in the stream, only those with orbital heliocentric distances equal to 1 au for ascending R_a and descending R_d nodes can traverse the Earth's orbit (Babadzhanov & Obrubov 1992). For most NEAs' orbits, this condition is satisfied four times during one cycle of changing the orbital perihelion argument. If the asteroid is indeed an extinct comet, then a meteoroid stream could have been formed during past cometary activity. This meteoroid stream can theoretically cause four observable meteor showers on the Earth—the nighttime shower with the northern and southern branches, as well as the daytime shower with the northern and southern branches. To determine the parameters of these theoretical showers, their orbits are needed. That is, the radiant, velocity and solar longitude of the predicted maximum activity for a shower can be calculated using a set of orbital elements for the asteroid at its Earth-crossing position. This kind of asteroid orbit that simultaneously corresponds to the theoretically predicted meteor shower orbit can be obtained by calculating the orbital evolution of the proposed parent body—the asteroid. The orbital evolution is calculated using various numerical integration methods of the equations of motion for time intervals equal to one period of the orbital perihelion argument change. As a rule, this time covers a period of 10–12 thousand years for NEAs. The methods of Everhart (1974) and Halphen-Goryachev (1937) are mostly used for the orbital evolution calculation.

Once the characteristics of theoretical meteor showers have been determined, accessible databases of observed meteor showers and individual fireball/meteor showers should be searched for observable activity that approximates the predicted showers. If the theoretical meteor showers are consistent with observed meteor showers, then this confirms a connection between the meteoroid streams that generate these showers and the asteroids. In this case, it is quite possible to assume that the asteroids have cometary properties.

In the end, only asteroids traveling in comet-like orbits and crossing Earth's orbit were studied. Note that a comet-like orbit is the necessary but not sufficient condition for an object's cometary origin. We use the Tisserand parameter T_j to classify the orbits here. If the Tisserand parameter value satisfies the condition $T_j \leqslant 3.12$, then the orbit is classified as comet-like; and when $T_j \geqslant 3.12$ the orbit is related to asteroidal type (Kresák 1969; Jewitt 2012). The condition for an asteroid's orbit to intersect the Earth's orbit has been verified in the NEODyS-2 database (https://newton.spacedys.com, 2021).

2.3. Near-Earth Asteroid Candidates for Extinct Comets

In the NEOP database (https://cneos.jpl.nasa.gov/, 2019), among all NEAs discovered until 2017 December 31, we selected asteroids which according to T_j are moving on the comet-like orbits. Then, among them, we selected NEAs which according to the data of database NEODyS-2 (https://newton.spacedys.com, 2021) intersect the Earth's orbit (note, not all NEA orbits cross the Earth's orbit). In this way we obtained about 3 thousand asteroids. Then we calculated their orbital evolution backward over the time interval equal to one cycle of the argument of perihelion variations. As a result of calculating the evolution, a number of NEAs (∼3%) were excluded due to chaotic motion. Using the results of orbital evolution calculation for the remaining NEAs, the theoretical parameters of meteor showers were calculated. Finally, we performed a computerized search for the observed showers/meteors/fireballs/NEAs whose parameters are close to the theoretically predicted showers. Initially, the result showed that among approximately 2.5 thousand investigated NEAs, theoretical showers of only 13 asteroids were identified with the observed showers of the δ-Cancrid complex. Under this, in spite of the identification of the theoretical showers with the observed δ-Cancrid showers, some NEAs were excluded since their values of π are not consistent with values of these 13 NEAs having averaged $\pi = 221 \pm 8°$ and of the δ-Cancrid showers having averaged $\pi = 220 \pm 10°$ (according to various published sources). This is an additional condition that is met when selecting candidate asteroids for suggested association. Note, as a result of search, relations of some studied asteroids from the sample to other new and known associations were also determined which are the subject of future papers.

The main parameters of 13 NEAs associated with the δ-Cancrid stream are given in Table 1, including the asteroid designation, the orbital elements (in Equinox 2000.0): a—the semimajor axis, e—the eccentricity, q—the perihelion distance, i—the inclination, Ω—the longitude of ascending node, ω—the argument of perihelion, π—the longitude of perihelion; as well as H—the absolute magnitude, d—the asteroid's equivalent diameter, N_i—the number of intersections of the asteroid's orbit with the Earth's ones during one cycle of variation of the argument of perihelion and T_j—the value of Tisserand parameter, p—geometrical albedo and S_p—taxonomic classification. The N_i value corresponds to the number of theoretically predicted meteor showers associated with a given asteroid (Babadzhanov & Obrubov 1992). The asteroid 1991 AQ has a value of $T_j = 3.16$, corresponding to the boundary value of the criterion between comets and asteroids; however, we classify the object's orbit as comet-like. Available information about the albedo and taxonomy of three asteroids from the ALCDEF database (www.alcdef.org) needs additional description. For NEA 1991 AQ the albedo of 0.24 ± 0.19 was measured with a large error; 2001 YB5 has a measured albedo of 0.20, but the measurement error is not given. In both cases, the albedo values are too uncertain; for this reason, and taking into account the comet-like orbits, asteroids are not excluded from consideration and a final conclusion on their nature requests additional investigation. The albedo of 2003 RW11 is measured as 0.02 ± 0.05 which is consistent with confirmed values for cometary nuclei. These NEAs are spectrally classified as S-type, for which a moderate albedo in the range 0.10–0.20 is typical (www.alcdef.org). However, the albedo of 2003 RW11 does not correspond to the S-type, and given the uncertainties in the albedo values of 1991 AQ and 2001 YB5, it is not yet possible to make a conclusion about their real spectral features. There are no data on the remaining 10 NEAs in the ALCDEF database, so for them we use the data accessible at the ssd.jpl.nasa.gov database assuming their albedo to be relevant to albedo values for cometary nuclei. For greater confidence and to strengthen the conclusions of our results, it is

Table 1
Main Properties of NEAs Related to the δ-Cancrid Complex

Asteroid	a (au)	e	q (au)	$i°$	$\Omega°$	$\omega°$	$\pi°$	H (mag)	d (km)	N_i	T_j	p (%)	S_p
1991 AQ (PHA)	2.221	0.777	0.494	3.1	339.5	241.1	222.6	17.2[a]	1.1[a]	4	3.16	0.24[a] ±0.19	S[a]
2001 YB5 (PHA)	2.340	0.865	0.316	5.5	108.3	115.3	223.6	20.9[a]	0.20[a]	4	2.89	0.20[a] ±?	S[a]
2003 AA83	2.452	0.773	0.555	6.8	87.7	127.4	215.1	21.8[b]	0.21[a]	4	2.98	⋯	⋯
2003 RW11	2.635	0.824	0.465	10.3	170.8	53.4	224.2	18.7[a]	1.5[a]	4	2.77	0.02[a] ±0.05	S[a]
2009 BB	2.412	0.848	0.368	18.8	72.4	154.9	227.3	18.4[b]	1.07	4	2.84	⋯	⋯
2009 BE77	2.522	0.826	0.439	21.1	201.2	26.9	228.1	18.1[b]	1.23	4	2.79	⋯	⋯
2010 XC11 (PHA)	2.516	0.850	0.377	9.1	94.3	121.2	215.5	18.7[b]	0.94	4	2.79	⋯	⋯
2010 XX58	2.238	0.864	0.305	22.2	53.1	174.6	227.7	18.6[b]	0.95	4	2.94	⋯	⋯
2011 AF3	2.312	0.817	0.422	7.8	99.5	112.2	211.7	25.1[b]	0.05	4	3.01	⋯	⋯
2014 SM260 (PHA)	2.259	0.884	0.262	7.8	336.8	246.9	223.8	21.0[b]	0.32	4	2.91	⋯	⋯
2014 YQ34	2.480	0.827	0.428	3.4	272.3	290.6	202.9	24.1[b]	0.08	4	2.87	⋯	⋯
2016 AM66	2.558	0.830	0.435	19.7	235.6	355.0	230.5	20.0[b]	0.51	4	2.77	⋯	⋯
2017 YO4	2.237	0.829	0.382	7.4	189.6	26.8	216.4	20.6[b]	0.33	4	3.05	⋯	⋯

Notes. Superscripts indicate data sources.
[a] https://alcdef.org
[b] https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html.

necessary to refine the albedos of NEAs in the future. The diameters including a superscript in Table 1 are accessible at the published databases such as ssd.jpl.nasa.gov and alcdef.org. In the cases where size estimation was lacking, the diameters were calculated using the known expression (Harris 2002)

$$d = \frac{1329}{\sqrt{p} \cdot 10^{0.2H}}, \tag{1}$$

where p is the geometrical albedo of an asteroid. For very dark asteroids of C, P, and D types, the albedo is as low as within 0.02–0.12, which indicates they are very likely to be extinct comets (Jewitt 1991). Thus the quoted diameters of asteroids were estimated with the median value of low albedos which is $p = 0.07$. There are four asteroids in this sample classified as potentially hazardous ones in NEOP, and in Table 1 they are signified by PHA. The 2D projection of the present orbits of 13 NEAs onto the ecliptic plane is given in Figure 1 where the Sun and the Earth's orbit are also shown.

