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The parent bodies of the Quadrantid meteoroid stream

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ABSTRACT

Aims. We attempt to prove or disprove the comet 96P/Machholz and asteroid 2003 EH1 as the parents of the Quadrantids. These two bodies have been regarded as the most probable candidates. Moreover, we investigate a possibility of an existence of their common progenitor, in the past.

Methods. For the moments of several perihelion passages of each parent-body candidate under consideration, we model the theoretical streams around the orbit of the candidate and, via a numerical integration, monitor the dynamical evolution of these streams. The perturbations by eight major planets are taken into account. For the end of the evolution, corresponding with the present, we construct the distributions of orbital elements of that part of a given stream, in which the particles approach the Earth's orbit. These distributions are compared with the corresponding orbital elements of the photographically detected Quadrantids.

Results. It is proved that at least one of 96P and 2003 EH1 is the parent body of the Quadrantid meteor stream. Due to an uncertainty in the orbit determination and unknown non-gravitational effects, it is impossible to decide which one of these two bodies is the dominant parent or whether both these bodies have significantly released the meteoroids into the stream. A large population of the Quadrantid stream had to be released from a parent (or parents) at least few millenia ago. If the Earth is also impacted with younger, several-century-old particles, these originate from the asteroid 2003 EH1. However, this young population can represent only a fraction of the entire Quadrantid-shower population. We also demonstrate some possibilities allowing an existence of a progenitor and its splitting to 96P and 2003 EH1. However, we suggest that, within a solely dynamical study, it is impossible to prove that the splitting event did actually happen. Neither of the other candidates considered, comet C/1939 B1 and asteroid 5496, associates any Earth-impacting meteor stream.

Key words. meteors, meteoroids

1. Introduction

The Quadrantids are the first major meteor shower in the calendar year. It can be observed on January 3 and 4. In contrast to most major meteor streams, its parent body still remains uncertain.

The dynamical evolution of the stream has been studied by several authors. Hamid & Youssef (1963) found large changes in both eccentricity and inclination to the ecliptic with a period of about 4000 years. More recent studies by Hughes et al. (1981), Froeschlé & Scholl (1982, 1986), Babadzhanov & Obrubov (1987), as well as Wu & Williams (1992) revealed rapid and large changes in all orbital elements within the periods of a few thousand years.

Concerning the parent, the researchers have usually attempted to reveal it by comparing the mean elements of the stream with the osculation elements of a considered candidate. The mean elements of all Quadrantids selected from the IAU MDC database of photographic meteor orbits (Lindblad 1987, 1991) are $\langle q \rangle = (0.981 \pm 0.008)$ AU, $\langle e \rangle = 0.663 \pm 0.066$, $\langle \omega \rangle = (169.9 \pm 3.4)^\circ$, $\langle \Omega \rangle = (283.4 \pm 0.9)^\circ$, and $\langle i \rangle = (71.7 \pm 1.7)^\circ$ (Porubčan et al. 1995). The first parent-body candidates, C/1939 B1 (Kozik-Peltier) and 8P/1790 A2 (Tuttle), were suggested by Bouška (1953). In 1954, Lovell studied the relationship of C/1860 D1 and C/1939 B1 with the Quadrantids, but with a negative conclusion. Another candidate, comet 1491 I, was suggested by Hasegawa (1979). In the 5-th edition of the Catalogue of Cometary Orbits (Marsden 1986), its osculation orbital elements are: $q = 0.761$ AU, $e \approx 1$, $\omega = 164.9^\circ$, $\Omega = 280.2^\circ$, and $i = 73.4^\circ$ (converted to the equinox J2000.0; all angular elements in our work are related to the equinox J2000.0). This orbit is actually similar to the mean orbit of the stream. It is, however, necessary to note that it was later corrected and new orbital elements in the 15th edition of the Catalogue of Cometary Orbits (Marsden & Williams 2003), where the comet is designed as C/1490 Y1, are $q = 0.7376$ AU, $e \approx 1$, $\omega = 129.84^\circ$, $\Omega = 295.89^\circ$, and $i = 51.65^\circ$. This orbit is much less similar to the mean orbit of the stream.

Williams & Wu (1993) investigated the possibility that the comet 1491 I was already observed earlier than in 1491 and suggested identifying it with comet 1385 having the elements $q = 0.79$ AU, $e \approx 1$, $\omega = 182^\circ$, $\Omega = 289^\circ$, and $i = 103^\circ$. According these authors, the comet passed its perihelion 20 times during the period 1385−1491. This implies an orbital period of 5.3 years and eccentricity of about 0.76, not very different from that of the Quadrantids.

In 1990, McIntosh suggested comet 96P/Machholz as the parent of the Quadrantids. Though the current orbit of this comet, with the elements $q = 0.124$ AU, $e = 0.959$, $\omega = 14.6^\circ$, $\Omega = 94.6^\circ$, and $i = 60.2^\circ$, is largely different from the known mean orbit of the stream, the past orbit of the comet, about 2500 years ago, with $q = 0.569$ AU, $e = 0.811$, $\omega = 348.3^\circ$, $\Omega = 103.6^\circ$, and $i = 73.9^\circ$ (Jones & Jones 1993), was much more similar to the mean orbit of the Quadrantids.

Babadzhanov & Obrubov (1992) modelled a theoretical stream assumed to be ejected from 96P/Machholz about 6500 years ago. Investigating the dynamics of this theoretical stream, the authors concluded that the Quadrantids and seven another recognizable meteor streams were produced by this comet. Hence, the Quadrantids may represent a part of a stream complex.

Williams & Collander-Brown (1998) suggested the first asteroidal candidate, the asteroid 5496, as the Quadrantid parent. Its orbital elements are $q = 0.881$ AU, $e = 0.638$, $\omega = 118.2°$, $\Omega = 101.1°$, $i = 68.0°$, and the absolute magnitude $H_0 = 15.3$. They argued that the strong similarity between the values of orbital elements of this asteroid and of the Quadrantid meteoroid stream was a strong indicator of some connection. They also showed a general similarity in the orbital evolution and the general physical characteristics of the asteroid. In conclusion, they offerred the following scenario. At some unspecified time or times in the past, but at least several thousand years ago, the nucleus of an original comet split into several fragments, three of which can be identified, namely the comets C/1490 Y1 and 96P/Machholz, and the asteroid 5496. The meteoroids were probably ejected throughout the interval from each of these three fragments, and possibly from other, yet unidentified fragments.

The last, but the most probable parent body of Quadrantids, was suggested by Jenniskens (2004), who suggested that the parent is the, at that time newly discovered, asteroid which was preliminarily designated as 2003 EH1. It was found in an orbit remarkably similar to the known mean orbit of Quadrantids. Further, Jenniskens suggested that the asteroid could be an extinct nucleus of comet C/1490 Y1.

Earlier, in 1997, Jenniskens, taking into account the observed narrowness of the activity, argued that the Quadrantid stream must be quite young. Most of the observed meteoroids had to have been released from the parent before only several hundred orbital revolutions. With this conclusion, we must, however, be careful, because the rate of a dispersion enlargement is very different for various streams. Emel'yanenko (2001) demonstrated that the typical change of the meteoroid semi-major axis, Δa, for the Quadrantids is about one order lower than Δa for Lyrids, Perseids, or Orionids/η-Aquarids. It implies an even larger than one-order difference in the orbital period and, thus, a measure of the dispersion of stream.

In accord with Jennisken's conclusion on the young age of the Quadrantids, Williams et al. (2004) assumed a formation of this stream more than 280 but less than a thousand years ago and studied the relationship between the stream and asteroid 2003 EH1. They supported Jennisken's suggestion that the asteroid is the parent.

In this paper, we follow the idea that the Quadrantid stream could be a part of a more complex meteor-stream structure and attempt to trace its parent among the most probable candidates, the comet 96P/Machholz and asteroid 2003 EH1. The fact, that the 96P is currently on a quite different orbit than the current mean orbit of the observed stream, does not eliminate this body from consideration as the parent. An example of such a parent, comet 14P/Wolf, was found by Neslušan (1999). Though its orbit before 1922 was relatively distant from the orbit of the Earth, a part of the stream has been moved to another corridor, whereby the meteoroids changing their orbits have hit our planet and are known as α-Capricornids. Another example is the resonant structure of Perseid stream revealed by Wu & Williams (1995) and confirmed by Kaňuchová et al. (2005) and Svoreň et al. (2006). In the last two papers, the authors demonstrated that the Perseid stream consists of several filaments with the mean orbital periods ranging from about 6 to 1700 years. This documents that even such a regular stream as Perseids has a complicated structure with some filaments which are quite different from the orbit of the parent.

A possible relationship between 96P/Machholz and asteroid 2003 EH1 is also studied. Two other possible parent-body candidates of the Quadrantids, comet C/1939 B1 and asteroid 5496, are investigated as well.

