

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

Authors: G. I. Kokhirova, M. Zhang, X. -G. Li, A. I. Zhonmuhammadi and X. Liu

Date: 2025-01-07T00:00:00+00:00

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.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:125002 (13pp), 2024 December
© 2024 National Astronomical Observatories, CAS and IOP Publishing Ltd. All rights, including for text and data mining, AI training, and similar technologies, are reserved. Printed in China.

<https://doi.org/10.1088/1674-4527/ad8c87>

Near-Earth Asteroids as the Parents of the δ -Cancrid Meteoroid Stream
X.-G. Li^{2,5}, A. I. Zhonmuhammadi¹, X. Liu^{2,3,4}, G. I. Kokhirova^{1,6}, M.

Zhang^{2, 3, 4, 6}

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 University of Chinese Academy of Sciences, Beijing 100049, China

⁴ National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

⁵ School of Physical Science and Technology, Xinjiang University, Urumqi 830046, China

⁶ Equal contributors and co-first authors of this paper

Received 2024 April 11; revised 2024 October 9; accepted 2024 October 28; published 2024 November 28

Abstract

The δ -Cancriid meteoroid stream forms four active meteor showers observable annually on Earth 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 by following the backward evolution of orbital elements for a sample of NEAs to locate their Earth-crossing positions. Using these orbits, we calculated the theoretical parameters of meteor showers associated with the considered NEAs. By comparing these predictions with published data on observable active showers, we identified that 13 NEAs produce predicted meteor showers matching the active showers of the δ -Cancriid meteoroid stream. The comet-like orbits of these NEAs and their established association with active meteor showers indicate a common cometary origin. These NEAs are moving within the stream and likely represent dormant remnants of a parent comet that disintegrated more than 12,000 years ago.

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

1. Introduction

Small bodies in the solar system preserve the state of the proto-solar disk from the solar system’s formation epoch. Consequently, studying these objects helps us deeply understand the formation and evolution of our planetary system. The family of small bodies includes comets, asteroids, and meteoroids, with meteoroids representing fragmental products of comet and asteroid disintegration. Meteoroid components divide into two main groups: sporadic background and stream meteoroids. In this paper, we focus on meteoroid streams, which we define as large numbers of meteoroids generated by a single parent body that move in interplanetary orbits similar to the parent’s orbit.

The formation of meteoroid streams can only be caused by cometary activity

or destruction. As Bredikhin (1954) demonstrated, only periodic, normal gas- and dust-producing activity during a comet's perihelion passage can form a stable, long-lived meteoroid stream. Additionally, catastrophic disintegration from impacts or other processes may produce streams. However, break-up of an asteroid through collision cannot ensure formation of a long-lived stream, as dust and debris ejection would be insufficient and one-time only. The theory of meteoroid stream formation, evolution, and structure is well-established in numerous studies (e.g., Whipple 1950, 1951; Hughes 1986; Babadzhanov & Obruchov 1992; Babadzhanov et al. 2008b, 2015b).

A notable exception to this paradigm is the connection between near-Earth asteroid (3200) Phaethon and the Geminid meteor shower, based on orbital similarity (Whipple 1983). The Geminids are observed annually during December 10–15, and extensive research suggests Phaethon is likely the parent body, implying a cometary nature for the asteroid (e.g., Williams & Wu 1993; Ryabova et al. 2019). Phaethon exhibited short-term cometary activity near perihelion in 2009 (Jewitt & Li 2010), with repeat observations in 2012 and 2016 (Jewitt et al. 2013; Hui & Li 2017), leading to its classification as an active asteroid (Jewitt 2012). Its geometric albedo of 0.107 ± 0.011 (<https://ssd.jpl.nasa.gov>) corresponds to dark asteroids and matches the 0.02–0.12 range for extinct cometary nuclei (Jewitt 1991). However, Wiegert & Brown (2004) argued that the Phaethon-Geminid link is extremely unlikely and may represent chance alignment. Therefore, convincing association between a primitive asteroid and meteor shower requires further research on both the connection and the object's nature.