2.4. Investigation of Orbital Evolution

We calculated the orbital evolution of a sample of NEAs during a periodic change in the argument of perihelion using the Everhart RADAU19 method (Everhart 1974). Then the gravitational perturbations of the major planets were taken into account in the evolution. As a result, it was found that all asteroids cross the Earth's orbit four times during one cycle of ω variation. It means that the sizes of R_a and R_d of asteroid orbits are equal to 1 au four times in a cycle, i.e., twice at each node. The variations of R_a and R_d for the asteroid orbits with time and the argument of perihelion are demonstrated in Figures 2–3, where the straight line drawn parallel to the abscissa through the 1 au value corresponds to the position of the Earth's orbit, and the intersection with the asteroid orbit is indicated by arrows. These graphs are similar for all considered NEAs, so we only present a sample of two plots for a pair of asteroids here. For asteroid 2001 YB5, it is displayed in Figure 2; for asteroid 2010 XC11, it is depicted in Figure 3.

The values of the argument of perihelion at the Earth's crossing positions for the considered NEAs and averaged values with their standard deviations are given in Table 2, where the theoretical showers are listed in the following order: 1. the northern branch of nighttime shower, 2. the southern branch of nighttime shower, 3. the northern branch of the daytime shower, 4. the southern branch of the daytime shower.

Using a set of orbital elements found from orbital evolution that correspond to the intersection of the asteroid's orbit and the Earth's orbit, we calculate the equatorial coordinates of the geocentric radiants (i.e., the R.A. α_g and the δ_g), the geocentric velocities V_g, the solar longitudes $L_\odot$ and corresponding dates for theoretical meteor shower activity associated with asteroids.

2.5. Association of Asteroids with Observable Showers of the δ-Cancrid Stream

A computer program search for theoretically predicted showers was conducted in the published catalogs of the observable meteor/fireball showers and detected fireball/meteors and meteorites. By comparing theoretical and observational parameters, we require that the difference between radiant positions should not exceed ±10° in both R. A. and decl., the difference between geocentric velocities should be $\Delta V_g \leqslant \pm 5$ km s^{-1} and the periods of activity may differ by no more than ±15 days (see, e.g., Babadzhanov et al. 2008a, 2008b, 2009; Rudawska et al. 2015). When these conditions are fulfilled then we can declare a closeness of the geocentric parameters of two compared showers-theoretical and observed ones. The closeness of theoretical and observable

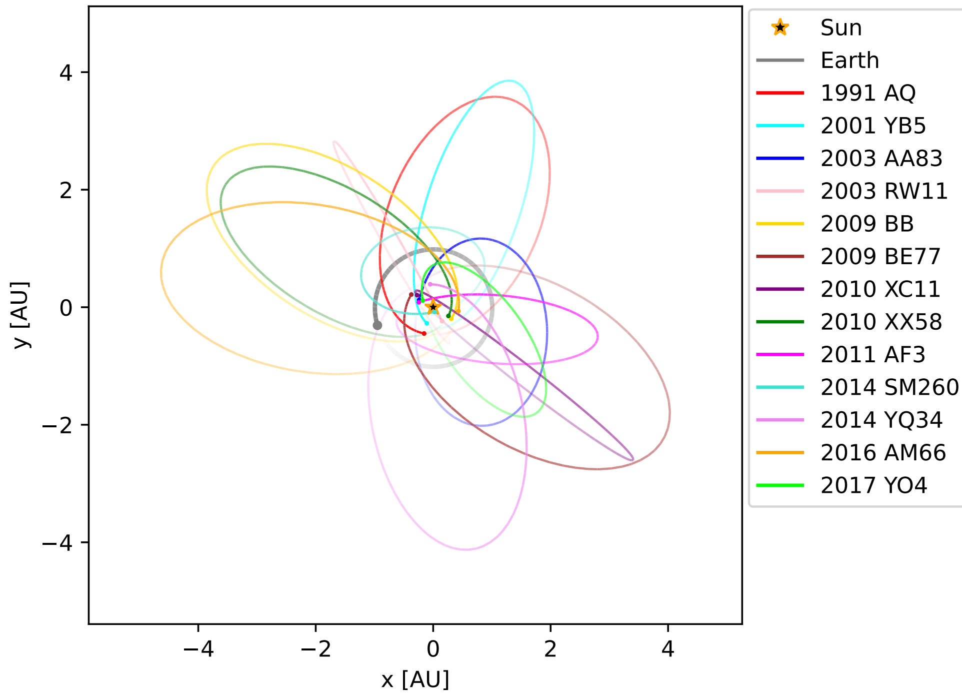

Figure 1. Projected orbits of 13 NEAs on the ecliptic plane. The fading line of an orbit indicates the direction of the object's revolution.

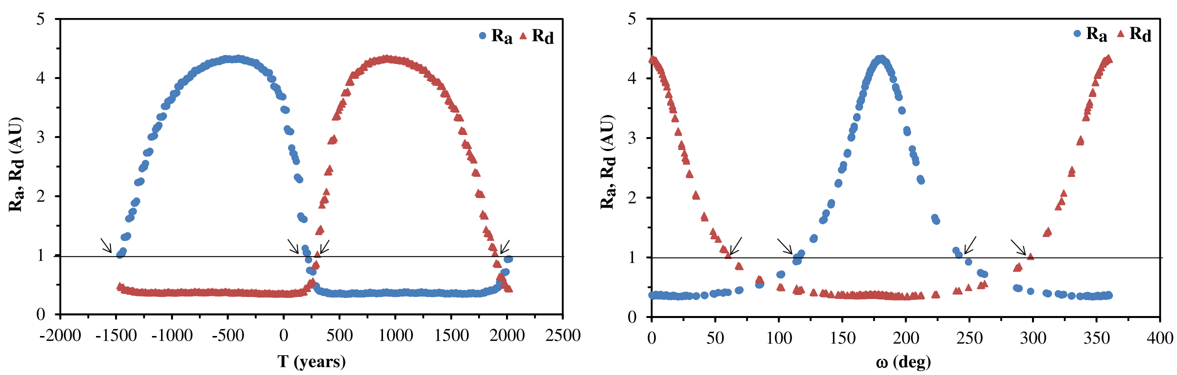

Figure 2. Changes in R_a and R_d of the asteroid 2001 YB5's orbit with time (left) and argument of perihelion (right).

orbits is checked using the Southworth & Hawkins (1963) criterion D_{SH}, which is a measure of the similarity between two orbits. They also showed that the threshold value of the D_{SH} criterion confirms the connection is 0.20. In this case, to calculate the threshold value D_{SH}^{max} while measuring similarity of the orbits of the meteor and the shower, the following relation is used: $D_{SH}^{max} = 0.2(360/N)^{1/4}$, where N is the meteor data sample size. In our case, where we compare 52 orbits (13 NEAs orbits × 4 multiple intersections with the Earth's orbit = 52) with the orbit of the active shower, according to this expression $D_{SH}^{max} = 0.32$. However, the use of a threshold D_{SH} criterion value of 0.20–0.25 is generally accepted both when identifying streams and when identifying the connection between the pairs of a comet shower, an asteroid shower, etc. Therefore, we settled on a value of 0.25. When the condition $D_{SH} \leqslant 0.25$ is met, the two orbits are considered similar.