2. The method of the stream identification

Our method is based on the modelling of a theoretical stream for a moment in the distant past, monitoring its orbital evolution up to the present, selecting that part of the stream, which occurred on a collisional course with the Earth, and comparing the characteristics of this part with the corresponding observed meteor shower. The dynamical properties of the modelled stream should be similar to those which are known as typical of real meteoroid streams. Since we want to study a dynamical evolution of the stream from the beginning of its occurrence, the stream should be quite compact, consisting of the meteoroids on orbits which are not very dispersed from that of their parent body. On the other hand, the Quadrantids have been observed annualy, therefore the meteoroids should fill the entire corridor of orbits around the parent's orbit. The frequency of the passages of particles through a chosen cross-section of the corridor should be, more or less, constant. It is well-known that the meteoroid particles are released from the surface of their parent body mainly around the perihelion of the parent. This fact implies that the dispersion of the perihelion points is, later, relatively small, while the dispersion of the aphelion points is much larger. To simulate all these properties, we proceed in the following way.

In the first step, we integrate, backward in time, the well-known catalogue orbit of the parent-body candidate. Considering the radius and position vectors of 8 planets, from Mercury to Neptune, given in the Astronomical Almanac for the Year 2004 (2002) for JDT = 2 453 040.5, we integrate the orbits of these planets and candidate into the past over the period equal to 1000 nominal orbital revolutions of a theoretical massless body moving in the known mean orbit of the Quadrantids. The nominal orbital period of the "mean Quandrantid", P_o, is 1814.08272 days (4.97 years), therefore our backward integration covers about 4950 years.

In the second step, we perform an iteration procedure to find the time of the perihelion passage of the candidate, which is closest to the final time of the previous numerical integration.

Having the time of the perihelion passage, we model a sample of theoretical particles (TPs) on the orbits that are similar to the orbit of the candidate, in the third step. At the modelling, a uniform, spherically symmetric ejection of TPs from the candidate in its perihelion is assumed. In reality, the ejection in a given moment is rather strongly asymmetric. In the modelling, it is, however, impossible to choose the right direction and an eventual change of its orientation, therefore we use the symmetric approximation. From a statistical point of view, it is the most suitable way to do the modelling. The magnitude of the ejection velocity is chosen to be identical for all TPs and to be a multiple, χ, of the candidate's perihelion velocity. Specifically, we consider $\chi = 0.0025$. In the case of 96P/Machholz (2003 EH1), it corresponds to the ejection velocity of 97 m s^{-1} (221 m s^{-1}). Assuming only a single value of the ejection-velocity magnitude is, of course, not consistent with a real process of a release of meteoroids from the parent's surface. However, we do not here attempt to simulate this physical process, but rather regulate a speed of the dispersing of TPs along the corridor of orbits and the width of this corridor. We empirically found that the value of $\chi = 0.0025$ leads to a relatively rapid filling of the orbital corridor with the TPs (within about 30 years in the case of the standard theoretical stream of 96P), but, on the other hand, the dispersion of their orbits remains low (an order lower than that of the compact cores of major meteoroid streams, when measured with the help of the Southworth-Hawkins' (1963) D-discriminant).

The procedure of the proper modelling of TPs is identical to that described in the paper by Neslušan (1999), where the specific details can be found. The result of the procedure are the orbits of 4586 TPs. The stream modelled in the time of perihelion passage of about 1000 P_o ago is referred as "standard stream", hereinafter.

In the fourth step, the orbits of all TPs are numerically integrated forward, to the present epoch being chosen in 1990.0 (JDT = 2 447 892.5). To perform the integration, we use the RADAU integrator (Everhart 1985) within the package MERCURY developed by Chambers (Chambers 1999, or `http://http://www.arm.ac.uk/jec/mercury/mercury6.tar`). As already metioned, the perturbations by eight planets are considered. An output from the integration is made every 200 years. The final output, at the end of the integration in 1990.0, is recorded, too. Since we mainly compare our theoretical predictions with the observed facts about the relatively large meteoroid particles detected photographically, it is not necessary to consider the non-gravitational effects. So, we ignore these effects.

The real Quadrantid meteoroids have been observed and their characteristics determined only in the moments of their collision with the Earth. So, we can compare with the real Quadrantids only those TPs which move in the present on the orbits passing close to the Earth's orbit (say, within 0.1 AU; but no significant difference is observed, when this limit is chosen to be, e.g., 0.05 AU). In the fifth step, we select the TPs on such orbits from the whole theoretical stream. They can be regarded as a sub-stream which approaches the Earth's orbit. Finally, we analyse the properties of this sub-stream and try to identify it with the Quadrantids.

Of course, the meteoroids can be released from the parent body near many perihelion passages or even far from the parent's perihelion. To gain more complex information about the evolution of the part of stream close to the Earth's orbit, we investigate the evolution of the parent's orbit between the time of 1000 P_o ago and the present and repeat the simulation of a theoretical stream for several further perihelion passages of the parent.

3. The orbital evolution of the stream associated with 96P

3.1. Evolution of the entire standard 96P-stream

Taking the catalogue orbit of comet 96P/Machholz (Marsden & Williams 2003) into account, we perform the procedure described in Sect. 2, i.e. we model the set of 4586 TPs and, through a numerical integration, we study the orbital evolution of these TPs, from the time of 1000 P_o ago to the present (epoch 1990.0, JDT = 2 447 892.5), i.e. over the period of about 4950 years.

The evolution of the distributions of orbital elements of the theoretical stream is demonstrated in Fig. 1. In plots (a), (c), and (f), we can obviously see a part of a common libration cycle of perihelion distance, q, eccentricity, e, and inclination, i, respectively, of the major part of the stream. Since the orbital evolution of the stream appears to be controlled by Jupiter, these elements are mutually coupled with respect to the Tisserand invariant. Initially a short q of the major part of the stream increases up to about 0.9 AU and, subsequently decreases to a small value, below 0.2 AU, again. Reciprocally, e decreases from a value close to 1 to the value of about 0.7 and, then, increases again toward 1.

According Fig. 1b, the semi-major axis, a, of a prevailing part of the stream orbits remains almost the same during the entire studied period. It proves a long life-time of the stream.

The strand of the stream corresponding to the observed Quadrantids begins to appear at only about 850 years ago. It is documented by the gradually increasing, Quadrantid-mean-orbit corresponding peaks in the argument-of-perihelion and longitude-of-ascending-node distributions in Fig. 1, plots (d) and (e). These peaks correspond to the values of about 167° and 287° of argument of perihelion, ω (plot d), and longitude of ascending node, Ω (plot e), respectively.

3.2. The standard 96P-stream at the Earth's orbit

At the present, the evolution of the entire stream associated with 96P can be studied exclusively in a theoretical way, since the only meteoroids from this stream which have actually been seen are those which cross the Earth's orbit. In Fig. 2, we illustrate the part of the theoretical stream consisting of the particles approaching the Earth's orbit closer than 0.1 AU. This part can, approximately, be identified to an observable meteor shower.

The first particles enter the Earth's region about 600 years after their ejection from the parent. A relatively numerous meteor shower occurs in the period of 2000−3600 years after the ejection. Its mean $\langle q \rangle$, $\langle e \rangle$, and $\langle i \rangle$ (Fig. 2, plots a, c, and f, respectively) are similar to the mean $\langle q \rangle$, $\langle e \rangle$, and $\langle i \rangle$ of the present-day Quadrantids, but the mean $\langle \omega \rangle$ (Fig. 2d) evolves from about 350° to 370° and mean $\langle \Omega \rangle$ (Fig. 2e) is about 100°. A peak corresponding with the orbital corridor of the present-day Quadrantids, distinguishable in the distributions of e, Ω, and i (Fig. 2, plots c, e, and f, respectively), begins to occur only about 250 to 150 years before the present. This prediction is roughly consistent with the fact that there are no records of the Quadrantids observed earlier than the beginning of the 19th century (Williams & Collander-Brown 1998) on the basis of the Chinese and Japanese documents published by Hasegawa (1993).

The distributions of the orbital elements of the Earth-orbit approaching part of the stream at the present is shown in Fig. 3. The dashed-line curves demonstrate the distributions of the entire mentioned part (these curves are identical to the upper curves in the plots of Fig. 2, but shown once more with better, more transparent resolutions). Several peaks in the distributions are obviously related to several strands of the stream. Specifically, in the distribution of q (Fig. 3a), there are two peaks corresponding with two strands. Let us assume that the strand with $q > 0.8$ AU corresponds with the Quadrantid shower having the mean perihelion distance $\langle q \rangle \doteq 0.98$ AU.