When a meteoroid stream's orbit intersects Earth's orbit, meteor showers are generated that we can observe and record using various techniques. As Babadzhanov & Obruchov (1992) showed, depending on the number of orbital intersections with Earth, meteor streams can generate four to eight observable annual showers during corresponding periods. Quadruple crossings are most common, making four showers the typical production. The Taurid meteoroid stream exemplifies this, producing four meteor showers: the Northern and Southern Taurids (pre-perihelion crossing, observed September–November) and the Daytime β -Taurids and γ -Perseids (post-perihelion crossing, observed June–July). While comet 2P/Encke is the parent body, more than 40 NEAs belong to this family, forming the Taurid asteroid-meteoroid complex. These asteroids likely represent extinct comet nuclei or dead fragments of a larger progenitor (e.g., Asher et al. 1993; Porubčan et al. 2006; Babadzhanov et al. 2008b).

The presence of extinct or dormant comet nuclei among NEAs is well-established. According to some estimates, they may account for up to 6% of discovered NEAs (Öpik 1963; Weissman et al. 1989; Babadzhanov & Kokhirova 2012). Weissman et al. (1989) define “dormant” or “extinct” comets as nuclei that were active in the past but have lost their ability to generate a visible coma. During evolution, such nuclei become covered with a thick, refractory

mantle that prevents gas and dust ejection, ceasing normal cometary activity (Whipple 1950, 1951; Öpik 1963). However, extinct comets can be reactivated by non-catastrophic collisions or meteoroid bombardment (Weissman et al. 1989), with confirmed observations of such events (Babadzhanov et al. 2017). Ground-based observations show extinct comet nuclei are indistinguishable from asteroids in appearance but can be distinguished by their orbital elements. The typical cometary orbit implies cometary origin, and established connections with observable meteor showers significantly strengthen this assumption.

Several asteroid-meteoroid complexes have been identified using this approach, including the Piscids (Babadzhanov et al. 2008a), η -Aquariids (Babadzhanov et al. 2009), δ -Scorpiids (Babadzhanov et al. 2013), σ -Capricornids (Babadzhanov et al. 2015a), and Virginids (Babadzhanov et al. 2012, 2015c; Kokhirova et al. 2024). Each complex contains several NEAs of cometary origin that may be parent bodies of relevant streams. However, parent bodies of all known meteoroid streams have not yet been identified. Since finding these parents is critical for understanding genetic connections between small solar system objects, we continue studying their relationships to discover new extinct comets among NEAs. This paper presents results from our investigation of the δ -Cancriid meteoroid stream.

2. δ -Cancriid Asteroid-Meteoroid Complex

2.1. Meteor Showers of the δ -Cancriid Meteoroid Stream

In the IAU MODC meteor shower database (www.ta3.sk, 2023), the confirmed δ -Cancriid showers are the nighttime Northern and Southern δ -Cancriids (00096 NCC and 00097 SCC, respectively), with maximum activity at the end of January, and the daytime Southern η -Leonids (00204 DXL) at the end of August. The daytime northern active period has not been established. The IAU MODC database indicates NEAs 1991 AQ and 2001 YB5 as possible parent bodies. We searched among NEAs discovered before 2018 and identified 13 asteroids related to the δ -Cancriid stream, also establishing the northern branch of the daytime shower, with results presented below.

2.2. Research Approach and Methodology

Our research approach is based on the theory of meteoroid stream formation and evolution (Babadzhanov & Obruchov 1992) and the presence of extinct comet nuclei among NEAs (Öpik 1963; Weissman et al. 1989; Babadzhanov & Kokhirova 2012). Among the many meteoroids in a stream, only those with orbital heliocentric distances equal to 1 au at ascending (Ra) and descending (Rd) nodes can intersect Earth's orbit (Babadzhanov & Obruchov 1992). For most NEA orbits, this condition is satisfied four times during one cycle of the argument of perihelion variation. If an asteroid is indeed an extinct comet, a meteoroid stream could have formed during past cometary activity, theoretically producing four observable meteor showers: nighttime showers with northern and southern

branches, and daytime showers with northern and southern branches.

