Search for possible connections of the h-Virginids meteor shower with near-Earth asteroids

M V Sergienko¹, M G Sokolova¹, A O Andreev¹2 and Y A Nefedyev¹

¹Kazan Federal University, Institute of Physics, Kazan, 420008 Russia
²Kazan State Power Engineering University, Kazan, 420066 Russia

E-mail: maria_sergienko@mail.ru

Abstract. Asteroids and comets are the oldest objects in the Solar System and contain the initial matter that existed at the moment of its formation. By studying those small celestial bodies one may describe the processes taking place at the early stages and conditions of the formation of the Solar System. The study of the genetic relationships (using metrics based on orbital elements) of meteor showers with parent bodies (asteroids and comets) can be used to develop the theory of evolutionary processes that took place at the time of the formation of the solar system. In this work, we have studied the genetic relationships of the small meteor shower of the h-Virginids (HVI) with the near-Earth asteroids of the Apollo group. An author’s multi-factor method is applied, which implies the use of D-criterion by Drummond, metric by Kholshevnikov, Tisserand’s parameter, \( \mu \) and \( \nu \) quasi-stationary parameters of the restricted three-body problem, and the analysis of the orbit’s perihelion longitude \( \pi \). The observational base includes television catalogues meteor orbits that are in the public domain: Meteoroid Orbit Database v2.0 (2010–2012) (CAMS) and the European meteor network EDMOND (2001–2016) catalogues. As a result of this study, the orbit of the h-Virginids (HVI), according to the values of Tisserand’s parameter, was found to be transitional, and thus, it was impossible to identify whether it was of cometary or of asteroid type. Using the author’s method, the asteroids 2001SZ269 and 2014HD19 were distinguished. The 2001SZ269 asteroid was distinguished as a candidate having a possible connection with the h-Virginids’ parent body.

1. Introduction

Comets, in most cases, form asteroid bodies due to the sublimation of ices that make up their composition, when approaching the Sun [1]. It is also possible for the cometary nucleus to disintegrate and to form secondary cometary nuclei, as well as many dust particles and meteoroids [2]. There is no hard data to confirm the difference between asteroids and comets. Among the asteroids, perhaps, there are “extinct” comets, which have lost their activity and volatile component. They move in orbits, typical for asteroids, but at the same time demonstrate cometary activity. For such objects, the Tisserand’s parameter \( T_j > 3 \), since according to [3], [4] objects with the value of the Tisserand constant \( T_j < 3.1 \) move relative to Jupiter along comet-like orbits, and with \( T_j > 3.1 \) – along asteroid orbits. They are also called “main-belt comets” [2], as well as “active asteroids” [5].

Extinct comets have a low albedo, which complicates their observation. Direct collisions between the bodies of the Solar System are not excluded either. This mainly concerns the main asteroid belt. In this case, separate fragments of different sizes are formed [6]. The evolution of cometary objects is also influenced by the thermal effect at the moment, when the comet passes the perihelion, rotational...
instability, and impacts of secondary-formed bodies [5, 7]. At the moment of separation from the parent body, the meteoroids have the velocity close to the one of the parent body, and therefore they move in similar orbits. In the course of time, gravitational and non-gravitational effects (such as the Poyting-Robertson effect [8]) cause the particles of the flow to “pull apart”. In this case, their new orbits no longer correspond to the parent one. Asteroids and comets differ in their composition. Comets contain a lot of ice in their structure, interspersed with dust and rocky fractions of different sizes. The main belt asteroids are mostly rocky. Any process of decay of comets and asteroids, regardless of its duration and stages, can lead to the formation of a meteoroid stream or an asteroid-meteoroid complex with substreams and split body fragments included in it [9, 10, 11].

The particles of the stream and their parent bodies may not coincide in their dynamics; therefore, it is important to determine the physical and dynamic properties of asteroids in order to reveal the conditions for the formation of asteroid-meteoroid complexes.

It should be noted that the parent bodies of meteor showers can only be near-Earth objects (NEO) - asteroids and comets. The meteoroid – comet – asteroid complex poses a potential danger to the Earth due to a possible collision. For the construction of more accurate models of the motion of small celestial bodies, the investigations related to the clarification of the nature of near-Earth objects, their origin and relationships, as well as the identification of extinct cometary nuclei and associated meteoroid showers among asteroids, are essential.