Subsequently, let us select all TPs with $q > 0.8$ AU from the strand and illustrate the distributions of their orbital elements again in Fig. 3, into the corresponding plots, with a solid line. (Notice that the solid line must overcover the dashed line wherever it rises above zero, in the given context.) We see that the appropriate peaks in the selected-TP distributions of the other elements also fit the corresponding mean values of Quadrantids well. In the plots, the observed mean values of $\langle q \rangle$, $\langle e \rangle$, $\langle \omega \rangle$, $\langle \Omega \rangle$, and $\langle i \rangle$ of the Quadrantids are shown by a short abscissa above the appropriate, solid-line peak. The length of the abscissa includes the dispersion of the given element as determined by

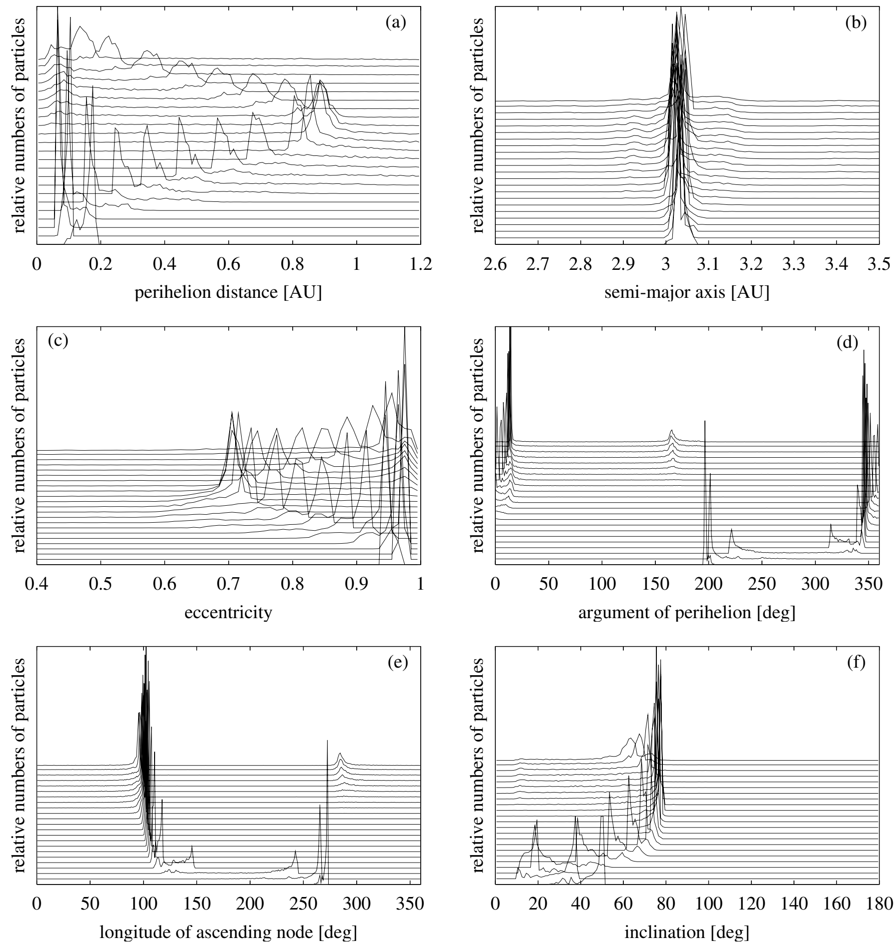

Fig. 1. The evolution of the distributions of orbital elements of a teoretical stream associated with comet 96P/Machholz. The stream is modelled for the time of 96P perihelion passage being closest to the time of 1000 P_o ago, where P_o is the orbital period of a body on the mean orbit of Quadrantids. The bottom curve illustrates the distribution in the moment of the modelling, while other successive curves above this curve illustrate the distributions separated with the interval of 200 years. The upper-most curve does so for a shorter separation of 52 years, i.e. 4952 years after the modelling (exactly in epoch 1990.0).

various authors (Poole et al. 1972; Wu & Williams 1992; Porubčan et al. 1995; Jenniskens et al. 1997), determination uncertainty included. A short, vertical, dotted line crossing the abscissa indicates the corresponding theoretical value derived from the study of the standard stream (the mean value of the peak).

For all five elements, the theoretical mean value is absolutely consistent, within the uncertainty, with the corresponding observed value. A remarkably high agreement can be seen in the case of Ω (Fig. 3e). This element, corresponding with the period of shower activity, is measured with the highest precision and is distributed in a very narrow interval, in the case of Quadrantids. The agreement is strong proof that the comet 96P is the actual parent body of Quadrantids. The very short interval of the Ω appearance and, thus, very short activity period of Quadrantids occur as a consequence of the resonant action of Jupiter and a narrow corridor of stream orbits in the orbital-element phase region, where the meteoroids cross the orbit of the Earth.

3.3. Further meteoroid-ejection times from the nucleus of 96P

The evolution of five orbital elements of 96P over the period of 1000 P_o is demonstrated in Fig. 4. With respect to this orbital evolution, we assume the formation of a stream in another four comet perihelion passages in the past. The Julian dates of these passages, including the modelling for the passage of 1000 P_o ago (or ≈4950 years ago), are given in Table 1.

From the work by Gonczi et al. (1992), it is well-known that a large change of the orientation of the orbit occurred about 3900 years ago. At that time, the comet perihelion distance was shorter than 0.1 AU. Our second modelling is made for the perihelion passage that occurred soon after this orbital change, specifically ≈3700 years ago (on purpose and in contrast to Gonczi et al., we do not choose the exact time of the change to model the stream, since the comet obviously spent only a short time in the rapidly changing orbit and no numerous and stable stream could form). The third and fifth modelling dates, ≈2550 and ≈500 years ago, correspond with the middle of a linear change of both perihelion distance and eccentricity and a slow change of angular orbital elements. During these periods, the gradient of the orbital change is low and we can expect a higher rate of meteoroid release from the parent into the appropriate orbital-element phase space than during other periods. To fill a gap between the third and fifth modelling, we choose the fourth modelling date, ≈1500 years ago, corresponding with the maximum value of i (Fig. 4b) and turn-points in the evolution of q and e (Fig. 4a).

Moreover, we choose another two modelling dates, 990 P_o and 1010 P_o (≈5000 and ≈4900 years ago), to verify if the standard stream, modelled in 1000 P_o ago, and its subsequent evolution can be regarded as characteristic for a longer adjacent period. An analysis of the evolution of the streams modelled for both adjacent dates does not indicate any significant difference in comparison with our conclusion that can be claimed about the standard stream.

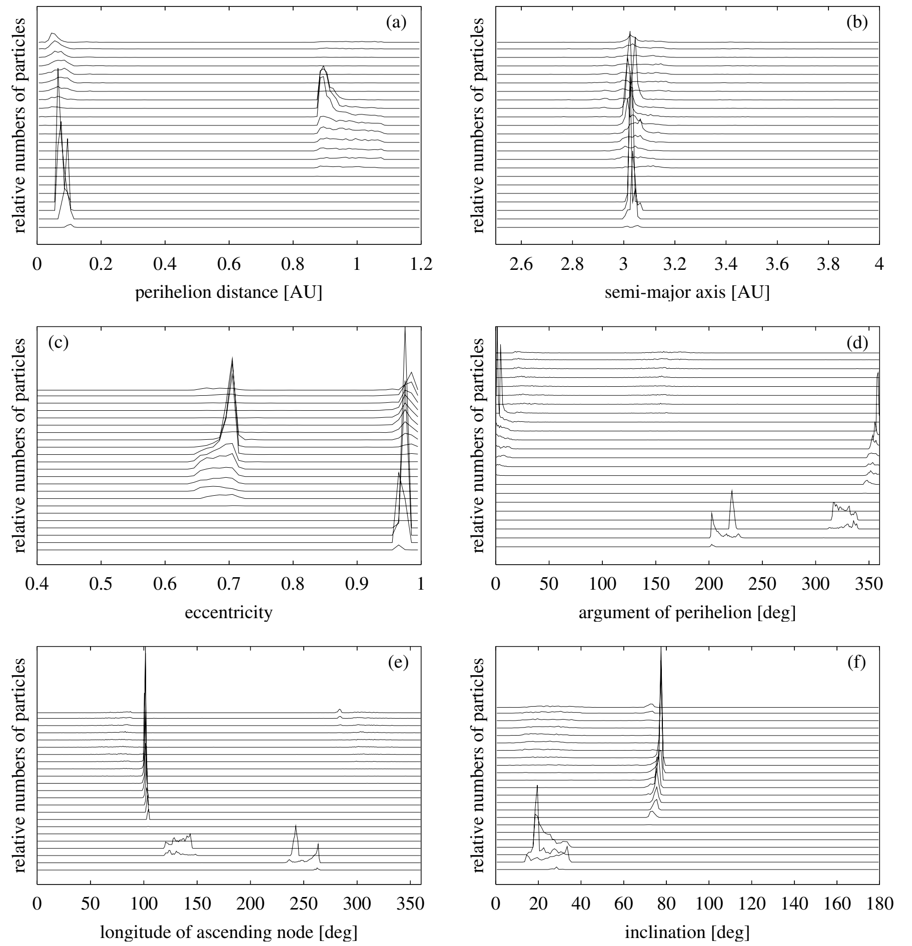

Fig. 2. The evolution of the distributions of orbital elements of that part of a teoretical stream mentioned in the caption of Fig. 1, the orbits of which approach the Earth's orbit within 0.1 AU. During the first ≈500 years after the modelling, no test-particle orbit passed within this limit, therefore the bottom curve here illustrates the distribution in the time of 600 years after the modelling and successive curves above this curve illustrate the distributions separated with the interval of 200 years. The upper-most curve does so for a shorter separation of 52 years, i.e. 4952 years after the modelling (exactly in epoch 1990.0).

From the theoretical streams modelled for the moments of ≈3700, ≈2550, ≈1500, and ≈500 years ago, only the stream modelled for ≈2550 years ago seems to have a part corresponding with the Quadrantids. At the streams modelled for ≈3700 and ≈1500 years ago, no particle passing near the Earth's orbit has its Ω within (or near) the Ω-peak corresponding to the Quadrantids. Concerning the stream modelled for ≈500 years ago, there is not a single particle, near the Earth's orbit, having its perihelion larger than 0.1 AU. This agrees with the conclusion by Jones & Jones (1993) that "the Quadrantid meteors presently observed must have been released from their parent comet (96P) at least 2000 years ago, since this is the shortest interval required for the Quadrantid branch of the complex (Quadrantids + Daytime Arietids + Southern δ-Aquarids) to appear".