To determine these theoretical shower parameters, we need the asteroid's orbit at Earth-crossing positions. This is obtained by calculating the orbital evolution of the proposed parent body using numerical integration methods for time intervals equal to one period of argument of perihelion variation, typically covering 10–12 thousand years for NEAs. The Everhart (1974) and Halphen-Goryachev (1937) methods are commonly used for orbital evolution calculations. Once theoretical shower characteristics are determined, we search published catalogs of observed meteor showers and fireballs for activity matching the predictions. If theoretical showers are consistent with observed ones, this confirms a connection between the generating meteoroid streams and the asteroids, suggesting the asteroids have cometary properties.

We studied only asteroids traveling in comet-like orbits that cross Earth's orbit. Note that a comet-like orbit is necessary but not sufficient for cometary origin. We use the Tisserand parameter T_j for classification: orbits with $T_j \leq 3.12$ are comet-like, while $T_j \geq 3.12$ are asteroidal (Kresák 1969; Jewitt 2012). The condition for Earth orbit intersection was verified using the NEODyS-2 database (<https://newton.spacedys.com>, 2021).

2.3. Near-Earth Asteroid Candidates for Extinct Comets

From the NEOP database (<https://cneos.jpl.nasa.gov/>, 2019), we selected NEAs discovered until December 31, 2017, that have comet-like orbits according to T_j . From these, we selected NEAs that intersect Earth's orbit according to NEODyS-2 (<https://newton.spacedys.com>, 2021), yielding approximately 3,000 asteroids. We calculated their orbital evolution backward over one cycle of argument of perihelion variation, excluding 3% due to chaotic motion. Using the evolution results for the remaining NEAs, we calculated theoretical meteor shower parameters and performed a computerized search for observed showers/meteors/fireballs with matching parameters.

Initially, among approximately 2,500 investigated NEAs, theoretical showers from only 13 asteroids matched observed δ -Cancrid showers. Some NEAs were excluded despite matching showers because their π values were inconsistent. The 13 selected NEAs have averaged $\pi = 221 \pm 8^\circ$, matching the δ -Cancrid showers' averaged $\pi = 220 \pm 10^\circ$ (from various sources). This additional condition was applied when selecting candidate asteroids. Note that some studied asteroids also showed relationships to other new and known associations, which will be addressed in future papers.

Table 1 presents the main parameters of the 13 NEAs associated with the δ -Cancrid stream, including designation, orbital elements (Equinox 2000.0: semi-major axis a , eccentricity e , perihelion distance q , inclination i , longitude of ascending node Ω , argument of perihelion ω , longitude of perihelion π), absolute magnitude H , equivalent diameter d , number of Earth orbit intersections N_i during one argument of perihelion cycle, Tisserand parameter T_j , geometric

albedo p , and taxonomic classification Sp . The N_i value corresponds to the number of theoretically predicted meteor showers per asteroid (Babadzhanov & Obruchov 1992).

Asteroid 1991 AQ has $T_j = 3.16$, at the boundary between cometary and asteroidal criteria, but we classify its orbit as comet-like. Albedo and taxonomy data for three asteroids from the ALCDEF database (www.alcdef.org) require additional description. NEA 1991 AQ has measured albedo 0.24 ± 0.19 with large error; 2001 YB5 has albedo 0.20 without reported error. These uncertain values, combined with comet-like orbits, mean we do not exclude these asteroids but require additional investigation. The albedo of 2003 RW11 is 0.02 ± 0.05 , consistent with confirmed cometary nuclei values. These NEAs are spectrally classified as S-type, which typically has moderate albedo (0.10–0.20). However, 2003 RW11's albedo does not correspond to S-type, and uncertainties for 1991 AQ and 2001 YB5 prevent conclusions about their real spectral features. No ALCDEF data exist for the remaining 10 NEAs, so we use ssd.jpl.nasa.gov data assuming albedo values typical for cometary nuclei.

