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DYNAMICS AND PHYSICS OF BODIES OF THE SOLAR SYSTEM

On the Cometary Nature of Near-Earth Asteroid 2003 EH1

P. B. Babadzhanov[a], G. I. Kokhirova[a, *], and Yu. V. Obrubov[b]

[a] *Institute of Astrophysics, Academy of Sciences of Republic of Tajikistan, Bukhoro 22, Dushanbe, 734042 Republic of Tajikistan*

[b] *Kaluga Branch of Bauman State Technical University, Bazhenova 2, Kaluga, 248000 Russia*

**e-mail: kokhirova2004@mail.ru*

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Abstract—Differential evolution of the orbits of near-Earth asteroid (NEA) 2003 EH1 and comet 96P/Machholz 1 under perturbing action of planets was investigated for the time interval of 28000 years. The similarity of the orbits was analyzed with the Southworth–Hawkins criterion D_{SH}. It has been shown that both the comet and the asteroid can be fragments of a nucleus of the same larger comet being a progenitor of the Quadrantid complex. A break-up of the parent comet apparently occurred approximately 9500 years ago. NEA 2003 EH1 is actually a dormant fragment of a nucleus of the parent comet. It was concluded that comet 96P/Machholz 1, NEA (186256) 2003 EH1 of the Amore group, and the Quadrantid meteorite swarm form a family of related objects.

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INTRODUCTION

By now, it has been established that some near-Earth asteroids (NEAs) are dormant comets. Noticeable indicators of the cometary nature of such NEAs are a cometary-like orbit and associations with meteoroid swarms and observed meteor showers. The first association between the Geminid swarm and asteroid 3200 Phaethon was found by Whipple [17]. A number of NEAs orbiting within the Taurid complex, where comet 2P/Encke is also moving, were detected as well [1, 4, 14]. Later, it was found that the orbit of 2003 EH1 asteroid is the same as that of the Quadrantid meteoroid swarm [5, 10, 19]. In papers [2, 6, 7], three associations were established; each of them contains several NEAs and the corresponding meteoroid swarm. It was shown that, within each of the associations, the orbits of the meteoroid swarm and NEAs are very close and their common origin is evident. Due to this, the hypothesis is current that each of such associations is a result of a break-up of a larger comet, being a parent of the meteoroid swarm, and, consequently, these “asteroids” are actually extinct fragments of comets; the term “near-Earth object” (NEO) is used to specify them. All of the mentioned associations were found from the similarity of the orbits of NEOs and the meteoroid swarm generating the currently observed meteor showers. By convention, such associations are called asteroid–meteoroid complexes [3]. To investigate the known complexes and find new ones is one of the critical tasks in the study of small bodies of the Solar System, since the results make it possible to reveal interrelations between these bodies and establish their origin.

NEAR-EARTH OBJECTS OF THE QUADRANTID COMPLEX

NEA (186256) 2003 EH1 of the Amore group was discovered at the Lowell Observatory (United States) on March 6, 2003. The absolute stellar magnitude of 2003 EH1 is $H = 16.67^m$ and the equivalent diameter $d = 2.32$ km. From the observations of the asteroid, its orbit was calculated. The similarity of this orbit with that of the known Quadrantid meteor stream became immediately evident [11]. From a simple comparison of the orbital elements of the asteroid and the Quadrantid stream, it was supposed that 2003 EH1 is the most probable parent body of the Quadrantid meteoroid swarm.

In point of fact, as compared to the objects earlier considered as a potential parent body of the Quadrantid swarm—namely, comet 96P/Machholz 1, comet 1491 I, and asteroid 5496 (1973NA)—NEA 2003 EH1 currently has the orbit closest to that of the Quadrantids [5, 10–12, 18, 10]. Elements of the recent orbits of comet 96P/Machholz 1, asteroid 2003 EH1 (http://new ton.dm.unipi.it/neodys/neodys.cat, http://neo.jpl.nasa.gov), and the Quadrantid meteoroid swarm [5] are listed in Table 1, where a is the major axis, e is the eccentricity, q is the perihelion distance, i is the inclination, ω is the ascending node-

Table 1. Elements of the recent orbits of comet 96P/Machholz 1, asteroid 2003 EH1, and the Quadrantid meteor stream (J2000.0)

Object	a, AU	e	q, AU	i, deg	ω, deg	Ω, deg	T_j
96P/Machholz 1	3.03	0.96	0.12	58.31	14.76	94.32	1.94
2003 EH1	3.12	0.62	1.19	70.88	171.35	282.96	1.96
Quadrantids	3.14	0.69	0.99	71.88	171.20	283.30	1.95

perihelion angle, Ω is the perihelion longitude, and T_j is the statistics of Tisserand's criterion that allows the orbits of objects to be distinguished between the cometary and asteroidal types [13].