The search found a group of 13 NEAs (Table 1) closely associated with meteoroid streams that produce nighttime Northern and Southern δ-Cancrids (96 NCC and 97 SCC) and Daytime Southern χ-Leonids (204 DXL). As mentioned above, the northern branch of the daytime shower has not yet been established. Our results suggest that this may be the τ-Cancrids meteor shower, listed as number 430 in the catalog of Lebedinets et al. (1973). The γ-Leonids meteor shower from the Sekanina (1976) catalog may also be the northern branch of the daytime shower, but its average orbit has a D_{SH} criterion value higher than that of the τ-Cancrids shower, so we chose the latter as the candidate of the northern branch of the daytime shower.

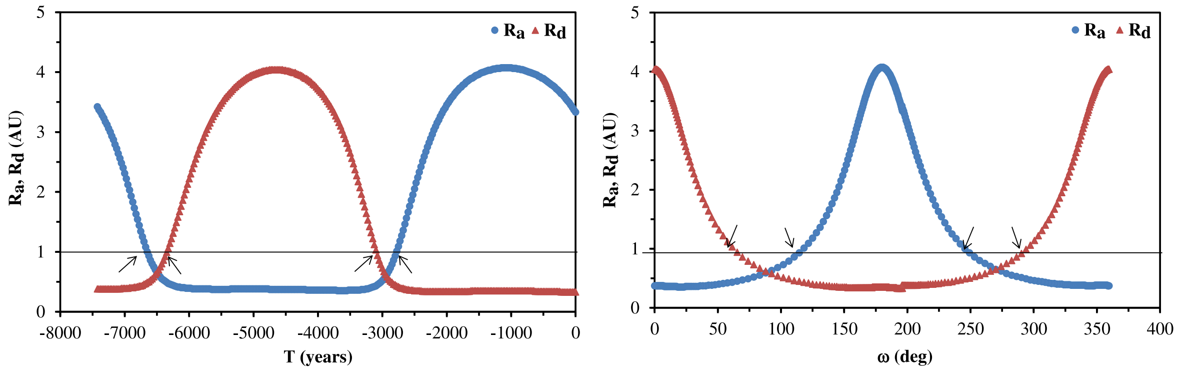

Figure 3. Changes in R_a and R_d of the asteroid 2010 XC11's orbit with time (left) and argument of perihelion (right).

Table 2
Values of the Argument of Perihelion of Asteroids' Orbits at the Earth's Crossing Positions

Shower	Northern Nighttime	Southern Nighttime	Northern Daytime	Southern Daytime
1991 AQ (PHA)	278.2	97.5	83.7	262.1
2001 YB5 (PHA)	297.2	114.2	61.8	244.2
2003 AA83	262.6	90.1	88.1	275.6
2003 RW11	280.6	100.8	80.3	260.2
2009 BB	290.2	114.9	68.3	249.9
2009 BE77	295.6	115.2	67.6	247.6
2010 XC11 (PHA)	294.5	110.1	68.8	247.1
2010 XX58	302.3	123.7	56.4	238.0
2011 AF3	280.8	104.6	75.5	254.8
2014 SM260 (PHA)	303.9	123.8	56.2	235.3
2014 YQ34	283.4	105.4	74.7	255.3
2016 AM66	296.8	112.7	67.7	248.8
2017 YO4	289.1	110.8	69.1	251.0
Mean value of ω°	288.8 ± 11.0	109.5 ± 9.4	70.6 ± 9.3	251.5 ± 10.1

Note. Averaged values with their standard deviations are given in the last line.

The search results for asteroids 1991 AQ and 2003 RW11 are shown in Tables 3 and 4 respectively. For the other asteroids in this set, the results are the same. The meteor shower parameters, including orbital elements, radiants, solar longitudes and activity dates of theoretically predicted showers, are given in bold in Tables 3 and 4; the northern branch of nighttime shower is labeled as NNS, the southern branch of nighttime shower is labeled as SNS, the northern branch of daytime shower is labeled as NDS, and the southern branch of daytime shower is labeled as SDS, where the letters "N" and "D" mean the night- and day-time showers respectively. Catalogs in which observable active showers and fireballs are found to be identical to the theoretical prediction are listed in Tables 3 and 4 as shortcodes: L1 (Lindblad 1971), S2 (Sekanina 1973), S3 (Sekanina 1976), J1 (Jenniskens 2007), J (Jenniskens et al. 2016), R (Rudawska & Jenniskens 2014), L (Lebedinets et al. 1973), N (Nilsson 1964), MORP (Halliday et al. 1996), and PN (McCrosky et al. 1978). As shown, the values of the D_{SH} criterion confirm the similarity between the theoretical and observable orbits. Identification of theoretical meteor showers with observable meteor showers and fireballs is confirmed by the proximity of radiant position, velocity, and date of activity. It then allows the conclusion that the connection between the asteroids and these showers exists, and therefore, it is likely that the NEAs under consideration are in fact of a cometary origin. Furthermore, these objects may be considered the parent bodies of the stream, or they could be extinct fragments of a larger comet precursor of the stream. This meteoroid stream just contains large-sized remnants of the parent comet that is currently dormant.

In addition, the associated the NEAs listed in Table 1, with theoretical and observable meteor showers and the connection between each other, were found based on the relevant radiants and the current asteroids' orbits (see Tables 3–4). A proposed link between the stream and NEAs 1991 AQ and 2001 YB5 (www.ta3.sk, 2023) is also confirmed. As noted, in this family four asteroids are classified as potentially hazardous objects. The current orbit of PHA 2001 YB5 corresponds to the southern nighttime shower 97 SCC, while the current orbits of PHAs 2014 SM260 and 2014 YS43 correspond to the southern daytime shower χ-Leonids. Consequently, asteroids may enter the Earth's atmosphere during associated meteor shower events

Table 3
Meteor Showers, Fireballs and NEAs Related to NEA 1991 AQ (J2000.0)