For greater confidence, NEA albedos should be refined in future work. Diameters with superscripts in Table 1 are from published databases (ssd.jpl.nasa.gov and alcdef.org). Where size estimates were lacking, diameters were calculated using the standard expression (Harris 2002) with geometric albedo p . For very dark C-, P-, and D-type asteroids, albedo is 0.02–0.12, indicating likely extinct comets (Jewitt 1991). Quoted diameters were estimated using the median low albedo value $p = 0.07$. Four asteroids in this sample are classified as potentially hazardous (PHA) in NEOP, indicated in Table 1. Figure 1 [Figure 1: see original paper] shows the 2D projection of the 13 NEAs' present orbits onto the ecliptic plane, with the Sun and Earth's orbit.

2.4. Investigation of Orbital Evolution

We calculated orbital evolution during periodic argument of perihelion variation using the Everhart RADAU19 method (Everhart 1974), including gravitational perturbations from major planets. All asteroids cross Earth's orbit four times during one ω variation cycle, meaning R_a and R_d equal 1 au four times per cycle (twice at each node). Figures 2–3 demonstrate R_a and R_d variations with time and argument of perihelion for sample asteroids. The straight line parallel to the abscissa at 1 au indicates Earth's orbit position, with intersections marked by arrows. These graphs are similar for all NEAs; we present samples for 2001 YB5 (Figure 2 [Figure 2: see original paper]) and 2010 XC11 (Figure 3 [Figure 3: see original paper]).

Table 2 gives argument of perihelion values at Earth-crossing positions for the NEAs, with averages and standard deviations. Theoretical showers are listed in order: (1) northern nighttime branch, (2) southern nighttime branch, (3) northern daytime branch, and (4) southern daytime branch.

Using orbital elements from evolution calculations corresponding to Earth orbit

intersection, we calculated equatorial coordinates of geocentric radiant (R.A. α_g and declination δ_g), geocentric velocities V_g , solar longitudes Le , and corresponding dates for theoretical meteor shower activity.

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

We conducted a computerized search for theoretically predicted showers in published catalogs of observable meteor/fireball showers and detected fireballs/meteors. By comparing theoretical and observational parameters, we require: radiant position differences $\leq \pm 10^\circ$ in both R.A. and declination, geocentric velocity differences $\Delta V_g \leq \pm 5 \text{ km s}^{-1}$, and activity periods differing by $\leq \pm 15$ days (e.g., Babadzhanov et al. 2008a, 2008b, 2009; Rudawska et al. 2015). When these conditions are met, we declare the geocentric parameters of theoretical and observed showers to be close.

Orbital similarity is checked using the Southworth & Hawkins (1963) criterion DSH. They showed the threshold value confirming connection is 0.20. When calculating the threshold DSHmax for meteor and shower orbit similarity, the relation $\text{DSHmax} = 0.2(360/N)^{1/4}$ is used, where N is the meteor data sample size. Comparing 52 orbits (13 NEAs \times 4 intersections) with the active shower orbit gives $\text{DSHmax} = 0.32$. However, the generally accepted threshold of 0.20–0.25 is used for identifying streams and connections between comet-shower and asteroid-shower pairs. We therefore adopted $\text{DSH} \leq 0.25$ as the similarity condition.

The search identified 13 NEAs (Table 1) closely associated with meteoroid streams producing nighttime Northern and Southern δ -Cancrids (96 NCC and 97 SCC) and Daytime Southern γ -Leonids (204 DXL). As mentioned, the daytime northern branch has not been established. Our results suggest this may be the τ -Cancrids meteor shower (number 430 in Lebedinets et al. 1973). The γ -Leonids from Sekanina (1976) may also be the daytime northern branch, but its average orbit has a higher DSH criterion value than τ -Cancrids, so we selected the latter as the candidate.

Tables 3 and 4 show search results for asteroids 1991 AQ and 2003 RW11; other asteroids give similar results. Meteor shower parameters (orbital elements, radiant, solar longitudes, activity dates) for theoretically predicted showers are given in bold, labeled as: NNS (northern nighttime branch), SNS (southern nighttime branch), NDS (northern daytime branch), and SDS (southern daytime branch).

Catalogs where observable active showers and fireballs match theoretical predictions are listed 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). The DSH values confirm similarity between theoretical and observable orbits. Identification of theoret-

ical showers with observed showers and fireballs, confirmed by proximity of radiant position, velocity, and activity date, allows us to conclude that a connection exists between the asteroids and these showers. Therefore, the NEAs under consideration are likely of cometary origin and may be parent bodies of the stream or extinct fragments of a larger comet precursor. This meteoroid stream contains large-sized remnants of a currently dormant parent comet.