The distributions of the orbital elements of the Earth-orbit approaching part of the theoretical stream, modelled for the perihelion passage of 96P about ≈2550 years ago, are illustrated in Fig. 5. We again assume that the second peak in q-distribution ($q > 0.8$ AU) corresponds to the Quadrantids. The corresponding peaks in e-, ω-, Ω-, and i-distributions (Fig. 5, plots c, d, e, and f, respectively) then more or less agree with the observed distributions of Quadrantids, but the predicted mean $\langle q \rangle$ is clearly outside of the observed mean-q interval (plot a).

The sub-stream with $q > 0.8$ AU is compact in the distributions of the elements q, e, and i. Looking at the distributions of ω and Ω (Fig. 5, plots d and e, respectively), we can see that peaks, other than those which correspond to the Quadrantids, occur. So, according to this prediction, other strands should be detected if the Quadrantids were actually released from the 96P nucleus during a period around ≈2550 years ago. To find if this actually happened, we searched for these stream strands in the IAU MDC photographic meteor catalogue (Lindblad et al. 2003). Selecting all meteors having $q \in (0.8, 1.1)$, $e \in (0.6, 0.8)$, and $i \in (60°, 90°)$, at the same time, one can draw a negative conclusion. All selected meteors are on the orbits with ω ranging from about 135° to 225° (with a higher peak spanning from about 165° to 180°). Therefore, there is no single meteor with $\omega \in (0°, 50°)$ or with $\omega \in (330°, 360°)$. And, there is no selected meteor with Ω in the peak between the values of 87° and 97° (a prevailing part of the selected meteors have $\Omega > 282°$; only few meteors have $\Omega \in (139°, 282°)$ and few meteors have $\Omega < 78°$). When comparing between a release of photographic-meteor-sized particles, which happened earlier than about 3900 years ago, and a release in a period centered to the date of 2550 years ago, the latter had to be negligible, if it happened at all. It could be a consequence of the difference in q of the parent body, 96P, in these epochs. While $q \lessapprox 0.1$ AU in the period of ≈3900 years ago, $q \to 0.6$ AU in the period of ≈2550 years ago (Fig. 4a).

It is worth noting that Jones & Jones (1993) showed that it is possible for comet 96P/Machholz to have given birth to the Quadrantid stream 2500 years ago. Their result obviously corresponds to the characteristics of our stream modelled ≈2550 years ago. Despite their positive conclusion about the stream and Quadrantid relationship, in contrast to our rather negative conclusion, they noticed a discrepancy between the longitudes of ascending nodes.

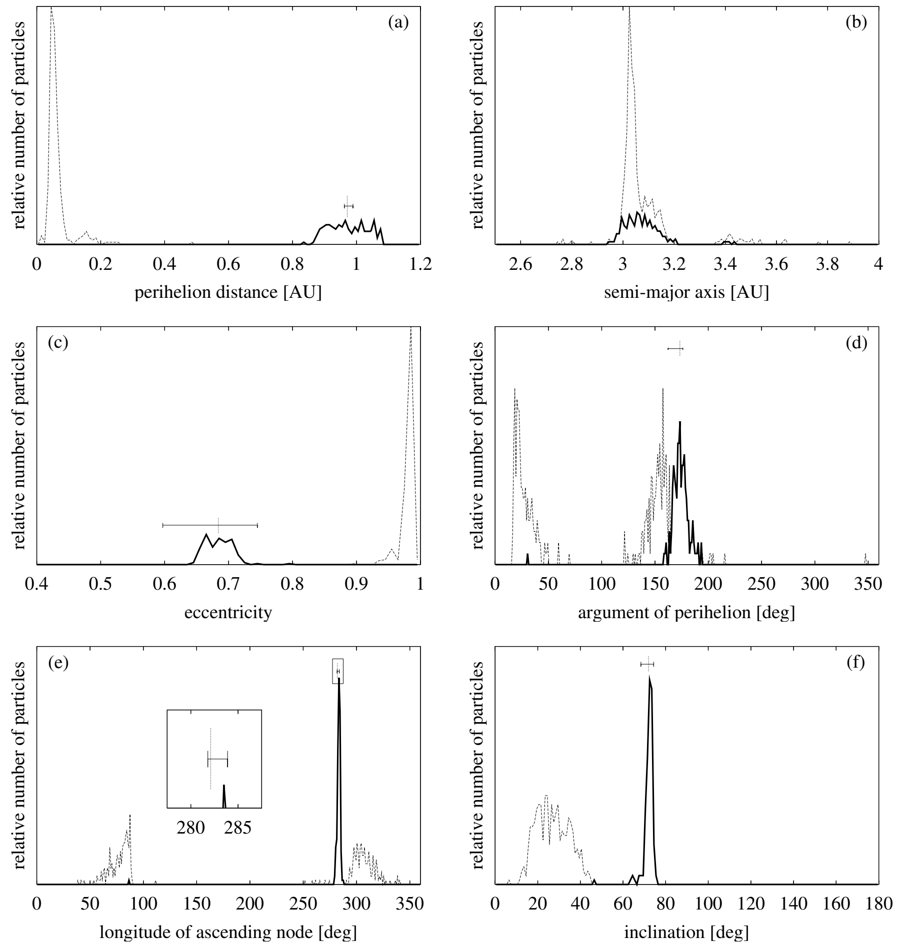

Fig. 3. The distributions of orbital elements of the Earth-orbit approaching part of a theoretical stream associated with comet 96P/Machholz. The stream was modelled for the time as in Fig. 1. Here, we more transparently illustrate the current (1990.0) distributions, which are shown in Fig. 2 by the upper-most curves in the corresponding plots. Each distribution of the strand with perihelion distance, q, larger than 0.8 AU is illustrated with the solid line, while the distribution of the entire Earth-orbit approaching part of the stream is shown by the dashed curve. A short abscissa above the peak corresponding with the $q > 0.8$ AU-strand shows the range of mean values of the given element as published by various authors, with the determination uncertainties included. A short, vertical, dotted line indicates the mean value of the peak.

3.4. On the age of Quadrantids

In 1997, Jenniskens et al. analyzed the dispersion of photographic and video orbits of Quadrantids observed on January 3, 1995, and concluded that the observed, very narrow, dispersion implies an age of the main stream component no older than about 500 years. Their estimate of the age is, however, based on an assumption that the dispersion increases linearly with time. Though this assumtion is undoubtedly valid for many streams, an evolution of some specific streams, having their corridors near a mean-motion resonance with Jupiter, can be different. A difference of up to two orders in the dispersion of semi-major axes of major streams was pointed out by Emel'yanenko (2001). The Quadrantid stream is just a stream controlled by the giant planet. The fact, that its orbital dispersion might be kept constant, especially for the relatively large, photographically detected particles, can be seen at the already mentioned part of the stream, which occurred as a shower 2000−3600 after time of our modelling. The corresponding peak in its Ω-distribution (Fig. 2e) remains narrow during the entire 1600-year period of its occurrence. The corresponding peak in its q-distribution (Fig. 2a) firstly occurs as a low and shallow peak and, later, its height increases and width decreases in time, so far.

Only a moderate decrease of the population of the Earth-orbit approaching part of 96P stream can also be noticed inspecting Fig. 6, especially the curves illustrating the evolution of the population for streams modelled in the 96P perihelion passages of ≈4950, ≈3700, and ≈2550 years ago. In the case of the first (≈4950) curve, the second peak is significantly lower when compared to the first peak, but the third peak is only slightly lower than the corresponding second peak. A very low decrease can also be seen from the second to third peak of the third (≈2550) curve. In the case of the second (≈3700) curve, the third peak is, so far, higher than the second peak.

Other proof that the dispersion of the 96P stream is minimal can be seen in Table 1, the most-right column. If the stream is modelled in the time of 2552 years before the present, for example, about 69% values of a remain in the original interval of its dispersion, after this period. The same quantitative conclusion can, however, be drawn for the modelling in the time of, e.g., 4952 years before the present. Even if some values of a are changed outside the original interval, a lot of them are changed backward, into the interval, due to a libration of this orbital element.

From Table 1, we can read that about 14% to 17% of the TPs reach the orbits in a vicinity of the Earth (within 0.1 AU) at the present, when they are assumed to escape from 96P about 5 millenia ago. And, about 10% to 12% of the modelled TPs reach, at the present, the strand of the stream, which can be identified with the Quadrantids.