Meteor Showers, Fireballs, NEAs	a[a] (au)	e[b]	q[c] (au)	i°[d]	Ω°[e]	ω°[f]	$L_{\odot}^{\circ}$[g]	Date[h]	α°[i]	δ°[j]	V_g[k] (km s^{-1})	D_{SH}[l]	Type[m]	Catalog[n]
NNS 1991AQ	2.214	0.774	0.501	2.5	304.5	278.1	304.5	Jan 24	131.8	21.0	24.5	⋯	N	⋯
00096 NCC	2.273	0.803	0.448	0.3	297.1	282.9	297.1	Jan 17	126.6	19.5	26.2	0.08	N	L1
00096 NCC	1.901	0.777	0.425	1.2	292.9	287.9	292.9	Jan 13	124.8	19.8	25.8	0.08	N	S2
00096 NCC	1.829	0.783	0.397	1.5	296.4	291.3	296.4	Jan 16	130.0	19.9	26.4	0.13	N	S3
00096 NCC	2.230	0.814	0.410	2.7	290.0	286.6	290.0	Jan 10	121.3	23.0	27.2	0.13	N	J1
00096 NCC	2.190	0.815	0.405	2.7	292.9	287.5	292.9	Jan 13	125.2	22.0	27.3	0.13	N	R
445	1.256	0.566	0.545	1.7	295.9	283.4	295.9	Jan 16	125.3	22.1	18.0	0.22	N	MORP
774	3.075	0.888	0.344	7.9	284.2	292.6	284.2	Jan 5	119.6	27.0	31.2	0.16	N	MORP
996	2.182	0.770	0.502	0.7	298.3	277.3	298.3	Jan 18	124.2	20.6	24.4	0.10	N	MORP
SNS 1991AQ	2.218	0.771	0.508	5.3	125.1	97.5	305.1	Jan 25	129.7	12.0	24.4	⋯	N	⋯
00097 SCC	2.260	0.811	0.427	4.7	109.3	105.0	289.3	Jan 9	118.5	16.1	26.9	0.15	N	J
00097 SCC	1.610	0.770	0.370	4.9	120.1	116.7	300.1	Jan 20	133.9	12.6	26.3	0.24	N	N
00097 SCC	2.240	0.791	0.468	5.2	111.8	100.3	291.8	Jan 12	118.8	15.1	25.7	0.15	N	R
995	1.989	0.793	0.412	4.2	113.3	108.3	293.3	Jan 13	124.0	15.6	26.6	0.10	N	MORP
660110	1.960	0.790	0.412	3.9	109.6	107.5	289.6	Jan 10	120.5	16.6	26.6	0.20	N	PN
660113a	1.330	0.670	0.439	8.4	112.7	111.7	292.7	Jan 13	124.8	9.7	22.5	0.22	N	PN
710131	3.120	0.830	0.530	9.1	130.7	91.6	310.7	Jan 31	132.0	7.0	26.2	0.09	N	PN
2001 YB5	2.349	0.862	0.324	5.5	109.4	114.2	289.4	Jan 10	124.2	15.4	30.8	0.21	N	⋯
NDS 1991AQ	2.227	0.768	0.517	5.3	138.9	83.7	138.9	Aug 12	140.0	22.0	24.2	⋯	D	⋯
γ-Leonids	1.969	0.710	0.571	7.0	152.5	87.3	152.5	Aug 26	156.5	19.7	22.1	0.24	D	S3
430 (τ-Cancrids)	1.490	0.660	0.507	11.4	140.1	74.9	140.1	Aug 13	139.1	30.7	21.9	0.18	D	L
SDS 1991AQ	2.216	0.772	0.505	2.5	320.5	262.1	140.5	Aug 13	138.2	13.1	24.5	⋯	D	⋯
00204 DXL	1.598	0.793	0.330	2.5	334.9	238.4	154.9	Aug 28	142.3	12.7	27.5	0.22	D	S3
2014 SM260	2.250	0.884	0.261	7.8	336.8	246.9	156.8	Aug 30	⋯	⋯	⋯	0.25	D	⋯

Notes.
[a] Semimajor axis. [b] Eccentricity. [c] Perihelion distance. [d] Inclination. [e] Longitude of the ascending node. [f] Argument of perihelion. [g] Solar longitude. [h] The date corresponding to the solar longitude. [i] Decl. of the geocentric radiant. [j] R.A. of the geocentric radiant. [k] Geocentric velocity. [l] Criterion of orbital similarity of Southworth & Hawkins (1963). [m] Night or daytime shower. [n] Published source.

and will have characteristics similar to those of that shower. For instance, it is theoretically predicted that the estimated impact date of the potentially hazardous asteroid 2001 YB5 is January 10, the geocentric speed is 30.8 km s^{-1}, and the equatorial coordinates of the point where it hits the Earth are $\alpha_g = 124^{\circ}.2$ and $\delta_g = 15^{\circ}.4$.

3. On the Probability of Random Similarity of Two Orbits

Since the proximity of orbits is not a sufficient condition to confirm the connection between two objects moving in heliocentric orbits, let us consider the probability of random similarity.

Assessing the plausibility of the associations between an NEA-type object and a meteor shower is not a simple matter. Numerous attempts were made to resolve this. For instance, Wiegert & Brown (2004) have defined the expectation value of the number of asteroids closer to the shower orbit than the test asteroid as $P = N/\langle n \rangle$, where N is the number of used asteroids and n is the average number of trials to select asteroid's orbits that have D' criterion values satisfying condition $D' \leqslant D'_0$ (D'_0 is value of the criterion of Drummond (1981) of the test asteroid). Further, they suggest that if this number is much greater than one, then more than one asteroid is at least as well aligned with the shower as the test asteroid, and so a chance alignment becomes more probable. If this number is less than one, P represents the probability that another asteroid is closer to the shower than the chosen asteroid. A small value of P implies there are few other asteroids in the phase space around the shower, and thus a chance alignment is unlikely. This approach was further realized in Ye et al. (2016), where for five pairs of asteroid-shower cases, the association was confirmed. Under this, the confirmation was supported by the values of P around 1%.

Wiegert & Brown (2004), and further development of this approach reported in Ye et al. (2016), when searching for the asteroid-shower linkage, initially used a random sample of a certain number of asteroids and shower orbits. However, we used a slightly different approach; its explanation and details on a selection procedure of objects for consideration are given in Section 2.3 from which it follows that the sample of orbits was selected systematically, not randomly. It is obvious that in our work, we did not compare all NEAs in the JPLSSD database but only the 13 NEAs as candidates for the parent bodies of the δ-Cancrid complex found as a result of systematical selection.

Table 4
Meteor Showers, Fireballs and NEAs Related to NEA 2003 RW11 (J2000.0)

Meteor Showers, Fireballs, NEAs	a[a] (au)	e[b]	q[c] (au)	i°[d]	Ω°[e]	ω°[f]	$L_{\odot}^{\circ}$[g]	Date[h]	α°[i]	δ°[j]	V_g[k] (km s^{-1})	D_{SH}[l]	Type[m]	Catalog[n]
NNS 2003 RW11	2.635	0.828	0.454	4.7	303.6	280.6	303.6	Jan 24	133.4	22.5	27.0	⋯	N	⋯
00096 NCC	2.273	0.803	0.448	0.3	297.1	282.9	297.1	Jan 17	126.6	19.5	26.2	0.10	N	L1
00096 NCC	1.901	0.777	0.425	1.2	292.9	287.9	292.9	Jan 13	124.8	19.8	25.8	0.10	N	S2
00096 NCC	1.829	0.783	0.397	1.5	296.4	291.3	296.4	Jan 16	130.0	19.9	26.4	0.10	N	S3
00096 NCC	2.230	0.814	0.410	2.7	290.0	286.6	290.0	Jan 10	121.3	23.0	27.2	0.12	N	J1
00096 NCC	2.190	0.815	0.405	2.7	292.9	287.5	292.9	Jan 13	125.2	22.0	27.3	0.08	N	R
774	3.075	0.888	0.344	7.9	284.2	292.6	284.2	Jan 5	119.6	27.0	31.2	0.17	N	MORP
996	2.182	0.770	0.502	0.7	298.3	277.3	298.3	Jan 18	124.2	20.6	24.4	0.16	N	MORP
SNS 2003 RW11	2.635	0.830	0.449	4.4	123.5	100.8	303.5	Jan 23	130.9	13.5	27.2	⋯	N	⋯
00097 SCC	2.260	0.811	0.427	4.7	109.3	105.0	289.3	Jan 9	118.5	16.1	26.9	0.15	N	J
00097 SCC	1.610	0.770	0.370	4.9	120.1	116.7	300.1	Jan 20	133.9	12.6	26.3	0.20	N	N
00097 SCC	2.240	0.791	0.468	5.2	111.8	100.3	291.8	Jan 12	118.8	15.1	25.7	0.18	N	R
995	1.989	0.793	0.412	4.2	113.3	108.3	293.3	Jan 13	124.0	15.6	26.6	0.07	N	MORP
660110	1.960	0.790	0.412	3.9	109.6	107.5	289.6	Jan 10	120.5	16.6	26.6	0.12	N	PN
660113a	1.330	0.670	0.439	8.4	112.7	111.7	292.7	Jan 13	124.8	9.7	22.5	0.18	N	PN
710131	3.120	0.830	0.530	9.1	130.7	91.6	310.7	Jan 31	132.0	7.0	26.2	0.12	N	PN
2001 YB5	2.349	0.862	0.324	5.5	109.4	114.2	289.4	Jan 10	124.2	15.4	30.8	0.13	N	⋯
NDS 2003 RW11	2.635	0.830	0.448	4.1	144.0	80.3	144.0	Aug 17	141.4	19.4	27.3	⋯	D	⋯
γ-Leonids	1.969	0.710	0.571	7.0	152.5	87.3	152.5	Aug 26	156.5	19.7	22.1	0.28	D	S3
430 (τ-Cancrids)	1.490	0.660	0.507	11.4	140.1	74.9	140.1	Aug 13	139.1	30.7	21.9	0.25	D	L
SDS 2003 RW11	2.635	0.828	0.454	4.4	324.1	260.2	144.1	Aug 17	139.2	11.3	27.1	⋯	D	⋯
00204 DXL	1.598	0.793	0.330	2.5	334.9	238.4	154.9	28 Aug	142.3	12.7	27.5	0.20	D	S3
1991 AQ	2.214	0.780	0.487	3.2	341.5	241.0	161.5	Sep 4	⋯	⋯	⋯	0.07	D	⋯
2014 SM260	2.250	0.884	0.261	7.8	336.8	246.9	156.8	Aug 30	⋯	⋯	⋯	0.21	D	⋯
2014 YS43	2.960	0.823	0.524	12.9	326.8	244.9	146.8	Aug 19	⋯	⋯	⋯	0.24	D	⋯

