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The study of near Earth objects and meteor showers

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Abstract. In this work, the physical parameters of near-Earth objects (NEO), i.e. small celestial bodies crossing the Earth's orbit, are investigated. First of all, the study of NEO, whose number exceeds 15 thousand, is important in terms of asteroid threats. NEO are mainly stony and iron, but also could be comet nuclei that had lost the icy component under the influence of solar radiation. As a result of analyzing 14800 near-Earth asteroids from the Apollo group, in this work near-Earth objects closely genetically related to the existing meteor showers are determined. 2002LV and 2001MG1 asteroids are the closest to the Kappa-Cygnids by orbital elements. 2014RS17, 2006BF56, 2001YB5 asteroids are the closest to the Delta-Cancrids by orbital elements. 2008VL14, 2006UF17, 2010VF, 2000DO1, 2010CF55, 2010TN55, 2007EJ88, 481482 2007CA19 asteroids are the closest to the Virginids by orbital elements. The D-criterion method was used in the analysis.

1. Introduction

NEO objects have highly elliptical orbits (HEO) with distances at perigee lower than 1.3 AU [1]. The major part of NEO formed in the main belt [2]. D-criterion method was introduced in [3].

The study of genetic connections between meteor showers and near-Earth objects allows refining physical, chemical, and dynamic parameters of NEO for assessing the probability of asteroid impact and creating asteroid protection system [4].

In this work, a search for parent bodies of low-activity small meteor showers – k-Cygnids, δ-Cancrids, and Virginids – are performed among asteroids that could be faded comets. To search for a parent body of an observed meteor shower, similarity criteria – D-criteria – are used. The minimum value for D indicates a high degree of similarity between orbits of 2 small bodies**.**

2. Method of the study near Earth objects and meteor showers

The widely used D-criterion:

$$D_{SH}^2 = (e_2 - e_1)^2 + (q_2 - q_1)^2 + (2\sin\frac{I_{21}}{2})^2 + (\frac{e_2 + e_1}{2})^2(2\sin\frac{I_{21}}{2})^2 + \left(\frac{e_2 + e_1}{2}\right)^2 (2\sin\frac{W_{21}}{2})^2, \quad (1)$$

where

$\left(2\sin\frac{I_{21}}{2}\right)^2 = \left(2\sin\frac{i_2 - i_1}{2}\right)^2 + \sin i_1 \sin i_2 \left(2\sin\frac{\Omega_2 - \Omega_1}{2}\right)^2,$

$W_{21} = \omega_2 - \omega_1 \pm 2\arcsin\left(\cos\frac{i_2 + i_1}{2}\right)\sin\frac{\Omega_2 - \Omega_1}{2}\sec\frac{I_{21}}{2}.$

I – orbits' mutual inclination angle; W – angle between directions towards perihelion; e, q, i, ω, Ω – orbital elements. The minus sign applies when $|\Omega_2 - \Omega_1| > 180°$. The method implies that measurement errors are much lower than real variance of orbits in a shower [4].
x. The interstellar extinction for astronomical bodies characterized by different spectral classes is unequal, when the radiation goes through the same interstellar substance. We may therefore conclude, the difference in magnitudes dependence on dust particles in the heterochromous case is not linear.

Later the criterion was modified repeatedly. The criterion by Drummond is as follows [5]:

$$D_{DR}^2 = (\frac{e_2 - e_1}{e_2 + e_1})^2 + (\frac{q_2 - q_1}{q_2 + q_1})^2 + (\frac{I_{21}}{180°})^2 + (\frac{e_2 + e_1}{2})^2 (\frac{\theta_{21}}{180°})^2, \quad (2)$$

where θ – angle between lines of apsides in orbits.

$$\theta = \arccos(\sin\beta_2 \sin\beta_1 + \cos\beta_2 \cos\beta_1 \cos(\lambda_2 - \lambda_1)), \quad (3)$$

where λ, β – ecliptic coordinates of perihelion points calculated as:
$\lambda = \Omega + \arctan(\cos i \tan\omega)$; 180° is added if $\cos\omega < 0$, $\beta = \arcsin(\sin i \sin\omega)$.

Jopek in [6] has shown that the functions by Drummond and Southworth-Hawkins are unequal. Based on results of numerical analysis of D_{SH} and D_{DR} properties, he proposed his mixed criterion:

$$D_{JOP}^2 = (e_k - e_l)^2 + (\frac{q_k - q_l}{q_k + q_l})^2 + (2\sin\frac{I_{kl}}{2})^2 + \left(\frac{e_k - e_l}{2}\right)^2 (2\sin\frac{\pi_{kl}}{2})^2. \quad (4)$$

In an earlier work of the authors [7], the value of the upper limit of D-criterion (by Southworth, Drummond, Jopek) was investigated for 7 meteor showers – Lyrids, Perseid, Orionides, Leonids, Ursids, Draconids, and Geminids – with known parent bodies. Analysis of the results showed that the criterion by Drummond D_{DR} was less sensitive to orbit geometry of small bodies and errors of their observations, as the value of D did not exceed 0.26 for all the showers and catalogues of meteor orbits under investigation.