In this paper, we investigate the possible connections of the h-Virginids meteor shower with asteroids crossing the Earth’s orbit. A multifactorial approach was used to search for small bodies with close orbits, which is described in detail in [12]. For the identification we used: D-criterion by Drummond [13], metric by Kholshevnikov [14], Tisserand’s parameter [15], μ and ν quasi-stationary parameters of the restricted three-body problem [16, 17], and orbit’s perihelion longitude π [18]. The use of the entire set of the above criteria for the analysis of the genetic relationships of meteoroids increases the reliability of the research results.

2. Object of study

The activity of the h-Virginids complex lasts from late February to early May. As follows from the work [19] the Virginid complex is composed of a dozen of mainly sporadic streams. There is no certainty yet concerning parent bodies of these different streams, but nevertheless, they are all connected by a common origin. One of the meteor showers Virginid complex is the h-Virginids. The h-Virginids meteoroid shower (HVI, #343, [20]) is a small meteor shower for which no parent body has been found. h-Virginids are observed from April 20 to May 10 and have low activity (ZHR < 2).

Table 1. Coordinates of radiant and elements of average orbit for branches of the h-Virginids (according to [21], as of March 8, 2021).

| Virginids            | α   | δ   | V_G (km/s) | a  (AU) | e   | ω  | Ω   | i   | Source |
|----------------------|-----|-----|------------|--------|-----|----|-----|-----|--------|
| h-Virginids, HVI #343| 204.2 | -1.6 | 18.7       |        |     |    |     |     | [22, 23] |
|                      | 214.1 | -1.4 | (24.1)     |        |     |    |     |     | [24]   |
|                      | 204.8 | -1.5 | 17.2       | 2.280  | 0.659| 72.7| 218.2| 0.9 | [20]   |
| Northern March       |      |     |            |        |     |    |     |     |        |
| Virginids, NVI #123  | 185.7 | 2.3 | 23.0       | 1.691  | 282.4| 358.0| 3.7 |     | [25]   |
|                      | 174.3 | 8.7 | 23.0       | 1.955  | 252.7| 353.5| 3.7 |     | [26]   |
| Southern March       |      |     |            |        |     |    |     |     |        |
| Virginids, SVI #124  | 179.7 | -8.5| 22.9       | 2.160  | 91.2 | 182.0| 6.1 |     | [25]   |
|                      | 172.6 | 2.7 | 20         | 1.95   | 83   | 175.7| 0.1 |     | [27]   |

According to [20], Table 1 shows the coordinates of the showers’ radiant, elements of average orbits and geocentric velocities for various branches of the h-Virginids complex (including h-Virginids
HVI #343, Northern March Virginids NVI #123, Southern March Virginids SVI #124). All angular elements are given for the epoch (J2000.0). As we can see, the radiants and dynamic parameters of the branches of the h-Virginids have similar values, which confirms the hypothesis of their possible common origin. In this case, the eccentricities of the orbits are determined unreliably (the values are given according to [20]).

The search for asteroids with orbits close to the ones of h-Virginids was carried out among the asteroids of the Apollo group. These objects cross the Earth’s orbit at the perihelion of their orbit with a perihelion distance $q < 1.017$ AU. More than 14000 asteroids of the Apollo family are discovered [28] (as of March 8, 2021), of which about 1700 are potentially dangerous objects for the Earth (objects brighter than $+22^m$, more than 150 m in size, approaching the Earth at a distance of less than 0.05 AU).

3. Method for selecting close orbits

According to the technique described in detail in [12], the following criteria were applied to search for close orbits of the small bodies under study. Drummond criterion [13]:

$$D^2 = \left( \frac{e_2 - e_1}{e_2 + e_1} \right)^2 + \left( \frac{q_2 - q_1}{q_2 + q_1} \right)^2 + \left( \frac{I_{21}}{180^\circ} \right)^2 + \left( \frac{\theta_{21}}{180^\circ} \right)^2,$$

where $	heta = \arccos(\sin \beta_2 \sin \beta_1 + \cos \beta_2 \cos \beta_1 \cos (\lambda_2 - \lambda_1))$,

$\lambda = \Omega + \arctg(\cos \iota \tan \omega)$; adding $180^\circ$, if $\cos \omega < 0$,

$\beta = \arcsin(\sin \iota \sin \omega)$,

$I, e, q$ – mutual inclination, eccentricities, and perihelion distances of two small bodies’ orbits.

The Kholshevnikov metric $\rho$ [13] is defined in three-dimensional factor space as

$$\rho^2 = (1 + e_1^2)p_1 + (1 + e_2^2)p_2 - 2\sqrt{p_1p_2(e_1e_2 + \cos(i_1 - i_2))}$$

where $p_1, p_2$ – focal parameters.