The association between NEAs in Table 1 and theoretical/observable meteor showers was found based on relevant radiants and current asteroid orbits (Tables 3–4). The proposed link between the stream and NEAs 1991 AQ and 2001 YB5 (www.ta3.sk, 2023) is confirmed. Four asteroids in this family are classified as potentially hazardous objects. The current orbit of PHA 2001 YB5 corresponds to the southern nighttime shower 97 SCC, while PHAs 2014 SM260 and 2014 YS43 correspond to the southern daytime δ -Leonids. Consequently, these asteroids may enter Earth’s atmosphere during associated meteor shower events with characteristics similar to those showers. For instance, the potentially hazardous asteroid 2001 YB5 has a theoretically predicted impact date of January 10, geocentric speed of 30.8 km s^{-1} , and impact coordinates $\alpha_g = 124^\circ.2$, $\delta_g = 15^\circ.4$.

3. On the Probability of Random Similarity of Two Orbits

Proximity of orbits is not sufficient to confirm connections between heliocentric objects, so we must consider the probability of random similarity. Assessing associations between NEAs and meteor showers is complex. Wiegert & Brown (2004) defined the expectation value of asteroids closer to a shower orbit than the test asteroid as $P = N/(n)$, where N is the number of asteroids used and n is the average number of trials selecting asteroid orbits satisfying $D \leq D_0$ (where D_0 is the Drummond (1981) criterion value of the test asteroid). If this number is much greater than one, chance alignment becomes probable; if less than one, P represents the probability that another asteroid is closer to the shower than the chosen asteroid. A small P implies few other asteroids in phase space around the shower, making chance alignment unlikely. This approach was implemented in Ye et al. (2016), confirming five asteroid-shower associations with P values around 1%.

Wiegert & Brown (2004) and Ye et al. (2016) used random samples of asteroids and shower orbits. However, we used a systematic selection procedure (Section 2.3), not random sampling. We did not compare all NEAs in the JPL-SSD database but only 13 NEAs as candidate parent bodies of the δ -Cancriid complex from systematic selection.

To assess the probability of random coincidence, we used the methodology from Babadzhanov et al. (2008a). These estimates depend on orbital similarity degree. We calculated mutual DSH criteria between modern orbits of the first four studied NEAs (Table 5). If asteroids were uniformly distributed in space, the maximum DSH between extreme cases would be 5. However, since asteroid

inclinations are less than 30° , the maximum DSH is 3 or 1.732 for such sets. Thus, the probability that two objects like 1991 AQ and 2001 YB5 (DSH = 0.24) are similar by chance is $0.24/1.732 \approx 14\%$. For 1991 AQ and 2003 AA83 (DSH = 0.15), the probability is about 9%. The probability that all four are similar by chance is thus about $3.5 \times 10^{-4}\%$. For the associations in our work, random association probabilities are negligible, suggesting at 100% confidence that a subset of selected NEAs is aligned with the δ -Cancriid complex.

We recognize that uniform distribution may be unjustified, and estimated probabilities could be off by an unknown factor. However, considering that many asteroids with $D \leq D_0$ imply high chance association probability (Wiegert & Brown 2004), we can use this assumption for initial assessment. Indeed, only 0.5% of asteroids in our sample satisfy this condition, strengthening the low probability of random association. Finally, as Wiegert & Brown (2004) noted, even high chance association probability does not exclude real association.

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

Fragmentation of asteroids and comets into large fragments occurs at low ejection speeds, with small orbital element dispersion determining low fragment dispersion speeds. When establishing object connections, we must study orbital evolution to find the moment of greatest similarity, which can be taken as the fragmentation time (e.g., Kholshchevnikov et al. 2016; Babadzhanov et al. 2017; Kholshchevnikov & Shaidulin 2017; Kokhirova et al. 2018).