It is interesting that the TPs do not spend a long time within the Earth-orbit approaching Quadrantid strand. Inspecting the 200-year-period outputs, some TPs occur only in a single output and no TP is present in more than five consecutive outputs, corresponding with a period of about 1000 years. The average number of the occurrence of a TP in the outputs is equal to 1.97. It means that a TP typically resides in the Earth-orbit approaching Quadrantid strand of the 96P's stream only about 400 years. Some TPs can enter the strand more than one time. The TPs

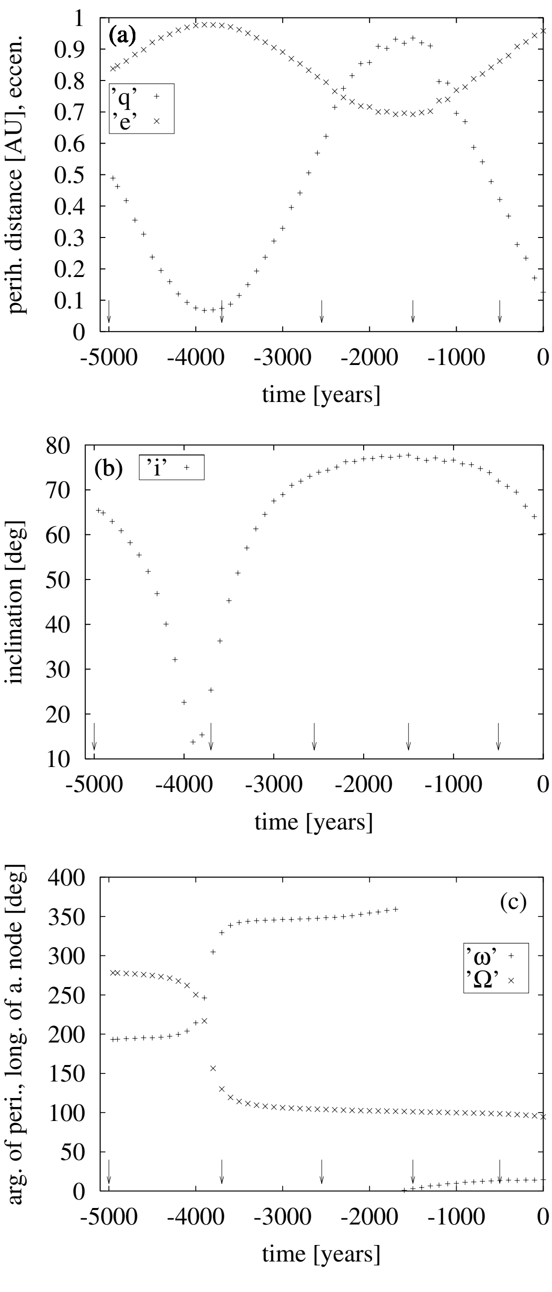

Fig. 4. The evolution of the orbital elements of comet 96P/Machholz from the time of 1000 P_o ago to the present (epoch 1990.0). Symbol P_o stands for the orbital period of a body on the known mean orbit of Quadrantids. The arrows above the horizontal axis of the plots point out the times, for which the theoretical streams associated with 96P are modelled.

leaving the strand are, however, replaced by other, incoming TPs, therefore the strand can be in a steady-state, quite numerous, for a significantly longer period than 400 years.

Briefly concluding, the meteoroids originating on the nucleus of 96P, which can be observed as meteors in the Earth's atmosphere today, were released from the nucleus at a time roughly 3900 years ago. A prevailing part of the population formed before this relatively long period has survived in the stream associated with the comet till now. However, only a small fraction of them are particles on the orbits in a collisional course with the Earth in a given moment. Such a particle moves on such an orbit typically for about 400 years. Then, it abandoms the collisional course and cannot be observed as an meteor in the Earth's atmosphere.

Table 1. The parameters of the theoretical streams modelled around the actual orbit of comet 96P/Machholz. T_o is the Julian date of the comet perihelion passage for which the stream is modelled; t_p is the corresponding approximative time counted from the present (epoch 1990.0) to T_o; $f_{0.1}$ is the fraction of the stream particles on orbits, which pass the Earth's orbit within the distance of 0.1 AU at the present; f_{qua} is the fraction of the stream particles on orbits, which pass the Earth's orbit within the distance of 0.1 AU at the present and, at the same time, the perihelion distance of these orbits is larger than 0.8 AU (these particles of the stream correspond to the Quadrantids); a_d and a_u are down and upper boundary, respectively, of the initial range of semi-major axis (i.e. the range in the moment of stream modelling); f_a is the fraction of the stream particles having their semi-major axis still within the interval from a_d to a_u at the present, i.e. in the end of the studied orbital evolution. The total number of the particles of each modelled stream is 4586.

T_o [JDT]	t_p [yr]	$f_{0.1}$ [%]	f_{qua} [%]	a_d [AU]	a_u [AU]	f_a [%]
620089.95	−5004	0.166	0.123	2.876	3.193	0.683
639136.40	−4952	0.137	0.096	2.854	3.197	0.694
656585.03	−4896	0.147	0.109	2.845	3.210	0.689
1095943.95	−3701	0.168	0.034	2.159	5.084	0.960
1515804.68	−2552	0.089	0.017	2.885	3.166	0.687
1899250.42	−1502	0.208	0.015	2.942	3.113	0.644
2265408.22	−500	0.044	0	2.856	3.269	0.914

4. The orbital evolution of the stream associated with 2003 EH1

4.1. Standard stream of 2003 EH1

Similar to the orbital evolution of the standard stream associated with 96P, for which the evolution is demonstrated in Figs. 1–3, the orbital evolution of the standard stream associated with the asteroid 2003 EH1 is demonstrated in analogous Figs. 7–9. The stream is obviously created in a different orbital-position phase of the main perturbing planet, Jupiter. This causes a shorter libration cycle in q, e, and i of the main part of the stream. In the appropriate plots a, c, and f of Fig. 7, respectively, we can observe more than two cycles, while in the corresponding plots a, c, and f of Fig. 1, displaying the evolution of the 96P stream, one can observe only an uncomplete cycle, whereby all the plots cover approximately the same periods of evolution.

In contrast to the evolution of the 96P stream, the 2003 EH1 stream does not seem to be so compact. In Fig. 7a, c, and f, we can see a formation of small but recognizable alternative strands.

In Fig. 8, there is demonstrated the evolution of that part of the stream, which approaches the Earth's orbit closer than 0.1 AU, and, in Fig. 9, there are the distributions of orbital elements of this part of the stream at the present (the dashed-line curves in the plots of Fig. 9 are identical to the upper curves in the corresponding plots of Fig. 8, but illustrated with a better resolution). As with the 96P stream, we assume that the strand with $q > 0.8$ AU corresponds to the Quadrantids. The distributions of the orbital elements of this strand are illustrated by the thick solid-line curves in Fig. 9.

In contrast to the Quadrantid-corresponding strand of the 96P standard stream, the mean $\langle\Omega\rangle$ and $\langle\omega\rangle$ of the Quadrantid-corresponding strand of 2003 EH1 standard stream (the theoretical mean values are indicated by the dotted vertical lines at the

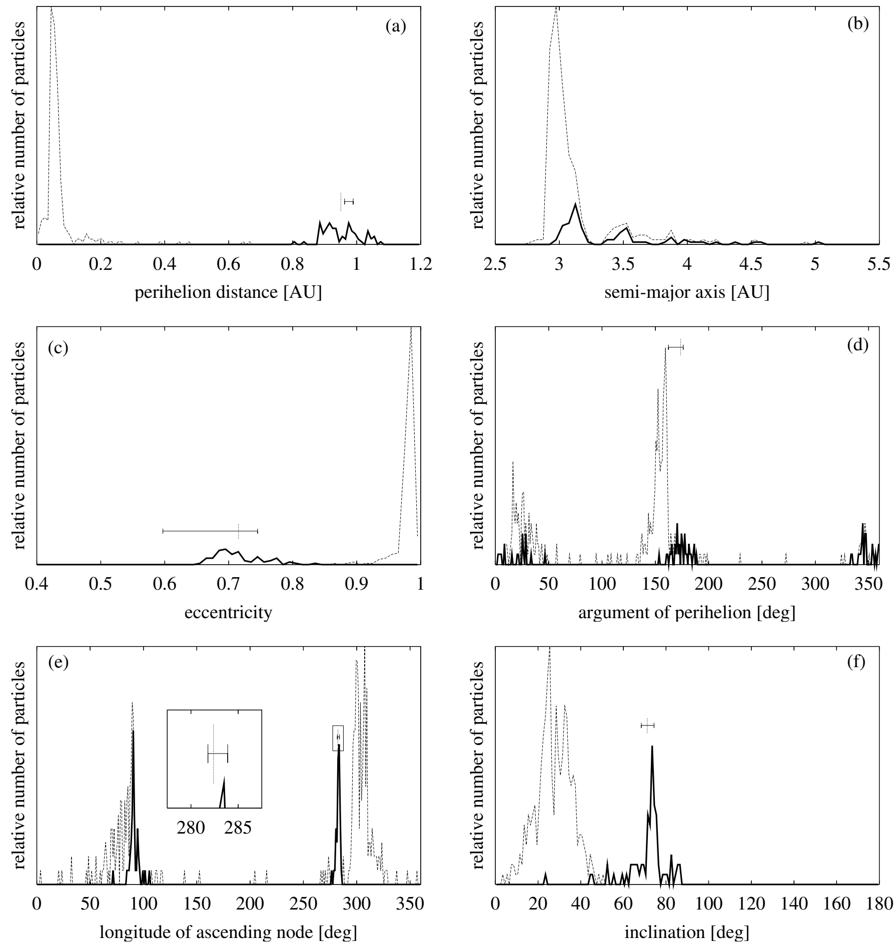

Fig. 5. The present-day (1990.0) distributions of orbital elements of the Earth-orbit approaching part of a theoretical stream associated with comet 96P/Machholz. The stream was modelled for the time of 96P perihelion passage, which happened ≈2550 years ago. Each distribution of the strand with perihelion distance, q, larger than 0.8 AU is illustrated with the solid line, while the distribution of the entire Earth-orbit approaching part of the stream is shown by the dashed curve. A short abscissa above the peak corresponding with the $q > 0.8$ AU-strand shows the range of mean values of the given element as published by various authors, with the determination uncertainties included. A short, vertical, dotted line indicates the mean value of the peak.