One of the characteristics of the evolution type of orbits of asteroids and comets is the intersection multiplicity for their orbits and that of the Earth, i.e., the number of intersections for a cycle of the change in the ascending node-perihelion angle of the object's orbit from 0° to 360°. The orbits may intersect only in the nodes of the orbit of a small body, when the heliocentric distances of the ascending and descending nodes R_a and R_d are approximately equal to the radius-vector of the Earth:

$$R_{a,d} = \frac{a\left(1-e^2\right)}{1 \pm e\cos\omega} \approx 1\ \mathrm{AU},$$

where the plus and minus signs correspond to R_a and R_d of the orbit, respectively [4]. If the values of a and e are specified, the above equation may have from one to eight roots for the value of ω, and the intersection multiplicity may, consequently, range from 0 to 8. According to this, the meteoroid swarm associated with the considered object can generate up to eight meteor streams observed on the Earth. Among NEOs, the fourfold intersection is the most frequent case, while the eightfold intersection least often occurs.

Analysis of the evolution of the orbit of the Quadrantid swarm showed that it intersects the Earth's orbit eight times. From the results of observations, eight meteor streams generated by this swarm were revealed. One of them is the Quadrantid meteor stream. In addition to the similarity of the current orbits, the results of the analysis of the orbit evolution for the asteroid and the Quadrantid swarm proved their kinship [5]. The performed studies suggested that asteroid 2003 EH1 is the most probable parent body (or a remnant of the parent body) of the Quadrantids. Since this asteroid is associated with eight observed meteor streams, we may suppose that it is a nucleus of an extinct comet.

Alternatively, one cannot exclude a probable kinship of asteroid 2003 EH1 with a short-period comet of Jupiter's family 96P/Machholz 1 discovered by Donald Machholz in May 1986. Before this discovery, the comet was specially searched for by the calculated ephemerid in the plates obtained at the telescopes with a wide field of view and a maximum stellar magnitude of $+19^m$ but with no success [9]. At the same time, it was found that at least three out of four of the passages of the perihelion were favorable for observations [15]. The most rational explanation of this fact is in the suggestion that, before 1986, this comet was in inactive, dormant, or extinct state [9, 15]. The analysis of the orbit evolution of the comet showed that it also intersects the Earth's orbit eight times, as NEA 2003 EH1 and the Quadrantid meteoroid swarm do. This naturally raises the question: is it possible that the comet, the asteroid, and the Quadrantid meteoroid swarm, generating eight streams, form a joint complex?

In this paper, we report the results of the analysis of the supposition that the active comet Machholz and the dormant comet 2003 EH1 are related bodies formed in the breaking up of a single progenitor comet.

EVOLUTION OF THE ORBITS OF COMET MACHHOLZ AND NEA 2003 EH1

First of all, we point to the close values of Tisserand's criterion (Table 1) indicating the cometary nature of the studied objects and their probable interrelation. If a break-up of the comet was an episode in its history, one may expect that several large fragments will be observed in the meteoroid swarm. Such fragments should evolve in the same way as the swarm does.

Fragmentation of asteroids and comets into large pieces occurs with small separation velocities, which initially also causes insignificant differences in the orbital elements. Due to this, to reveal the relation between the objects, it is necessary to analyze the evolution of the orbits and determine the moment of the

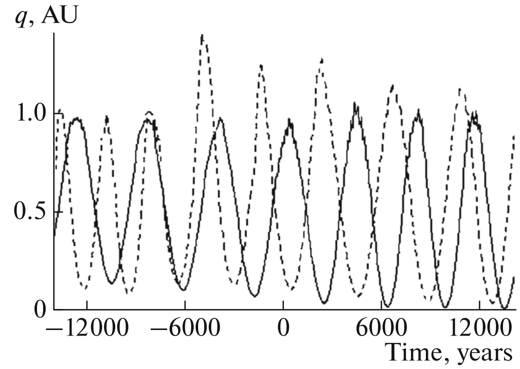

Fig. 1. Long-term changes in the perihelion distance q of the orbit of comet Machholz (solid curve) and 2003 EH1 (dashed curve).

closest similarity. If such similarity is found, this moment can be assumed to be the moment of separation of the fragments.

To analyze the evolution of the orbits, different numerical methods for integrating the differential equations of the disturbed motion of many bodies are used. In this study, we used Everhart's method [8] for calculating the differential planetary disturbances. In the model, we calculated the gravity effects from all eight major planets of the Solar System taking into account their mutual perturbations.

From calculations of the osculating elements of the orbits, it has been revealed that these objects coincide by the evolutionary type: both of them intersect the Earth's orbit eight times with inclinations, eccentricities, and perihelion distances varying in wide ranges. The long-term changes in the perihelion distance q and the heliocentric distances of the ascending (R_a) and descending (R_d) nodes for the interval of 28000 years are shown in Figs. 1–3.