Notes.
[a] Semimajor axis. [b] Eccentricity. [c] Perihelion distance. [d] Inclination. [e] Longitude of the ascending node. [f] argument of perihelion. [g] Solar longitude. [h] The date corresponding to the solar longitude. [i] R.A. of the geocentric radiant. [j] decl. of the geocentric radiant. [k] Geocentric velocity. [l] Criterion of orbital similarity of Southworth & Hawkins (1963). [m] Night or daytime shower. [n] Published source.

For this reason, to assess the degree of probability of a random coincidence of two orbits, we used the methodology from our earlier work (Babadzhanov et al. 2008a). Such estimates depend on the degree of similarity of the orbits. For clarity, we calculated the mutual D_{SH} criterion between the modern orbits of the first four studied NEAs (Table 5).

Table 5
Mutual Values of the D_{SH} Criterion for NEAs

NEA	1991 AQ	2001 YB5	2003 AA83	2003 RW11
1991 AQ	0	0.24	0.15	0.22
2001 YB5	0.24	0	0.25	0.22
2003 AA83	0.15	0.25	0	0.22
2003 RW11	0.23	0.22	0.22	0

If asteroids were uniformly distributed in space, then the maximum value of D_{SH}^2 between extreme cases would be 5. However asteroids' inclinations are less than 30°, so that for such a set, the maximum value is 3 or 1.732 for D_{SH}. Thus the probability that two objects such as 1991 AQ and 2001 YB5, having $D_{SH} = 0.24$, by chance is 0.24/1.732 or about 14%. For 1991 AQ and 2003 AA83, where D_{SH} is 0.15, the probability that this is by chance is about 9%. The probability that all four are similar by chance is thus about 3.5×10^{-4}%. For the associations given in our work, the probabilities that these are random associations are negligible. Thus it appears that, at a confidence level ~100%, a subset of the selected NEAs is aligned with the δ-Cancrid complex. We recognize that the assumption of uniformly distributed asteroids in space could be unjustified, and the estimated probability of chance alignment could be off by an unknown factor. However, taking into account a statement that, if the number of asteroids having $D' \leqslant D'_0$ is large, the probability of a mere chance association is high (Wiegert & Brown 2004), and we can consider this assumption for the initial assessment of the probability of random similarity of two orbits. Indeed, the fraction of asteroids in our sample that satisfy this condition is ~0.5% of the total number of asteroids, which also strengthens the assumption of a slight probability of a random association. Finally, as was expressed by Wiegert & Brown (2004), even if the probability of a chance association is high, this does not exclude the existence of a real association between the stream and the asteroid.

4. A Possible Mechanism of the Parent Comet Break-up

The fragmentation of asteroids and comets into large fragments occurs at low ejection speeds. At the initial stage, small dispersion in the elements of the orbits determines the low speeds at which the fragments disperse. Therefore, when establishing the connection of objects, it is necessary to study the evolution of orbits and find the moment of their greatest similarity. If such similarity is found, then this moment can be taken as the moment of separation of the fragments (see, e.g., Kholshevnikov et al. 2016; Babadzhanov et al. 2017; Kholshevnikov & Shaidulin 2017; Kokhirova et al. 2018). However, over time, due to various perturbations of both gravitational and non-gravitational nature, the difference in the elements of the two orbits can increase significantly, especially such angular elements as Ω and ω (in this case, it is necessary to control the stability of the value of π). For this reason, the modern orbits of fragments originating from the same parent comet can differ greatly from each other. One shortcoming in using the $D_{\rm SH}$ criterion for comparing orbits over long time intervals is that the angular elements Ω and ω change over a reasonable timescale so that $D_{\rm SH}$ can become large simply by these changes. Asher et al. (1993) proposed a simplified D criterion that avoided this, namely

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

with the condition $D \leqslant 0.15$ showing similar orbits.

In the absence of disturbances, the orbits will constantly pass through the fragmentation point, that is, they will intersect at this point. However, over time, this information disappears and is erased due to various disturbances of both gravitational and non-gravitational nature. To establish the moment of greatest orbital similarity we calculated the $D_{\rm SH}$ criterion and simplified D criterion of Asher et al. (1993) between the orbits of studied NEAs and followed their behavior backward over 12 thousand years. The secular variations of both similarity criteria for the sample of NEAs, between which fragmentation very likely occurred, are presented in Figure 4. Note that we calculated both similarity criteria, but in the analysis, we relied mainly on the $D_{\rm SH}$ criterion as the strongest indicator of the proximity of two orbits. Changes in criterion D are presented to demonstrate their analogy to changes in criterion $D_{\rm SH}$. In addition, the mutual values of the D criterion for the studied NEAs, much lower than the accepted threshold, along with the $D_{\rm SH}$ criterion, are an additional indirect indicator of the similarity of the orbits of objects and, therefore, their common origin. Analyzing obtained dependences, we make the following suggestions of a scenario for the parent comet break-up:

Starting from the four largest NEAs of our sample, 2003 RW11 (1.5 km), 2009 BE77 (1.2 km), 2009 BB (1.1 km) and 1991 AQ (1.1 km), we recognized that 2003 RW11 and 2009 BE77 have minimal values $D_{\rm SH} = 0.17$ and $D = 0.05$ around 1094 yr; 2003 RW11 and 2009 BB have minimal values $D_{\rm SH} = 0.15$ and $D = 0.08$ around 1094 yr; 2009 BE77 and 2009 BB have minimal values $D_{\rm SH} = 0.02$ and $D = 0.02$ around 1184 yr. Fragmentation of 2009 BB and 2009 BE77 from 2003 RW11 occurred ∼1094–1184 yr, therefore about one thousand years ago. 2003 RW11 and 1991 AQ have the smallest values $D_{\rm SH} = 0.14$ and $D = 0.11$ around −2236 yr, and 1991 AQ probably broke away from 2003 RW11 about 4.2 thousand years ago. Both pairs 2009 BE77 and 1991 AQ, and 2009 BB and 1991 AQ do not have $D_{\rm SH} \leqslant 0.25$ values for the period under review, and for this reason, there was no fragmentation between them.