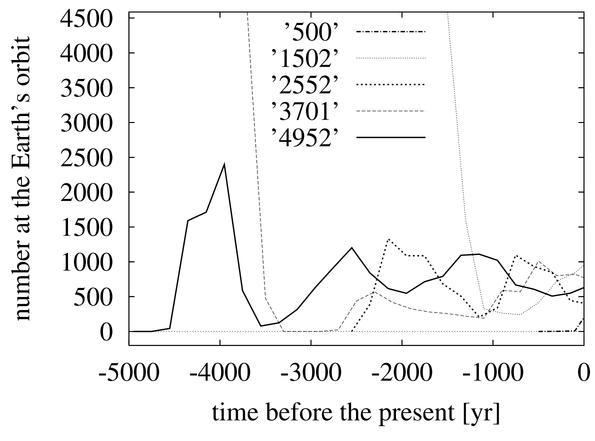

Fig. 6. The evolution of the population at the Earth's orbit of theoretical streams associated with the comet 96P/Machholz. The total number of considered particles of each stream is 4586. The evolution is illustrated for 5 streams modelled in the 96P-perihelion-passage times of ≈4950, ≈3700, ≈2550, ≈1500, and ≈500 years before the present (1990.0). Specifically, the numerousity of particles on the orbits approaching the Earth's orbit within 0.1 AU is diplayed.

tops of corresponding peaks) are outside of the interval of the observed mean values (horizontal abscisses at the tops of peaks). Moreover, if 2003 EH1 were the parent body of a large meteoroid stream, created 1000 $P_{\rm o}$ (≈4950 years) ago, with a part of this stream as observable on the Earth as Quadrantids, then we should also observe a diffuse shower with the Quadrantid-like $q \in (0.85$ AU, 1.1 AU$)$, $e \in (0.62, 0.80)$, and $i \in (60°, 80°)$ (Fig. 9, plots a, c, and f, respectively), but with a different interval $\Omega \in (88°, 93°)$ (Fig. 9e; period activity around June 21st) and a wider interval $\omega \in (155°, 200°)$ with the highest peak at $\omega \approx 187°$ (Fig. 9d). In the IAU MDC photograpic-meteor database (Lindblad et al. 2003), there are actually 70 meteors with q, e, and i in the above mentioned intervals, but no single one of these meteors has $\Omega \in (88°, 93°)$ and the interval of their ω spans from about 165° to 180°. No high maximum beyond the value of 180° is observed. These facts imply that the asteroid 2003 EH1 cannot be the parent body of those Quadrantids released about five millenia ago.

4.2. Another theoretical streams of 2003 EH1

With respect to the orbital evolution of 2003 EH1, we model another three appropriate theoretical streams of this asteroid. Specifically, the modelling is done in JDTs 841 928.83, 1 461 551.83, and 2 265 448.83, i.e. approximately 4400, 2700, and 500 years ago. The parts of these streams approaching the Earth's orbit within 0.1 AU, we are interested in, have their mean orbital elements similar to the corresponding orbital elements of the photographically observed Quadrantids. However, some fine differences can be noticed. The perihelion-distance and longitude-of-ascending-node distributions of these parts of the streams are illustrated in Fig. 10.

The part of the stream approaching the Earth's orbit modelled for the epoch of ≈4400 years ago does not have any recognizable strand with the mean $\langle\Omega\rangle \approx 90°$ (Fig. 10b),

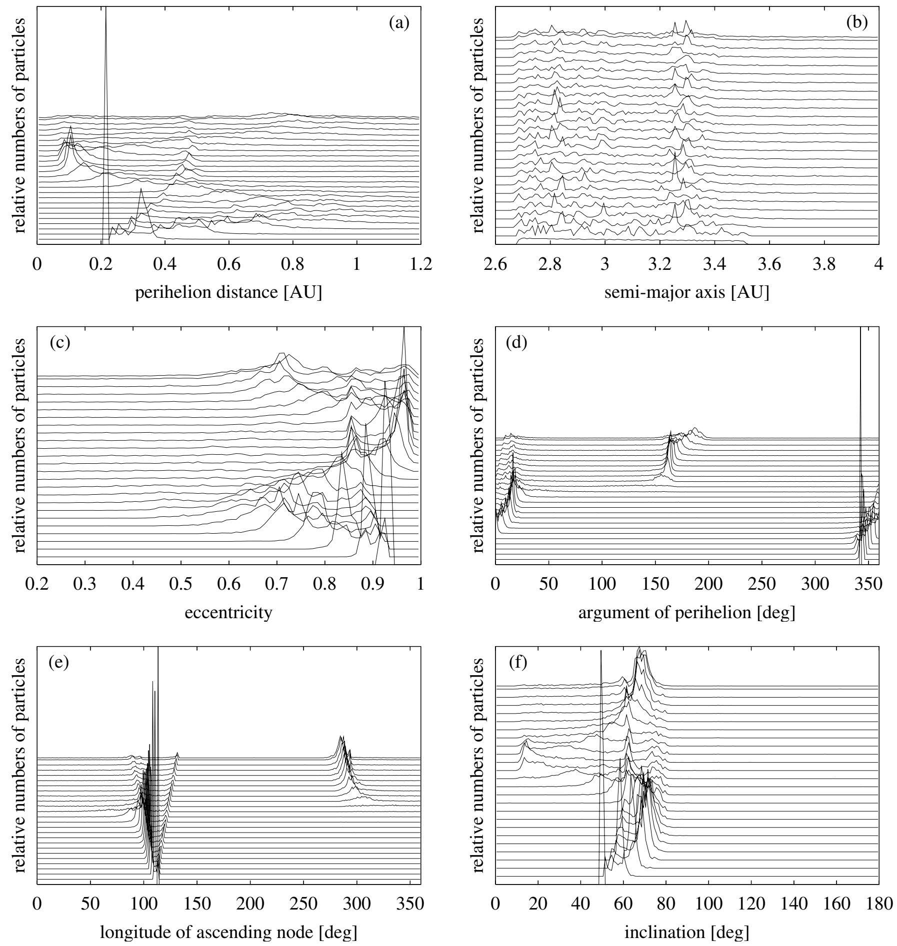

Fig. 7. The evolution of the distributions of orbital elements of a teoretical stream associated with asteroid 2003 EH1. The stream is modelled for the time of 2003 EH1 perihelion passage being closest to the time of 1000 P_o ago, where P_o is the orbital period of a body on the mean orbit of Quadrantids. The bottom curve illustrates the distribution in the moment of the modelling, while another successive curves above this curve illustrate the distributions separated with the interval of 200 years. The upper-most curve does so for a less separation of 52 years, i.e. 4952 years after the modelling (exactly in epoch 1990.0).

which is predicted at the standard stream. The main peak in the ω-distribution corresponds with the mean $\langle\omega\rangle$ of observed Quadrantids. If the meteoroid particles were released during a period around the time of ≈4400 years ago, then 2003 EH1 could be the parent of this meteor shower.

Also the parts of the streams approaching the Earth's orbit, which are modelled for the periods of ≈2700 and ≈500 years ago, do not have the strand with the mean $\langle\Omega\rangle \approx 90°$ (Fig. 10d, f) and their main peaks in the ω-distribution correspond to the observed mean values. Both these parts are compact, single-strand sub-streams. For the part of the first (≈2700-years-ago) stream, the mean $\langle q\rangle = 0.993$ AU (Fig. 10c) and mean $\langle\Omega\rangle = 284.39°$ (Fig. 10d). Both the values are above the corresponding observed upper border (0.989 AU and 283.89°, respectively). The $\langle q\rangle$ being too high is an effect of the chosen limit of the particle approach to the Earth's orbit. In reality, the meteors having their perihelion distance beyond the Earth's aphelion distance cannot belong to any observable meteor shower. If the limit of 0.1 AU is reduced to, e.g., 0.05 AU, then the mean perihelion distance occurs to be reduced from 0.993 to 0.981 AU, which is inside the observed interval of mean $\langle q\rangle$. The mean longitude of the ascending node is, however, equal to 284.34°, still above the upper limit of acceptable observed mean values. It indicates that 2003 EH1 cannot be the parent of Quadrantids, if the stream was created during a period around the time of ≈2700 years ago.

Asteroid 2003 EH1 could significantly contribute to the observed Quadrantid shower, if a release of the meteoroid particles from its surface was an event that happened not much earlier than several centuries ago. The mean elements predicted for the Earth-orbit approaching (within 0.05 AU) part of the stream modelled ≈500 years ago well agree with the observed mean orbital elements of Quadrantids (Fig. 10e, f). (For the limit of the approach within 0.1 AU, the particles with q beyond the Earth's aphelion again cause an increase of the mean $\langle q\rangle$ above the upper observed limit.) However, there are no predicted strands with small q (Fig. 10e), corresponding with the Daytime Arietids and the Southern δ-Aquarids (see Sect. 7 for a general discussion), therefore another parent is necessary, anyway.