Over time, gravitational and non-gravitational perturbations can significantly increase orbital element differences, especially angular elements Ω and ω (while controlling π stability). Consequently, modern orbits of fragments from the same parent comet can differ greatly. One shortcoming of using DSH over long intervals is that changing Ω and ω can inflate DSH values. Asher et al. (1993) proposed a simplified D criterion avoiding this: $D = 2 \sin(I/2) + 0.5(e_1 - e_2)^2 + 0.15(\pi_1 - \pi_2)^2$, with $D \leq 0.15$ indicating similar orbits.

Without disturbances, orbits would constantly pass through the fragmentation point. However, this information erodes over time due to perturbations. To establish the moment of greatest orbital similarity, we calculated DSH and simplified D criteria between studied NEA orbits and tracked them backward over 12,000 years. Figure 4 [Figure 4: see original paper] shows secular variations of both similarity criteria for NEA pairs where fragmentation likely occurred. We relied mainly on DSH as the strongest orbital proximity indicator, while presenting D variations to demonstrate analogy. Mutual D values much lower than the accepted threshold, along with DSH, provide additional indirect evidence of orbital similarity and common origin.

Analyzing these dependencies suggests the following parent comet break-up scenario: Starting with the four largest NEAs—2003 RW11 (1.5 km), 2009 BE77 (1.2 km), 2009 BB (1.1 km), and 1991 AQ (1.1 km)—we found 2003 RW11 and 2009 BE77 have minimal DSH = 0.17 and $D = 0.05$ around 1094 years ago;

2003 RW11 and 2009 BB have minimal $DSH = 0.15$ and $D = 0.08$ around 1094 years ago; and 2009 BE77 and 2009 BB have minimal $DSH = 0.02$ and $D = 0.02$ around 1184 years ago. Thus, fragmentation of 2009 BB and 2009 BE77 from 2003 RW11 occurred 1094–1184 years ago, about one thousand years in the past.

2003 RW11 and 1991 AQ have smallest values $DSH = 0.14$ and $D = 0.11$ around -2236 years, suggesting 1991 AQ broke away from 2003 RW11 about 4,200 years ago. Pairs 2009 BE77–1991 AQ and 2009 BB–1991 AQ have no $DSH \leq 0.25$ values during the review period, indicating no fragmentation between them.

Examining the largest and medium-sized NEAs 2010 XC11 (0.9 km) and 2010 XX58 (0.9 km), we found they have minimum $DSH = 0.07$ and $D = 0.03$ between -6646 and -6966 years, suggesting separation approximately 8.6–8.7 thousand years ago. 2010 XX58 and 2003 RW11 have no $DSH \leq 0.25$ values, while 2010 XC11 and 2003 RW11 have $DSH = 0.17$ – 0.25 three times from 2014 until -2000, but these do not correspond to smallest D values. Consequently, 2003 RW11 could not have fragmented into 2010 XX58 and 2010 XC11, confirming these two asteroids are debris of a single body. 2009 BE77 and 2010 XC11 have no $DSH \leq 0.25$ values, and since 2009 BE77 appeared later than 2010 XX58, they could not have fragmented. Although 2009 BB and 2010 XC11 have minimum $DSH = 0.08$ and $D = 0.01$ between -3486 and -3526 years, we assume no division occurred because 2009 BB is more closely related to 2003 RW11 and 2009 BE77. Since 1991 AQ and 2010 XC11 have no $DSH \leq 0.25$ and $D \leq 0.15$ values, and given that 1991 AQ separated much later than 2010 XC11 and 2010 XX58, a break-up between them is unlikely. The same applies to the pair 1991 AQ–2010 XX58.

Including the remaining small NEAs, we found 2003 AA83 (0.2 km) has no $DSH \leq 0.25$ values with 2003 RW11, 2009 BB, 2009 BE77, 2010 XX58, or 2014 YQ34, and no $D \leq 0.15$ with 2010 XX58, meaning fragmentation of these pairs could not occur. However, 2003 AA83 and 2010 XC11 have minimum $DSH = 0.19$ and $D = 0.16$ between 964 and 914 years, indicating 2003 AA83 separated from 2010 XC11 about 1,100 years ago.