Next, we examined the largest NEAs and medium-sized NEAs 2010 XC11 (0.9 km) and 2010 XX58 (0.9 km). It turned out that 2010 XC11 and 2010 XX58 have minimum values of $D_{\rm SH} = 0.07$ and $D = 0.03$ between −6646 and −6966 yr and it can be assumed that they separated approximately 8.6–8.7 thousand years ago. 2010 XX58 and 2003 RW11 do not have $D_{\rm SH} \leqslant 0.25$ and $D \leqslant 0.15$ values during the considered time, and 2010 XC11 and 2003 RW11 have values of $D_{\rm SH}$ around 0.17–0.25 three times starting from 2014 until −2000 but they do not correspond to smallest values of the D criterion. Consequently, 2003 RW11 could not have been fragmented into 20010 XX58 and 2010 XC11 which confirms that the last two asteroids are debris of a single body. 2009 BE77 and 2010 XC11 do not have $D_{\rm SH} \leqslant 0.25$ values, and due to this and taking into account the fact that 2009 BE77 appeared later than 2010 XC, their split is impossible. The same was found for 2009 BE77 and 2010 XX58. This pair also does not have $D_{\rm SH}$ values bigger than 0.25 and given that 2009 BE77 occurred after 2010 XX58, they could not have been fragmented. Although 2009 BB and 2010 XC11 have minimum values of $D_{\rm SH} = 0.08$ and $D = 0.01$ between −3486 and −3526 yr, since 2009 BB was allocated later and has lower $D_{\rm SH}$ values with 2003 RW11 and 2009 BE77 than with 2010 XC11, we assume there was no division between them. Since 1991 AQ and 2010 XC11 do not have $D_{\rm SH} \leqslant 0.25$ and $D \leqslant 0.15$ values, and given that 1991 AQ separated much later than 2010 XC11 and 2010 XX58, a break-up of 1991 AQ and 2010 XC11 is unlikely. The same thing is observed for the pair AQ 1991 and 2010 XX58. They also do not have $D_{\rm SH} \leqslant 0.25$ and $D \leqslant 0.15$ values, and for the above reason, the separation of 1991 AQ and 2010 XX58 could not occur.

Next, we included the remaining small-sized NEAs into consideration. It is shown that 2003 AA83 (0.2 km) does not have $D_{\rm SH} \leqslant 0.25$ values with 2003 RW11, 2009 BB, 2009 BE77, 2010 XX58 and 2014 YQ34, and in addition, there are no $D \leqslant 0.15$ values with 2010 XX58, which mean that a fragmentation of the corresponding pairs could not happen. However, 2003 AA83 and 2010 XC11 were found to have minimum values of $D_{\rm SH} = 0.19$ and $D = 0.16$ between 964 and 914 yr, leading to the conclusion that 2003 AA83 separated from 2010 XC11 about 1.1 thousand years ago. PHA 2001

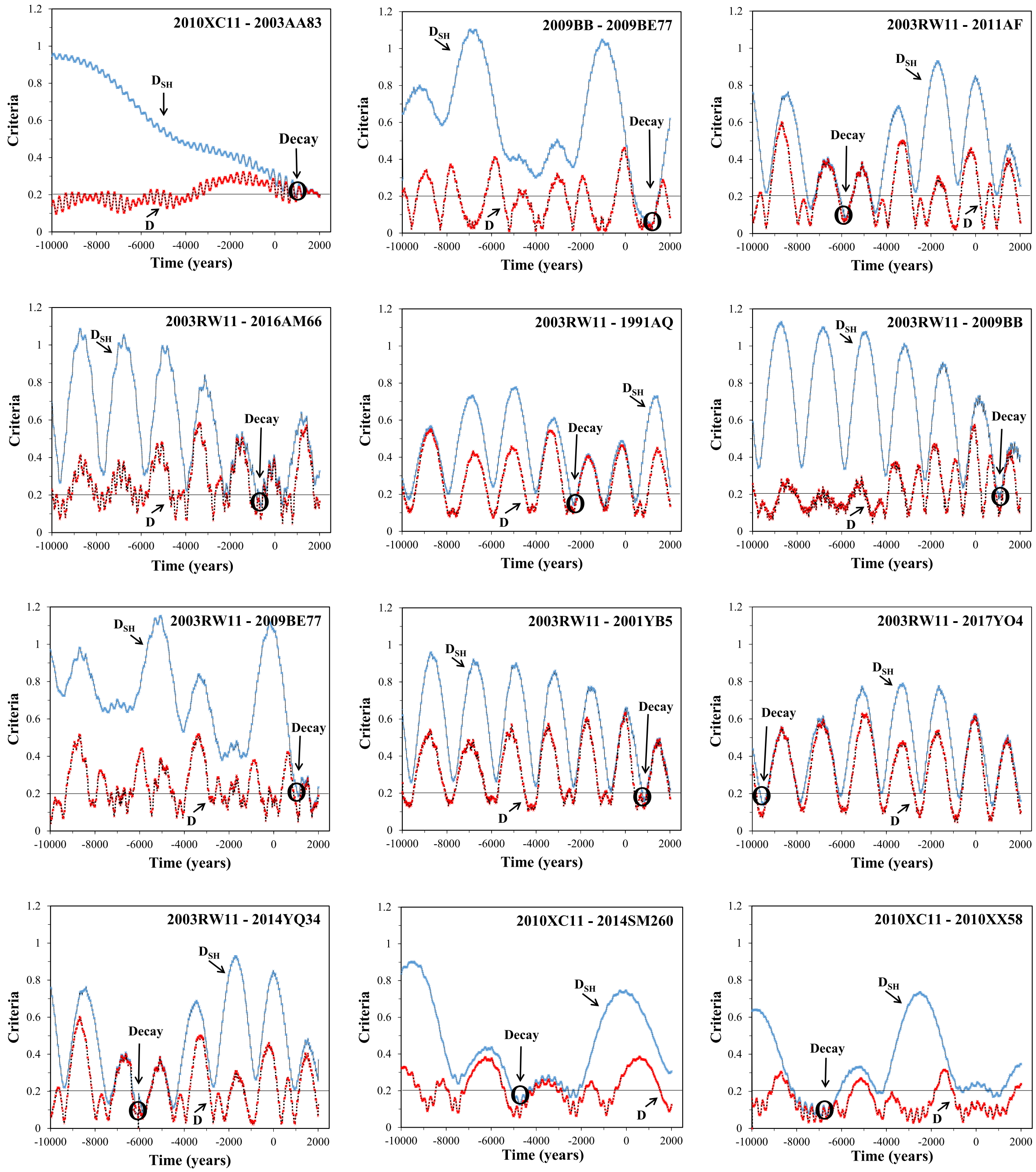

Figure 4. Secular variations of the similarity criteria for NEAs fragmented from the parent comet of the δ-Cancrid complex. The abscissa plots the time interval studied, the ordinate gives the mutual value of the similarity criterion of the two orbits compared. The period of decay is indicated by a big-O circle.

YB5 has no values of the D_{SH} criterion satisfying the threshold with 1991 AQ, 2009 BE77, 2014 SM260. The values of both criteria show that the orbit of 2001 YB5 (0.20 km) is similar to the orbits of 2009 BB and 2016 AM66 during almost the total considered period, and there are several minimal values of both criteria between 2001 YB5 and 2010 XX58, 2010 XC11, etc. However, when analyzing mutual values of both criteria for 2001 YB5 and 2003 RW11, we consider that their fragmentation very likely occurred in the period of 864–844 yr, about 1.2 thousand years ago.

2017 YO4 (0.33 km) has no values of $D_{SH} \leqslant 0.25$ with 2009 BB, 2009 BE77, 2010 XX58, 2010 XC11, 2014 YQ34, 2003 AA83, and 2014 SM260 in the studied period. 2003 RW11 and 2017 YO4 have the smallest values of $D_{SH} = 0.13$ and

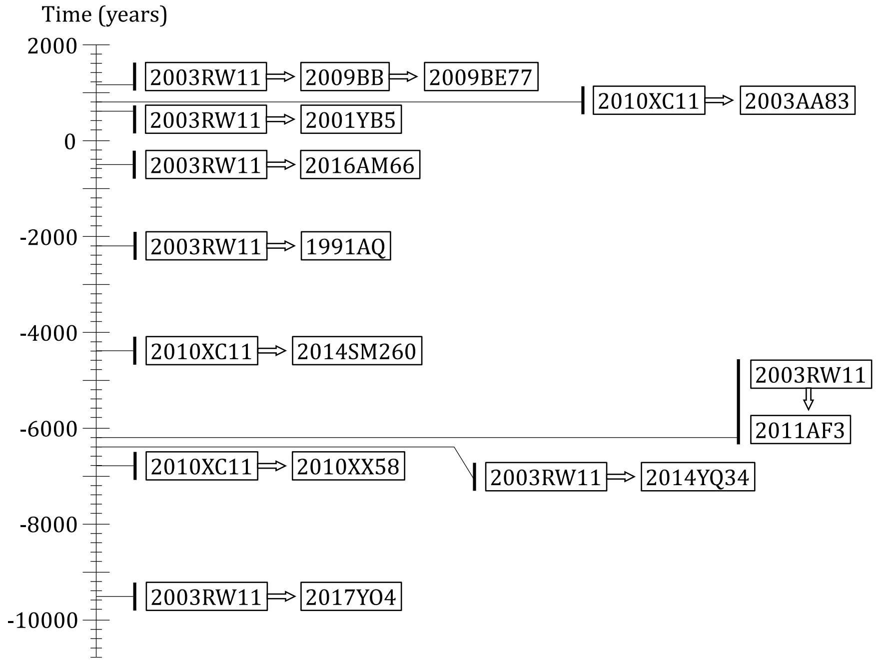

Figure 5. Scheme of fragmentation of the parent comet of δ-Cancrid complex. The time interval is plotted on the vertical axis and the boxes attached to the established decay period show between which NEAs it occurred.