5. A relationship between 96P and 2003 EH1

In the previous sections, we found that both comet 96P/ Machholz and asteroid 2003 EH1 occupy the same orbital-element phase space. In some periods, their orbits could have been very similar. This implies a possibility that these bodies might originate from a common progenitor, which could have split sometime in the past. In this section, we investigate this possibility.

If the progenitor existed and split, then (i) the orbit of both bodies had to be very similar in a moment in the past and (ii) both bodies had to be in the same position (measured by, e.g., true anomaly) on their orbits. Since neither the orbit of 96P nor that of 2003 EH1 are known with perfect precision, we proceed in following two steps.

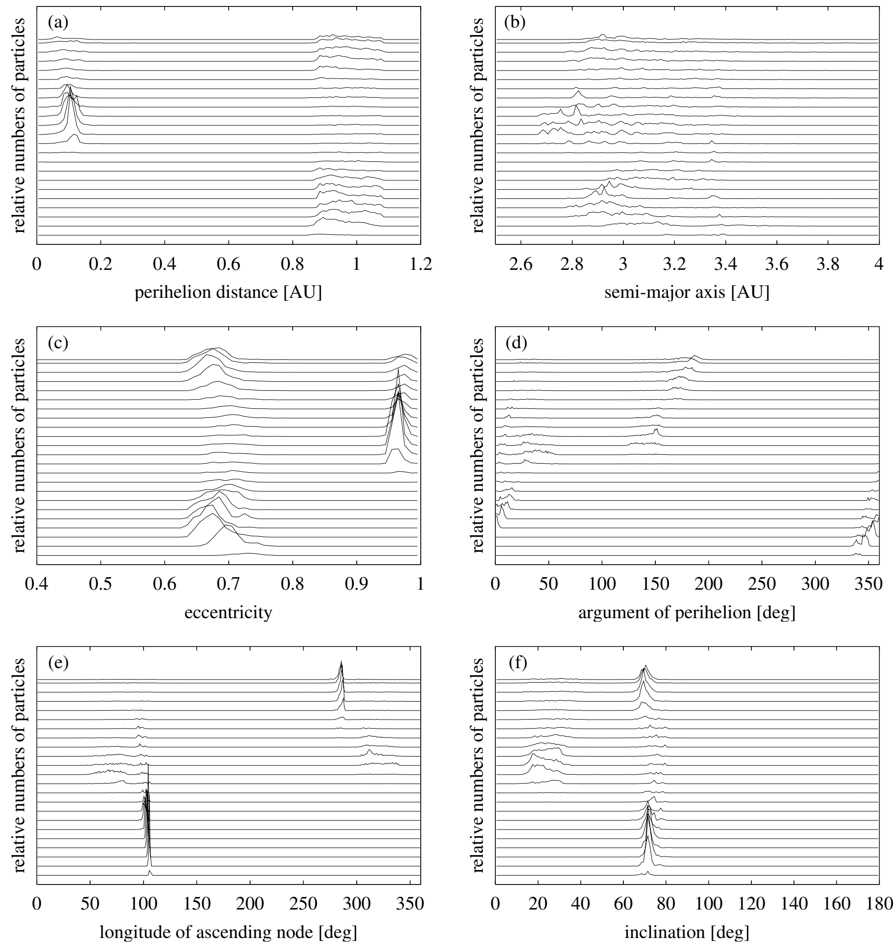

Fig. 8. The evolution of the distributions of orbital elements of that part of a theoretical stream mentioned in the caption of Fig. 7, the orbits of which approach the Earth's orbit within 0.1 AU. During the first ≈500 years after the modelling, no test-particle orbit passed within this limit, therefore the bottom curve here illustrates the distribution in the time of 600 years after the modelling and successive curves above this curve illustrate the distributions separated with the interval of 200 years. The upper-most curve does so for a less separation of 52 years, i.e. 4952 years after the modelling (exactly in epoch 1990.0).

5.1. Step A: uncertainty of the orbit of 96P

We create the clones moving in orbits very similar to the 96P's orbit. Specifically, the clones are created by the procedure described in Sect. 2, whereby the release of the particles from the 96P nucleus is assumed to happen at the moment of the perihelion passage of 96P in JDT = 2 448 459.32 (1991, July 21.82). The orbits of clones represent possible alternative orbits, on which 96P could move due to the uncertainty of the determination of its known current orbit or due to changes in this orbit that is influenced by the non-gravitational effects. The motion of the clones, 96P, as well as 2003 EH1 is integrated over the period of 1000 $P_{\rm o}$ backward in time. An output from the integration is made every 100 years. Using the Southworth-Hawkins D-discriminant (Southworth & Hawkins 1963), a comparison of the orbital similarity between the orbits of each of the clones and 2003 EH1 is made for each output.

The best found agreements between the orbit of a clone and the orbit of 2003 EH1 are given in Table 2, part I. They occurred about 4500 Julian years ago. The degree of the similarity is high enough. (The difference between the orbits of 2003 EH1 and clone, ranging in terms of D from 0.056 to 0.063, can be compared to the dispersion of meteors in the central, compact parts of major meteor showers as, e.g., Perseids, Geminids, Orionids, Quadrantids, and Leonids, which can be characterized with D = 0.32, 0.10, 0.20, 0.14, and 0.17, respectively (Neslušan et al. 1995).) It implies that the first condition for the common origin, the similarity of orbits, is satisfied.

For a comparison, the orbit of 96P for the same epoch is given in Table 2, part I, too. The orbit of the comet itself is considerably diverse from that of 2003 EH1. Here, one can see the situation, when a very small difference between the determined and possible orbits at the present can lead to extremly different orbits in the past. While the diversity between the orbits of clone No. 3616 (Nos. 1596, 1594) and parent comet 96P can be characterized by D = 0.00509, (0.00378, 0.00362) at the moment of modelling the theoretical stream at the present, this diversity at the time of 4500 Julian years ago rises to D = 1.78 (1.76, 1.79).

To find en even more appropriate orbit than that of clone No. 1596, on which a clone of 96P approaches 2003 EH1, we model another theoretical set of clones around the orbit of clone No. 1596 for the clone's perihelion passage at the present. The clone is chosen because it has the smallest diference between its true anomaly and that of 2003 EH1 (see Table 2). The initial dispersion of ejection velocities is chosen to be 0.001 of the No. 1596 perihelion velocity, instead of the factor of 0.0025, in order to refine our search. We find that the new clones Nos. 2675, 3472, and 2795 approach 2003 EH1 at a distance of 0.0027, 0.0046, and 0.0059 AU in 2466 B.C., on May 20, 23, and 14, respectively.

5.2. Step B: uncertainty of the orbit of 2003 EH1

We create the clones moving in orbits very similar to the 2003 EH1's orbit. The release of the particles from the asteroid is assumed to happen when the asteroid passed its perihelion in JDT = 2 448 647.41 (1992, January 25.91). Again, the orbits of clones represent possible alternative orbits, on which 2003 EH1

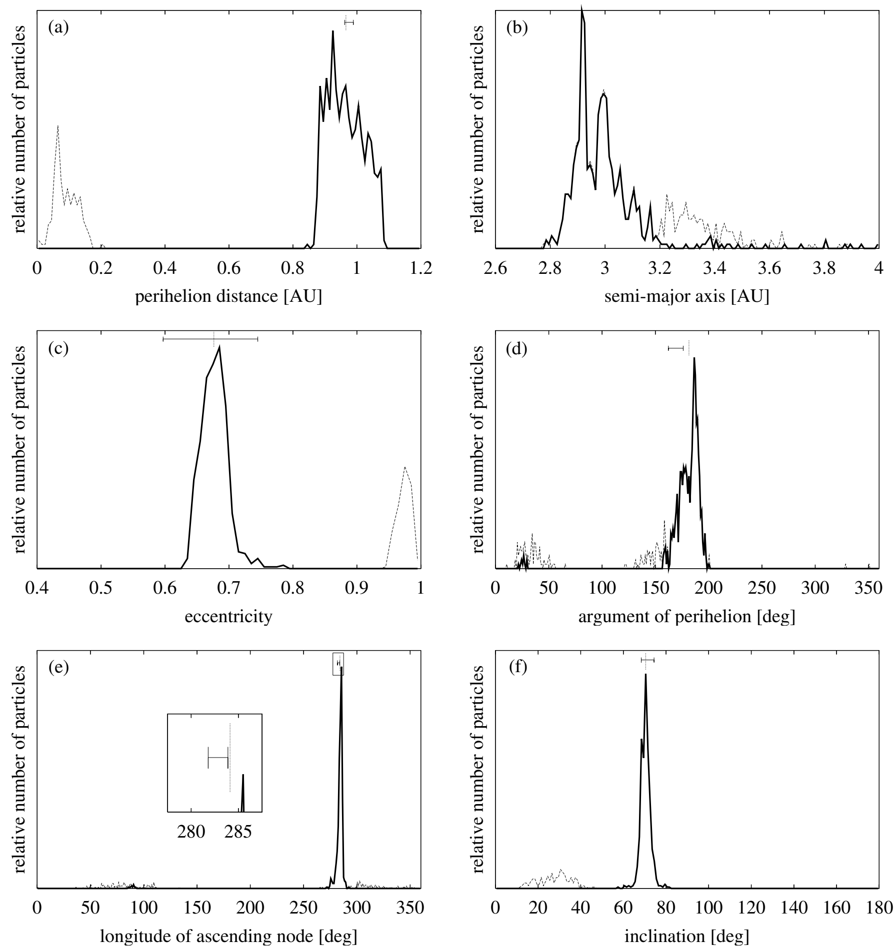

Fig. 9. The distributions of orbital elements of the Earth-orbit approaching part of a theoretical stream associated with asteroid 2003 EH1. The stream was modelled for the time as in Fig. 7. Here, we more transparently illustrate the current (1990.0) distributions, which are shown in Fig. 8 by the upper-most curves in the corresponding plots. Each distribution of the strand with perihelion distance, q, larger than 0.8 AU is illustrated with the solid line, while the distribution of the entire Earth-orbit approaching part of the stream is shown by the dashed curve. A short abscissa above the peak corresponding with the $q > 0.8$ AU-strand shows the range of mean values of the given element as published by various authors, with the determination uncertainties included. A short, vertical, dotted line indicates the mean value of the peak.