PHA 2001 YB5 (0.20 km) has no DSH threshold-satisfying values with 1991 AQ, 2009 BE77, or 2014 SM260. Its orbit is similar to 2009 BB and 2016 AM66 during almost the entire period, with several minimal values with 2010 XX58 and 2010 XC11. Analyzing mutual criteria values, we consider fragmentation between 2001 YB5 and 2003 RW11 very likely occurred during 864–844 years ago, about 1,200 years in the past.

2017 YO4 (0.33 km) has no $DSH \leq 0.25$ values with 2009 BB, 2009 BE77, 2010 XX58, 2010 XC11, 2014 YQ34, 2003 AA83, or 2014 SM260. 2003 RW11 and 2017 YO4 have smallest $DSH = 0.13$ and $D = 0.09$ at -9486 to -9496 years. 2011 AF3 and 2017 YO4 have smallest $DSH = 0.13$ and $D = 0.03$ at -96386 to -96466 years. While 2017 YO4 and 1991 AQ show D criterion closeness three times, and 2017 YO4 and 2016 AM66 four times, we chose the linkage of 2017 YO4

with the largest 2003 RW11 as more likely. Supposedly, 2017 YO4 fragmented from 2003 RW11 about 11,500 years ago, and the closeness of 2017 YO4 and 2011 AF3 orbits observed 8.4–8.5 thousand years ago matches the period of 2011 AF3 formation from 2003 RW11.

2014 SM260 (0.3 km) and 2010 XC11 have minimum DSH = 0.14 and D = 0.10 between -4656 and -4676 years, suggesting 2014 SM260 separated from 2010 XC11 almost 6,700 years ago. 2014 SM260 and 2009 BE77 have minimum DSH = 0.14 and D = 0.07 between -96416 and -96436, -96686 and -96696 years; with 2009 BB it has minimum DSH = 0.17 and D = 0.10 between -2236 and -2256 years, and DSH = 0.17 and D = 0.11 at -92436 and -92456 years. However, since 2009 BE77 and 2009 BB appeared about one thousand years ago while 2014 SM260 separated from 2010 XC11 6,700 years ago, 2014 SM260 could not have separated from 2009 BE77 or 2009 BB. Pairs 2014 SM260–2003 RW11 and 2014 SM260–2010 XX58 have no DSH \leq 0.25 and D \leq 0.15 values, so they likely did not fragment from each other. Since 2014 SM260 and 2003 AA83 have no DSH \leq 0.25 and D \leq 0.15 values, and 2003 AA83 divided from 2010 XC11 about 1,100 years ago, fragmentation of 2014 SM260 from 2003 AA83 is impossible.

Based on smallest DSH and D values, NEAs 2014 YQ34 (0.08 km) and 2011 AF3 (0.05 km) could have separated approximately 7.8–8.1 thousand years ago. 2003 RW11 and 2014 YQ34 have minimal criteria values at -6096 years, so 2014 YQ34 separated from 2003 RW11 almost 8,100 years ago. 2003 RW11 and 2011 AF3 have smallest values at -5856 years, with break-up about 7,800 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 D values at -8000 years, but since 2016 AM66 fragmented from 2003 RW11 2,600 years ago while 2011 AF3 separated 7,800 years ago, the pair 2011 AF3–2016 AM66 has not divided. NEA 2014 YQ34 has no DSH \leq 0.25 values with NEAs 2009 BB, 2009 BE77, 2010 XC10, 2010 XX58, 2014 SM260, or 1991 AQ, suggesting no fragmentation between them.

NEAs 2003 RW11 and 2016 AM66 have smallest criteria values between -500 and -600 years, so 2016 AM66 very probably separated from 2003 RW11 about 2,600 years ago. The proposed parent comet disintegration mechanism is clearly shown in Figure 5 [Figure 5: see original paper].