The physical dimension $\rho$ is the square root of the unit of length (in our case, the astronomical unit, AU), so $\rho^2$ is calculated. Accordingly, for the Drummond criterion (1), the quantity $D^2$ (dimensionless) is determined. The hypothesis about the proximity of the orbits of two small bodies’ $x$ and $y$ is considered confirmed if

$$D^2(x, y) \leq D_c^2,$$

$$\rho^2(x, y) \leq \rho_c^2,$$

where $D_c, \rho_c$ – the upper threshold value of the Drummond criterion $D$ and the Kholshevnikov metric. The threshold values of $D_c$ and $\rho_c$ are determined as the average values of $D$ (1) and $\rho$ (2). They are calculated by pairs of orbits: meteoroid orbit – average shower’s orbit [12]. Table 2 shows the upper threshold values of the Drummond criterion $D_c$ and the Kholshevnikov metric $\rho_c$ calculated by the CAMS and EDMOND catalogues and their mean square errors (RMSE) for h-Virginids.

To describe the dynamics of small celestial bodies, the Tisserand’s parameter, determined relative to Jupiter, is used. This parameter remains constant for the circular restricted three-body problem and characterizes the measure of the speed of approach to Jupiter. For Jupiter, the Tisserand’s parameter is $T_j = 3$. For asteroids in the main belt, the parameter is $a < a_j$ and $T_j > 3$.

The value of the Tisserand’s parameter relative to Jupiter [15] changes little during the evolution of the orbits of small celestial bodies:

$$T = \alpha^{-1} + 0.168660a(1 - e^2)^{1/2} \cos i.$$  

Two quasi-stationary parameters [15, 16]

$$\mu = \sqrt{\alpha(1 - e^2) \cos i},$$
\[ \nu = \left( 1 - e^2 \right) \left( 0.4 - \sin^2 \omega \sin^2 i \right), \]  

where \( a, e, i, \omega \) are semi-major axis, eccentricity, inclination, perihelion argument and longitude of the orbital node of the small body.

**Table 2.** Threshold values of Drummond criterion \( D_c \) and Kholshevnikov metric \( \rho_c \) for h-Virginids

| Catalogue | \( D^2_c \pm \sigma \) | \( \rho^2_c \pm \sigma \) |
|-----------|-----------------|-----------------|
| CAMS      | 0.001 ± 0.0004  | 0.002 ± 0.001   |
| EDMOND    | 0.007 ± 0.011   | 0.025 ± 0.034   |

In this case, for the longitude of the perihelion, one can write

\[ \pi = \omega + \Omega. \]  

At large time intervals, this parameter remains constant [18]. Table 3 for h-Virginids shows the average values of the parameters \( T, \nu, \mu \) and \( \pi \).

**Table 3.** Average values of Tisserand’s parameter \( T \), quasi-stationary parameters \( \mu, \nu \), longitude of perihelion \( \pi \) for h-Virginids

| Catalogue | \( T \pm \sigma \) | \( \mu \pm \sigma \) | \( \nu \pm \sigma \) | \( \pi \pm \sigma \) |
|-----------|-----------------|-----------------|-----------------|-----------------|
| CAMS      | 3.276 ± 0.194   | 1.118 ± 0.018   | 0.220 ± 0.015   | 11.930 ± 3.454  |
| EDMOND    | 2.987 ± 0.720   | 1.101 ± 0.040   | 0.185 ± 0.059   | 15.881 ± 3.985  |

The selection of asteroids for analysis was carried out according to the algorithm described in detail in [12]. If condition (3) is observed for a pair of orbits (x is the orbit of the asteroid, y is the mean orbit of the flow), then the Drummond criterion (1) and the Kholshevnikov metric (2) are satisfied with the factors \( P_1 = 1, P_2 = 1 \). If condition (3) is satisfied taking into account the standard deviation, then the criteria (1) and (2) are assigned the values of the factors \( P_1 = 0.9, P_2 = 0.9, P_1 = 0.8, P_2 = 0.8 \), etc.

The fulfillment of criterion (4) for the Tisserand’s parameter \( T \) for a pair of orbits (x is the orbit of the asteroid, y is the average orbit of the shower) is also evaluated depending on the standard deviation (Table 3). As a result, criterion (4) is assigned the values of the factors \( P_3 = 0.9, P_3 = 0.8 \), etc.