$D = 0.09$ at the interval −9486 to −9496 yr. 2011 AF3 and 2017 YO4 have the smallest values of $D_{\rm SH} = 0.13$ and $D = 0.03$ at the interval between −96386 and −96466 yr. A closeness of the orbits of 2017 YO4 and 1991 AQ is confirmed by the D criterion values three times over considered period, and the orbits of 2017 YO4 and 2016 AM66 are similar four times, however, analyzing a behavior of the mutual D criterion values we chose a linkage of 2017 YO4 with the largest 2003 RW11 as more likely. Supposedly, 2017 YO4 fragmented from 2003 RW11 about 11.5 thousand years ago, and a closeness of the 2017 YO4 and 2011 AF3 orbits, observed approximately 8.4–8.5 thousand years ago, matches a period of 2011 AF3 formation from 2003 RW11.

2014 SM260 (0.3 km) and 2010 XC11 have minimum values of $D_{\rm SH} = 0.14$ and $D = 0.10$ between −4656 and −4676 yr, therefore it can be assumed that 2014 SM260 separated from 2010 XC11 almost 6.7 thousand years ago. 2014 SM260 and 2009 BE77 have minimum values of $D_{\rm SH} = 0.14$ and $D = 0.07$ between −96416 and −96436, −96686 and −96696 yr; and with 2009 BB it has minimum values of $D_{\rm SH} = 0.17$ and $D = 0.10$ between −2236 and −2256 yr, $D_{\rm SH} = 0.17$ and $D = 0.11$ at −92436 and −92456 yr. However, as established, 2009 BE77 and 2009 BB appeared about one thousand years ago, and 2014 SM260 separated from 2010 XC11 6.7 thousand years ago. For this reason, despite satisfying values of the criteria, 2014 SM260 could not have separated from 2009 BE77 and 2009BB. The pairs 2014 SM260-2003 RW11 and 2014 SM260-2010 XX58 do not have values of $D_{\rm SH} \leqslant 0.25$ and $D \leqslant 0.15$, so they are likely not fragmented from each other. Because 2014 SM260 and 2003 AA83 have no values of $D_{\rm SH} \leqslant 0.25$ and $D \leqslant 0.15$ and taking into account that 2003 AA83 divided from 2010 XC11 about 1.1 thousand years ago, a fragmentation of 2014 SM260 from 2003 AA83 is impossible.

According to the smallest values of the $D_{\rm SH}$ and D criteria, NEAs 2014 YQ34 (0.08 km) and 2011 AF3 (0.05 km) could separate approximately between 7.8 and 8.1 thousand years ago. 2003 RW11 and 2014 YQ34 have minimal values of both criteria at −6096 yr, therefore 2014 YQ34 separated from 2003 RW11 almost 8.1 thousand years ago. 2003 RW11 and 2011 AF3 have the smallest values of both criteria at −5856 yr and their break-up occurred about 7.8 thousand years ago, consequently, 2011 AF3 and 2014 YQ34 fragmented from 2003 RW11 during 7.8–8.1 thousand years ago. NEAs 2011 AF3 and 2016 AM66 (0.51 km) have minimal values of the D criterion at −8000 yr, however, taking into account that 2016 AM66 fragmented from 2003 RW11 2.6 thousand years ago while 2011 AF3 separated from 2003 RW11 7.8 thousand years ago, the pair 2011 AF3 and 2016 AM66 has not divided. NEA 2014 YQ34 has no values of the $D_{\rm SH} \leqslant 0.25$ with NEAs 2009 BB, 2009 BE77, 2010 XC10, 2010 XX58, 2014 SM260, 1991 AQ so we can suggest there is no fragmentation between them. NEAs 2003 RW11 and 2016 AM66 have the smallest values of both criteria between −500 and −600 yr, and very probably, 2016 AM66 was separated from 2003 RW11 about 2.6 thousand years ago. The proposed mechanism of parent comet disintegration is clearly shown in the diagram in Figure 5.

5. Discussion

As a result of our study, a dynamic link between active meteor showers generated by the δ-Cancrid meteoroid stream and a set of asteroids was established. This stream and the meteor showers it generates, along with the 13 NEAs, together form the δ-Cancrid asteroid-meteoroid complex. The identified association between the stream and showers is a very convincing indicator that 13 NEAs moving in comet-like orbits have a cometary origin. Given the results of dynamical modeling and following the behavior of the criteria of orbital similarity we can assume the possible scenario of the formation of this complex: initially, the giant parent Jupiter-family comet of the stream was destructed into two large pieces more than 12 thousand years ago, so there are 2003 RW11 and 2010 XC11. We can confidently say that it was a giant comet, since almost half of its remnants are on the order of or greater than 1 km in size. Next, the cascade division of each of these objects began. 2017 YO4, 2011 AF3, and 2014 YQ34 were fragmented from 2003 RW11 about 11.5 and during the period around 8 thousand years ago, correspondingly. 1991 AQ, 2016 AM66, 2001 YB5, 2009 BB and 2009 BE77 were separated from 2003 RW11 4.0–4.2, 2.5–2.6, 1.2, 1.0 and 0.8 thousand years ago, correspondingly. 2010 XX58, 2014 SM260, and 2003 AA83 were fragmented from 2010 XC11 8.9, 6.6–6.7 and 1.1 thousand years ago, respectively. Of course, we realize that this is only a supposed mechanism of fragmentation of the parent comet of the complex, and the approach used for this assumption has certain shortcomings. For greater persuasiveness of the given possible mechanism, it would be necessary to statistically estimate the level of its probability taking into account the number of discovered NEAs. Such a task is beyond the scope of the present study and will be considered in the authors' subsequent works. Thus, we can only suppose that objects were formed by the disintegration of a giant comet—the progenitor of the stream, and followed by the fragmentation of the largest fragments. Presently, the cometary objects are in an extinct stage. Coming from this, we can conclude that the δ-Cancrid complex includes a meteoroid stream that produces an observable active meteor shower and contains 13 large-sized extinct remnants of the parent comet. Furthermore, it was revealed that in addition to small meteoroids, the stream also contains large objects ranging in size from 50 m to 1.5 km. Among them, four asteroids are classified as potentially hazardous objects.