The D-criteria of orbits closeness has a number of disadvantages [8]. One of the most important is that they cannot be applied to near-circular orbits. Besides, some of the criteria depend not only on the orbits but also on the choice of inclination reference plane. It is worth noting that during the search for parent bodies of meteor showers one compares modern orbits of the bodies that used to be close many years ago but have separated by now. After an ejection, meteoroids move within a meteor shower along orbits similar to the ones of a parent body. As their velocities are not high (tens and hundreds m/s), initially the variance of orbits is small and the values of D-criteria are minimum. But later, due to gravitational and non-gravitational perturbations, the dynamic evolution of a meteor shower increases forming a meteor complex that is complex in structure. These problems do not appear in a metric created by K. V. Kholshevnikov as a spatial metric [8]:

$$\rho^2 = (1 + e_1^2)p_1 + (1 + e_2^2)p_2 - 2\sqrt{p_1 p_2}(\cos I + e_1 e_2 \cos P), \quad (5)$$

where $\cos I = c_1 c_2 + s_1 s_2 \cos\Delta$, $c = \cos i$, $s = \sin i$, $\Delta = \Omega_1 - \Omega_2$. The minus sign applies when $|\Delta| > \pi$ at the usual assumption
$0 \leq \Omega \leq 2\pi$,

$$\cos P = s_1 s_2 \sin\omega_1 \sin\omega_2 + (\cos\omega_1 \cos\omega_2 + c_1 c_2 \sin\omega_1 \sin\omega_2)\cos\Delta + (c_1 \cos\omega_1 \sin\omega_2 - c_1 \sin\omega_1 \cos\omega_2)\sin\Delta\,.$$

As $0 \leq P \leq \pi$, angle P is uniquely determined by its cos.

3. Results of the study near Earth objects and meteor showers

Using D-criterion by Drummond [5] and the metric by Kholshevnikov [8] we have performed the search for asteroid probably genetically connected with the k-Cygnids, δ-Cancrids, and Virginids meteor showers. These showers refer to small ones with low activity, whose zenith hourly rate (ZHR) is about 10. These meteor showers are orphan-showers, as their parent body is undefined. In the δ-Cancrids meteor complex one distinguishes 2 branches – northern (NCC) and southern (SCC). Table 1 presents period of observation, date of highest activity, and geocentric velocity of meteoroids.

Table 1. Data on small meteor showers (according to [9], date of application March 22, 2020).

Meteor Shower	Period of Observation	Velocity V_G	Date of ZHR_{max}
k-Cygnids (KCG)	August 3 – August 25	24 km/s	August 18
δ-Cancrids	January 1 – January 31	25 km/s	January 17
Virginids (VIR)	March 1 – May 6	30 km/s	March 5

Based on data provided by IAU Minor Planet Center, International Meteor Organization, and NASA, described in articles [10 – 12] by comparing orbital and physical parameters of asteroids from various groups we have selected the Apollo group as the most probable candidate to be a parent body for the meteor showers [13]. Today, there are 12437 asteroids from the Apollo group discovered, among them 1473 are numbered. Orbit catalogues of meteor showers that could be found in the public domain were used: TV- (Croatian Meteor Society, Japanese Meteor Society SonatoCo, MSSWG, Astronomical Institute of the Czech Academy of Sciences, Dutch Meteor Society, SMSPRC2001) and photo-catalogues (Lund Meteor Orbit Catalogue IAU MDC , described in articles [14 - 20], McCrosky [21]). From all the catalogues about 700 orbits of k-Cygnids, 200 orbits of δ-Cancrids, 12 orbits of Virginids are selected. In some catalogues orbits are not identified with meteor showers (without indicating a shower), so the identification of orbits with meteors was performed by the parameters such as radiant's coordinates, geocentric velocity, and period of a meteor shower's activity (the variance did not exceed 10° in radiant's coordinates and 5 km/s in velocity).

Table 2. Asteroids selected for k-Cygnids.