5. Discussion

Our study establishes a dynamic link between active meteor showers generated by the δ -Cancriid meteoroid stream and 13 NEAs, forming the δ -Cancriid asteroid-meteoroid complex. This association is a convincing indicator that these NEAs moving in comet-like orbits have cometary origin. Based on dynamical modeling and orbital similarity criteria behavior, we propose a formation scenario: initially, a giant Jupiter-family parent comet destructed into two large pieces more than 12,000 years ago—2003 RW11 and 2010 XC11. We confidently

identify it as a giant comet since almost half its remnants are ≈ 1 km in size. Subsequent cascade division occurred: 2017 YO4, 2011 AF3, and 2014 YQ34 fragmented from 2003 RW11 about 11,500 and around 8,000 years ago, respectively; 1991 AQ, 2016 AM66, 2001 YB5, 2009 BB, and 2009 BE77 separated from 2003 RW11 4.0–4.2, 2.5–2.6, 1.2, 1.0, and 0.8 thousand years ago, respectively; 2010 XX58, 2014 SM260, and 2003 AA83 fragmented from 2010 XC11 8.9, 6.6–6.7, and 1.1 thousand years ago, respectively.

We realize this is only a supposed fragmentation mechanism with certain shortcomings. For greater persuasiveness, statistical estimation of its probability considering the number of discovered NEAs would be necessary. Such a task is beyond our present scope and will be addressed in future work. We can only suppose these objects formed by disintegration of a giant parent comet, followed by fragmentation of the largest fragments. Presently, these cometary objects are in an extinct stage. Thus, the δ -Cancriid complex includes a meteoroid stream producing observable active showers and containing 13 large extinct remnants of the parent comet. The stream contains both small meteoroids and large objects ranging from 50 m to 1.5 km, with four classified as potentially hazardous.

6. Conclusions

Our investigation establishes a new δ -Cancriid asteroid-meteoroid complex. The complex includes a meteoroid stream producing active meteor showers confirmed by observations, plus 13 NEAs probably dynamically associated with it. This association and their comet-like orbits indicate likely cometary origin. These objects may be fragments of the δ -Cancriid complex's parent comet, now in an extinct or dormant phase.

We acknowledge the advanced method of Ye et al. (2016), especially with modern computing. Our analytical method uses simplified assumptions based on meteoroid stream formation and evolution theory, following and comparing orbital evolution. This widely used approach has established known complexes whose reliability is confirmed by numerous publications including Wiegert & Brown (2004) and Ye et al. (2016). Underestimating chance association probability is the main shortcoming. Distinguishing genuine parent-stream linkage from chance alignment remains challenging, complicated by difficulty obtaining precise orbits and fragmentation history (Ye & Jenniskens 2022). However, our approach conveniently yields correct probability to order-of-magnitude. More realistic estimation requires Monte Carlo Bayesian prediction with objective priors to suppress selection bias, as described by Ye et al. (2016). The proposed cascade fragmentation scenario is phenomenological rather than a physical mechanism and should be considered only as possible. More physical inference requires introducing fragmentation criteria and Monte Carlo simulation to determine possible forms and probabilities.

Our results show meteoroid streams contain both millimeter-scale particles and decameter-scale objects, posing potential hazards to Earth, confirmed by space

missions, theoretical studies, and observations. Our research enables prediction of parameters for such objects entering Earth's atmosphere, needed to develop mitigation strategies. Future work should continue searching for other large fragments of the parent comet among known and newly discovered NEAs.

Acknowledgments

The authors express deep gratitude to anonymous reviewers for careful study and prudent comments that greatly improved the scientific level of this work. The N-body integrator REBOUND (Rein & Spiegel 2015) was used to model and plot asteroid orbits. Chinese co-authors acknowledge support from the National Program (2023YFE0102300/2022YFE0133700), Regional Collaborative Innovation Project of Xinjiang (2022E01013), 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., & Obruchov, Y. V. 2015b, *SoSyR*, 49, 165
- Babadzhanov, P. B., Kokhirova, G. I., & Obruchov, Y. V. 2015c, *A&A*, 579, A119
- Babadzhanov, P. B., Kokhirova, G. I., Williams, I. P., & Obruchov, Y. V. 2017, *A&A*, 598, A94
- Babadzhanov, P. B., & Obruchov, Y. 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 Sec-*

- ular 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
- 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 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)

Hui, M.-T., & Li, J. 2017, AJ, 153, 23

Ye, Q.-Z., Brown, P. G., & Pokorný, P. 2016, MNRAS, 462, 3511

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.