6. Conclusions

Our investigation suggests the establishment of a new δ-Cancrid asteroid-meteoroid complex. The complex includes the meteoroid stream which produces active meteor showers and it is confirmed by the observations. In addition, 13 NEAs were found to be probably dynamically associated with this complex. This association and comet-like orbits indicate that the asteroids are likely of a cometary origin. In this case, they may be regarded as the fragments of a parent comet of the δ-Cancrid complex, currently in an extinct or dormant phase. We should acknowledge the advanced nature of the method introduced by Ye et al. (2016), especially with the development of computing technology today. Our analytical method uses a simplified assumption based on the concept of the formation and evolution of meteoroid streams, following and comparing the objects' orbital evolution. However, this widely used approach has yielded the establishment of a set of known complexes, whose reliability has been confirmed by numerous publications including Wiegert & Brown (2004) and Ye et al. (2016). Underestimating the probability of chance association is the main shortcoming of the assumption. It is always a challenge to distinguish a genuine parent-stream linkage from a chance alignment, which is further complicated by the difficulty in obtaining their precise orbits and fragmentation history (Ye & Jenniskens 2022). However, it is still a convenient approach to get the right probability at least to the order of magnitude. For a more realistic estimation of the association between the meteor showers and asteroid orbits, we need to utilize the Monte Carlo method to do Bayesian prediction with objective priors, suppressing the selection bias, as described by Ye et al. (2016). The proposed scenario of cascade fragmentation of the cometary parent is a phenomenological interpretation rather than a physical mechanism so it can be considered only as a possible mechanism. For more physical inference, we should introduce the physical criterion of asteroid fragmentation and do the Monte Carlo simulation to get the possible physical forms and probability of fragmentation. The results point to the meteoroid streams containing both small particles on the millimeter scale and large objects over the decameter scale, posing a potential hazard to the Earth and space exploration missions. This is confirmed by both theoretical studies and observational data.

Our research allows the prediction of parameters for such objects entering the Earth's atmosphere, which is needed to develop mitigation strategies to prevent the consequences. The search for other putative large fragments of the parent comet should continue in the future. They are also extinct at present and may be found in known NEAs and newly discovered NEAs.

Acknowledgments

The authors express their deep gratitude to the anonymous reviewers for their careful study and prudent comments on the article, which greatly improved the scientific level of the work. The *N*-body integrator REBOUND (Rein & Spiegel 2015) was utilized to model and plot the asteroids' orbits in this paper. Co-authors from China acknowledge the support from the National Key R&D Intergovernmental Cooperation Program (2023YFE0102300/2022YFE0133700), the Regional Collaborative Innovation Project of Xinjiang (2022E01013), the National Natural Science Foundation of China (12173078) and the "Belt and Road" Innovative Talent Exchange Program (DL2023046004).

ORCID iDs

M. Zhang https://orcid.org/0000-0002-8315-2848

References

Asher, D. J., Clube, S. V. M., & Steel, D. I. 1993, MNRAS, 264, 93
Babadzhanov, P., & Kokhirova, G. 2012, in Proc. of the Int. Astronomical Union, ed. T. Montmerle (Cambridge: Cambridge Univ. Press), 169
Babadzhanov, P. B., Kokhirova, G. I., & Khamroev, U. K. 2015a, AdSpR, 55, 1784
Babadzhanov, P. B., Kokhirova, G. I., & Obrubov, Y. V. 2015b, SoSyR, 49, 165
Babadzhanov, P. B., Kokhirova, G. I., & Obrubov, Y. V. 2015c, A&A, 579, A119
Babadzhanov, P. B., Kokhirova, G. I., Williams, I. P., & Obrubov, Y. V. 2017, A&A, 598, A94
Babadzhanov, P. B., & Obrubov, I. V. 1992, CeMDA, 54, 111
Babadzhanov, P. B., Williams, I. P., & Kokhirova, G. I. 2008a, A&A, 479, 249
Babadzhanov, P. B., Williams, I. P., & Kokhirova, G. I. 2008b, MNRAS, 386, 1436
Babadzhanov, P. B., Williams, I. P., & Kokhirova, G. I. 2009, A&A, 507, 1067
Babadzhanov, P. B., Williams, I. P., & Kokhirova, G. I. 2012, MNRAS, 420, 2546
Babadzhanov, P. B., Williams, I. P., & Kokhirova, G. I. 2013, A&A, 556, A25
Bredikhin, F. A. 1954, in Sketches About Meteors (Classics of Science), ed. S. V. Orlov (Moscow: Publishing House of the USSR Academy of Sciences), 613, in Russian language
Drummond, J. D. 1981, Icar, 45, 545
Everhart, E. 1974, Celest. Mech., 10, 35
Goryachev, N. N. 1937, in Halphen's Method for Calculation of Planetary Secular Perturbations and its Application to Ceres, ed. L. A. Vishnevsky (Tomsk: Red Banner), 115, in Russian language
Halliday, I., Griffin, A. A., & Blackwell, A. T. 1996, M&PS, 31, 185
Harris, A. W. 2002, Icar, 156, 184
Hughes, D. W. 1986, The Relationship between Comets and Meteoroid Streams, in IN: Asteroids, comets, meteors II; Proc. of the International Meeting, ed. C. I. Lagerkvist et al., 503
Hui, M.-T., & Li, J. 2017, AJ, 153, 23
Jenniskens, P. 2007, in Proc. of the 25th Int. Meteor Conf., ed. F. Bettonvil & J. Kac (Mechelen: International Meteor Organization), 56
Jenniskens, P., Nénon, Q., Gural, P. S., et al. 2016, Icar, 266, 355
Jewitt, D. 1991, in Proc. of IAU Colloq. 116, ed. J. Newburn et al. (Dordrecht: Kluwer Academic Publishers), 19
Jewitt, D. 2012, AJ, 143, 66
Jewitt, D., & Li, J. 2010, AJ, 140, 1519
Jewitt, D., Li, J., & Agarwal, J. 2013, ApJL, 771, L36
Kholshevnikov, K. V., Kokhirova, G. I., Babadzhanov, P. B., & Khamroev, U. H. 2016, MNRAS, 462, 2275
Kholshevnikov, K. V., & Shaidulin, V. S. 2017, CeMDA, 128, 75
Kokhirova, G. I., Kholshevnikov, K. V., Babadzhanov, P. B., Khamroev, U. H., & Milanov, D. V. 2018, P&SS, 157, 28
Kokhirova, G. I., Zhonmuhammadi, A. I., Khamroev, U. H., Latipov, M. N., & Jopek, T. J. 2024, P&SS, 243, 105869
Kresák, L. 1969, BAIC, 20, 177
Lebedinets, V. N., Korpusov, V. V., & Sosnova, A. 1973, in Proc. of the Institute of Experimental Meteorology, 1 (Obninsk: Institute of Experimental Meteorology), 88, in Russian language
Lindblad, B. A. 1971, SCoA, 12, 1
McCrosky, R. E., Shao, C. Y., & Posen, A. 1978, Metik, 37, 44
Nilsson, C. S. 1964, AuJPh, 17, 205
Öpik, E. J. 1963, AdA&A, 2, 219
Porubčan, V., Kornoš, L., & Williams, I. P. 2006, CoSka, 36, 103
Rein, H., & Spiegel, D. S. 2015, MNRAS, 446, 1424
Rudawska, R., & Jenniskens, P. 2014, in Proc. of the Astronomical Conference: Meteoroids 2013, ed. T. J. Jopek et al. (Poznań: A.M. University Press), 217
Rudawska, R., Matlovič, P., Tóth, J., & Kornoš, L. 2015, P&SS, 118, 38
Ryabova, G. O., Avdyushev, V. A., & Williams, I. P. 2019, MNRAS, 485, 3378
Sekanina, Z. 1973, Icar, 18, 253
Sekanina, Z. 1976, Icar, 27, 265
Southworth, R. B., & Hawkins, G. S. 1963, SCoA, 7, 261
Weissman, P. R., A'Hearn, M. F., McFadden, L. A., & Rickman, H. 1989, in IN: Asteroids II; Proc. of the Conference, ed. R. P. Binzel et al. (Tucson, AZ: Univ. of Arizona Press), 880
Whipple, F. L. 1950, ApJ, 111, 375
Whipple, F. L. 1951, ApJ, 113, 464
Whipple, F. L. 1983, IAUC, 3881, 1
Wiegert, P., & Brown, P. 2004, EM&P, 95, 19
Williams, I. P., & Wu, Z. 1993, MNRAS, 262, 231
Ye, Q., & Jenniskens, P. 2024, in to appear in Comets III, ed. K. J. Meech et al. (Tucson, AZ: Univ. of Arizona Press)
Ye, Q.-Z., Brown, P. G., & Pokorný, P. 2016, MNRAS, 462, 3511