Similarly, the degree of fulfillment of criteria (5) – (7) was assessed on the basis of their standard deviation (Table 3) and according to factors \( P_3, P_4 \) and \( P_6 \), respectively. For criteria (5) – (7), one assesses namely the interval scatter of the values of \( T, \mu, \nu, \pi \) between the orbits of the asteroid and the mean orbit of the shower, rather than their complete coincidence. Therefore, factors \( P_3, P_4, P_5 \) and \( P_6 \) are not assigned the values of 1. The measure of fulfillment of the entire set of criteria (2) – (7) is estimated as the product of \( P_i \) factors, \( i = 1, ..., 6 \).

4. **Search for asteroids with orbits close to h-Virginids**

As a result of using the technique described in the previous section, we selected the asteroids, for which the parameters of the criteria do not exceed \( 2\sigma \) of their average values [28]. That is, criteria (2) –
(7) are fulfilled with the values of the factors $P_i \geq 0.8$ (taking into account rounding to tenths). With this approach, for the CAMS and EDMOND catalogues, the $P_i$ measure of all the criteria was higher than 0.5. Table 4 shows the selected asteroids with orbits close to the ones of h-Virginids. Results from other sources are also presented.

| Selected Asteroids | Catalogue  | P Factor | Data from other sources (HVI #343) |
|--------------------|------------|----------|-----------------------------------|
| 2014 HD198         | CAMS       | 0.7      | [29] 2001SZ269, 2010RL43, 2010TP55, 2014HU2, 2014JH15; |
|                    | EDMOND     | 0.7      | [30] 2001SZ269, 2007RS146, 2009SD15, 2010RL43, 2010RZ11, 2010TD, 2010TP55, 2012KZ41, 2014HN199, 2014HU2, 2014JH15, 2016RO40 |
| 2001 SZ269         | CAMS       | 0.5      |                                    |
|                    | EDMOND     | 0.6      |                                    |

In [29], asteroids were chosen according to the D criteria of Southworth-Hawkins [31], Jopek [32], and Drummond [3, 13]. In [29], the search for asteroids was carried out according to the D criteria of Southworth-Hawkins, Jopek, and Asher [29]. As a result, the asteroid 2001SZ269 turned out to be the most consistent with the criteria in all the studied sources. Since the search for genetically close asteroids was carried out for the HVI meteor shower without dividing them into branches, there were a significant number of them [29, 30].

Objects with the Tisserand’s parameter relative to Jupiter $T < 3.1$ move in comet-like orbits, whose with $T > 3.1$ – in asteroid orbits [5, 18]. The average orbit of the h-Virginids shower has the Tisserand’s parameter close to 3.0 ($T_p = 2.987$ for EDMOND and $T_p = 3.276$ for CAMS), which does not allow to unambiguously determine whether the type of orbit is cometary or asteroid.

Asteroids 2001SZ69 and 2014HD198, according to the classification of the Tisserand’s parameterer, have an asteroid type of orbit. Asteroids selected by other researchers [32, 33], except for asteroid 2014HN199, also have an asteroid orbit. The selected asteroids become potentially dangerous when approaching the Earth closer than 900 thousand km, and fall into the sphere of influence of its gravitational field. Asteroid 2001SZ69, according to the classification based on the quantitative and qualitative description of NEA, taking into account their collisional properties, belongs to the G3 class. In this case, the probability of collision with the Earth is estimated as 0.7163 [34]. It is worth noting that, usually, there are no data on physical and chemical properties of asteroids. And that complicates the task on their identification with meteor shower, and requires conducting additional studies.

5. Summary and conclusions
In this work, a search for possible parent bodies for the poorly studied small meteor shower h-Virginids was carried out using the multifactor approach described in detail in [12]. This stream belongs to the Apollo asteroid group, which crosses the Earth’s orbit. The set of the corresponding criteria was applied to those data. As a result, asteroids 2001SZ269, 2014HD198 were selected. According to the analysis of the works by other authors, the asteroid 2001SZ269 was identified as the most probable object, possibly associated in the past with the parent body of the h-Virginids shower.

The h-Virginids meteor shower is a complex of subshowers with identified and unidentified parent bodies. The h-Virginids showers is just one of its branches. Considering that the asteroids selected in the work are small in size, it is likely that they are elements of another body’s disintegration. Therefore, it is necessary to conduct additional studies on the chemical composition of these asteroids to confirm or refute this hypothesis.
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