Catalogues					
With indicating meteor shower				*Without indicating meteor shower*	
CMN, TV *140 orbits*	SonotaCo TV *544 orbits*	Astronomical Institute of the Czech Academy of Sciences TV *18 orbits*	Dutch Meteor Society TV *5 orbits*	DMSPRC 2001, TV *21 orbits*	IAU MDC, Foto *59 orbits*
153311 2001 MG1	*153311 2001MG1*	*153311 2001MG1*	–	*153311 2001MG1*	*153311 2001MG1*
385343 2002LV	*385343 2002LV*	*385343 2002LV*	–	*385343 2002LV*	*385343 2002LV*
	2012LL9	2012LL9		2012LL9	
		2002JY8			
		2005LP40			

The identification of meteors from a shower was implemented for 12437 asteroids from the Apollo group, whose orbits are presented on NASA website [12]. When determining similarity between meteoroids' orbits and asteroids' orbits, the following conditions were accepted:
I) The value of D-criterion by Drummond (DDR) should not exceed 0.20;

II) The percentage of meteoroids' orbits coinciding with asteroids' orbits: higher than 80% for k-Cygnids and Virginids, 70% for δ-Cancrids and 60% for Lund Meteor Orbit Catalogue (IAU MDC), as this was the highest identification percentage for this catalogue;
III) For the metric introduced by Kholshevnikov ρ, a threshold value has not been introduced, as ρ is defined with taking into account orbit perturbations over time, and its value for the meteor showers under investigation does not exceed 0.20.

Therefore, among the asteroids meeting the conditions 1 and 2, were selected those that had the lowest value of Kholshevnikov's metric ρ. The results of identification of the Apollo asteroids with showers by each meteor catalogue are presented in Tables 2–4.

Table 3. Asteroids selected for δ-Cancrids.

Catalogues			
With indicating meteor shower		*Without indicating meteor shower*	
CMN TV *7 orbits*	SonotaCo TV *169 orbits*	MSSW TV *22 orbits*	IAU MDC Foto *40 orbits*
2001YB5	*2014RS17*	–	*2014RS17*
2007TL23	*2006BF56*	–	*2006BF56*

Table 4. Asteroids selected for Virginids.

Catalogues	
With indicating meteor shower	*Without indicating meteor shower*
McCrosky, Foto, *5 orbits*	IAU MDC, Foto, *7 orbits*
2000DO1	*2000DO1*
2006UF17	*2006UF17*
2008VL14	*2008VL14*
2010CF55	*2010CF55*
2010TN55	*2010TN55*
2010VF	*2010VF*
2007EJ88	*2007EJ88*
(481482) 2007CA19	*(481482) 2007CA19*
1999VF22	2013VO5
2001FB90	2015FP33
2003EP4	
2003FB5	
143487 2003CR20	

For k-Cygnids (Table 2) by all the catalogues of meteor orbits 2 asteroids are selected – 153311 2001MG1, 385343 2002LV, whose orbits provide from 90% to 100% compliance with meteoroids' orbits of a shower. The 2012LL9 is only selected by 3 catalogues of meteor orbits. By catalogue of Astronomical Institute of the Czech Academy of Sciences other asteroids – 2002JY8 and 2005LP40 – are selected.

For δ-Cancrids, without division into northern and southern branches (see Table 3), no asteroids are selected that could have been distinguished by all the catalogues of meteor orbits. The 2014RS17 asteroid is selected by 2 catalogues – Japanese Meteor Society SonatoCo and Lund Meteor Orbit Catalogue; the 2006BF56 is only selected by Japanese Meteor Society catalogue SonatoCo; the 2001YB5 and 2007TL23 are selected by Croatian Meteor Society CMN catalogue.

For Virginids (see Table 4) the results of identification are less definite. By 2 catalogues of meteor orbits – McCrosky and Lund Meteor Orbit Catalogue – 7 asteroids are selected: 2000DO1, 2006UF17, 2008VL14, 2010CF55, 2010TN55, 2010VF, 2007EJ88. By McCrosky catalogue the 1999VF22, 2001FB90, 2003EP4, 2003FB5, and 143487 2003CR20 are selected; by Lund Meteor Orbit Catalogue the 2013VO5, 2015FP33 asteroids are selected. The 481482 2007CA19 is selected by Lund Meteor Orbit Catalogue (IAU MDC) is selected with lower percentage of compliance between an asteroid and a meteoroid.

4. Summary and conclusions

As a result, Thus, the k-Cygnids meteor shower is most likely connected with the 153311 2001MG1 and 385343 2002LV asteroids, that provide the highest percentage of identification by all the catalogues of meteor orbits of the meteor shower and also shows the lowest values of the metric by Kholshevnikov ρ. The search for the parent body of the k-Cygnids meteor shower has been performed by various researchers. In [22, 23, 24] based on retro-modeling of orbits, the 53311 2001MG1, 2004LA12, and 2008ED69 asteroids are selected. In [25] using the D-criteria by Southworth-Hawkins and Drummond, the 53311 2001MG1 and 385343 2002LV asteroids are selected.

For the δ-Cancrids by similarity of orbital elements, the connections with the 2014RS17, 2006BF56, and 2001YB5 selected with the high degree of observing the criteria and noted by other authors [26, 27].

For the Virginids, the 2000DO1, 2006UF17, 2008VL14, 2010CF55, 2010TN55, 2010VF, 2007EJ88 are selected as well as 481482 2007CA19 selected by only one of the catalogues but with a high degree of observing all the criteria and noted in researches of other authors [28].

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