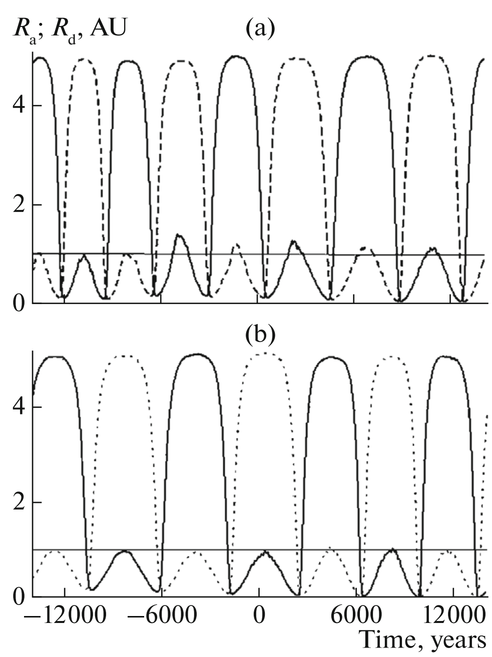

Fig. 2. Long-term changes in R_a (dashed curve) and R_d (solid curve) of the orbits of (a) asteroid 2003 EH1 and (b) comet Machholz 1 for the interval of 28000 years. The distance of 1 AU corresponds to the moments of the Earth's orbit intersections.

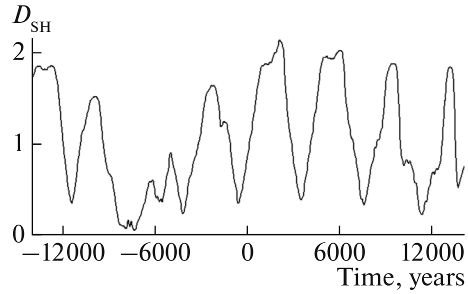

Fig. 3. Changes in the D_{SH} statistics between the orbits of 2003 EH1 and comet Machholz for the interval of 28000 years. The moment of the closest approach is shown by an arrow.

IDENTIFICATION OF THE MOMENT OF THE CLOSEST SIMILARITY BETWEEN THE COMET AND ASTEROID ORBITS

At the present stage, it is necessary to compare the orbits of the comet and the asteroid for a long time interval and to find the moment of their closest coincidence.

As a measure of the closeness of the objects' orbits, we took the most important and frequently used criterion of Southworth and Hawkins D_{SH} [16]. To calculate the D_{SH} statistics, five elements of the compared orbits are considered:

$$D_{SH}^2 = (e_2 - e_1)^2 + (q_2 - q_1)^2 + \left(2\sin\frac{i_2 - i_1}{2}\right)^2 + \sin i_1 \sin i_2 \left(2\sin\frac{\Omega_2 - \Omega_1}{2}\right)^2 + \left[\left(\frac{e_2 + e_1}{2}\right) 2\sin\frac{(\Omega_2 + \omega_2) - (\Omega_1 + \omega_1)}{2}\right]^2.$$

It is accepted that small bodies may be of common origin, if the value of the D_{SH} statistics of their orbits does not exceed 0.20.

The calculated values of D_{SH} for comet Machholz and object 2003 EH1 for the time interval of 28000 years are shown in Fig. 3. It is seen that the smallest value of $D_{SH} = 0.029$ and, consequently, the closest coincidence of the orbits occurred in 7415–7465 B.C., i.e., approximately 9500 ya. The orbital elements of the objects for the moment of the closest coincidence are listed in Table 2.

DISCUSSION

The comparative analysis shows that the orbits of the objects were mostly close only once for a long time period; moreover, the orbits intersected near the perihelion, which was approximately at 1 AU at that moment. If there were no perturbations, the orbits would always go through the fragmentation (break-up) point, i.e., would intersect at this point. However, with the lapse of time, this information vanishes due to different perturbations of both gravitational and nongravitational nature. Consequently, such an intersection was not observed before and will not occur in the future.

One of the causes of fragmentation of the comet-progenitor may be a collision with another object. Though such an event is of low probability, it cannot be excluded. One more cause may be the tidal attraction of the Sun, the Earth, and Venus at the previous evolution stages. In the considered time interval, the objects approached the Sun, the Earth, and Venus to the distances less than 0.05 AU many times, while they approached Jupiter to the distance less than 0.2 AU only two to three times.

The analysis of the dynamic properties showed that, in each scenario of the parent comet fragmentation, comet 96P/Machholz 1 and object 2003 EH1 are most likely of common origin; a break-up of the

Table 2. Elements of the orbits of comet 96P/Machholz 1 and asteroid 2003 EH1 for the moment of 7415 B.C. (J2000.0)

Object	a, AU	e	q, AU	i, deg	ω, deg	Ω, deg	T_i
96P/Machholz 1	3.037	0.795	0.622	65.82	13.28	98.56	1.94
2003 EH1	3.039	0.798	0.615	65.03	15.55	97.78	1.96

common progenitor into these two fragments occurred almost 9500 ya, and asteroid 2003 EH1 is actually an extinct piece of the comet.

CONCLUSIONS

Thus, the identified moment of time can be considered as that of fragmentation of a nucleus of the comet that is a progenitor of the Quadrantid complex. It can also be supposed that the comet and the asteroid are large fragments of a nucleus of the parent comet. As a result, the complex currently contains the active comet 96P/Machholz 1, NEA (186256) 2003 EH1, being an extinct piece of the parent comet nucleus, and the Quadrantid meteorite swarm with a family of eight meteor streams. It is reasonable to keep searching for analogous extinct fragments, formed in a break-up of a comet-progenitor, among NEAs.

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