could move due to the uncertainty of the determination of its known current orbit or, possibly, due to the non-gravitational effects, if this body once was an active comet. The motion of the clones, 2003 EH1, as well as comet 96P is integrated over the period of 1000 P_o backward in time. Also the rest of the procedure is analogous to that performed in step A. The orbits of the 2003 EH1's clones being most similar to the orbit of 96P are given in Table 2, part II. The diversity measured by the D-discriminant ranges from 0.012 to 0.039. So, we are able to find very similar orbits in this case, too.

To also find a good agreement in the position, we model new sets of clones around the orbits of two presented clones: Nos. 1020 and 0713. The orbit of clone No. 1020 is most similar, at the time of 4900 Julian years ago, with the orbit of 96P, but the true anomaly of these bodies differs about 46°. The closest values of the true anomaly occur between the second similar-orbit clone, No. 0713, and 96P. These values differ by about 15°. The initial velocity disperion is again chosen to be 0.001 multiple of the No. 1020 or No. 0713 perihelion velocity. Integrating the new clones backward and monitoring the distance between each of them and 96P, one can find that no new clone associated with the old clone No. 1020 approaches 96P at a distance closer than 0.09 AU. A better result is obtained for the old clone No. 0713. New clones Nos. 1545, 1170, and 2881 associated with this old clone approach 96P at the distance of 0.0044, 0.0059, and 0.0073 AU in 2110 B.C. March 7, 2126 B.C. May 1, and 2116 B.C. December 3, respectively.

Our above described results prove that the comet 96P and asteroid 2003 EH1 could actually not only be in very similar orbits, but at a very close distance. This permits an assumption that they could be a single body that split in the past. However, our procedure and its results do not prove the split. Among a number of clones of each set, there are clones with a large difference in their position on the orbit (i.e. with a large difference in true anomaly). A coincidence of the position of a clone with the compared orbit of 2003 EH1 (step A) or 96P (step B) can occur by chance. Moreover, we found more coincidences in different times. Good proof of the splitting would require a single convergence of orbits and positions of the bodies on these orbits. We suggest that the potential relationship between 96P and 2003 EH1 cannot be proved within an exclusively dynamical study. The question of the common origin will, perhaps, be able to be answered after including a study of physical properties of these bodies in the investigations.

6. Another two Quadrantid-parent-body candidates

To demonstrate an exceptionality of 96P and 2003 EH1 as the candidates for the Quadrantid-meteor-shower parent body, we also search, performing the same procedure, for a possible relationship between another two parent-body candidates and Quadrantids. We select one cometary (comet C/1939 B1) and one asteroidal (asteroid 5496) representant.

6.1. Comet C/1939 B1

As mentioned in Sect. 1, the comet C/1939 B1 (Kozik-Peltier) was suggested as a possible parent body of the Quadrantids by

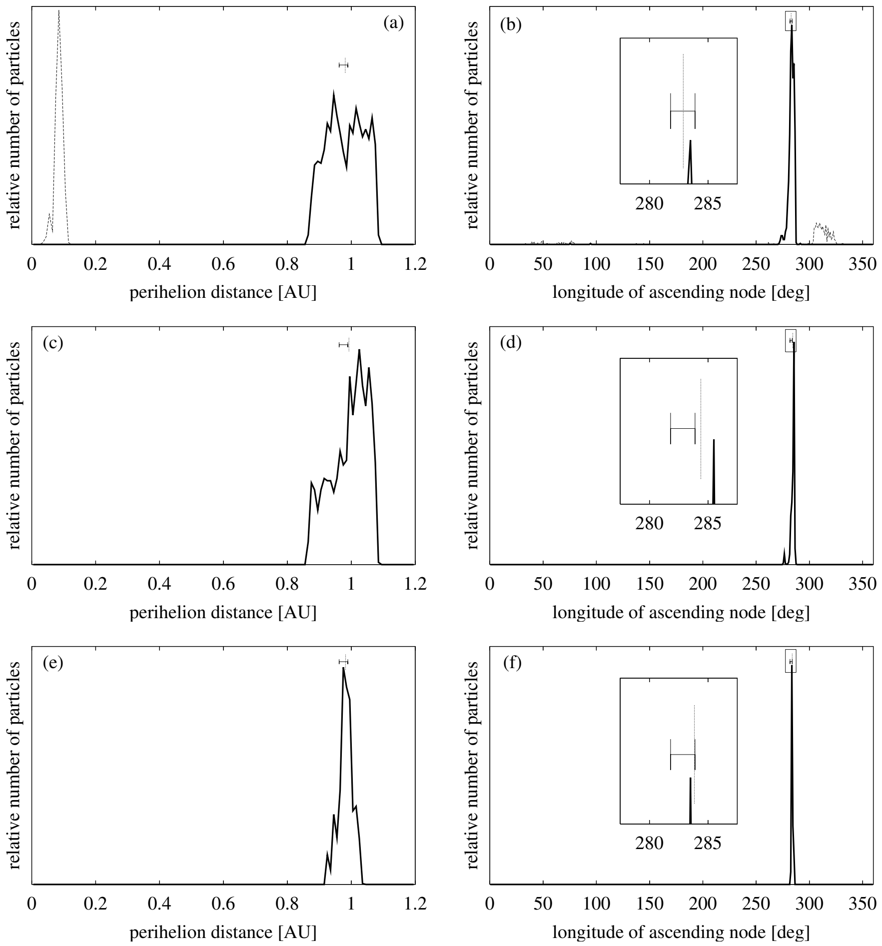

Fig. 10. The q (left plots, a, c, and e) and Ω (right plots, b, d, end f) distributions of the Earth-orbit approaching part of the theoretical streams associated with asteroid 2003 EH1 at the present (1990.0). The streams are modelled for the moments of 2003 EH1 perihelion passages, which happened ≈4400 (plots a and b), ≈2700 (plots c and d), and ≈500 (plots e and f) years ago. A short abscissa at the upper border of the plots shows the range of mean values of the given element as published by various authors, with the determination uncertainties included. A short, vertical, dotted line indicates the found mean value of the strand corresponding with the Quadrantid shower. The limit of the approach to the Earth's orbit is 0.1 AU for the first two streams (plots a to d) and 0.05 AU for the third stream (plots d and f).

Table 2. The closest similarities between (part I:) the orbits of asteroid 2003 EH1 and a clone of comet 96P, (part II:) the orbits of comet 96P and a clone of asteroid 2003 EH1. For a detailed explanation, see the text of Sect. 5. Used symbols: q, e, ω, Ω, and i − orbital elements, f − true anomaly, D − D-discriminant between the osculating orbits in the corresponding times of (part I:) 2003 EH1 and clones (96P), (part II:) 96P and clones (2003 EH1). The time is counted in the Julian years from (part I:) JDT = 2 448 459.32 (July 21, 1991; perihelion passage of 96P), and (part II:) JDT = 2 448 647.41 (January 26, 1992; perihelion passage of 2003 EH1).

body	time [yr]	q [AU]	e	ω [deg]	Ω [deg]	i [deg]	f [deg]	D
				part I: orbits of 2003 EH1 and clones of 96P				
2003 EH1	−4500	0.62899	0.79854	341.876	107.476	65.255	180.114	
clone No.3616	−4500	0.62928	0.81145	343.364	109.823	66.423	208.500	0.05625
clone No.1596	−4500	0.61426	0.81736	343.402	109.812	64.980	177.065	0.05670
clone No.1594	−4500	0.66203	0.80257	343.257	109.863	66.322	197.617	0.06314
96P	−4500	0.23780	0.92144	195.359	274.632	55.406	319.573	1.77901
				part II: orbits of 96P and clones of 2003 EH1				
96P	−4900	0.46242	0.84671	193.539	277.971	64.855	161.596	
clone No.1020	−4900	0.46089	0.84650	193.331	277.371	64.730	115.532	0.01198
clone No.0899	−4900	0.45623	0.84710	191.704	279.025	64.907	202.110	0.02715
2003 EH1	−4900	0.21993	0.92731	342.829	112.085	51.854	187.513	1.71047
96P	−4200	0.11976	0.96049	199.744	267.586	40.038	193.004	
clone No.0713	−4200	0.10814	0.96319	196.481	270.463	40.035	177.475	0.03875
2003 EH1	−4200	0.80774	0.73420	345.336	105.179	70.786	196.090	1.78439

Bouška (1953). Though the semi-major axis, a, of this comet is much larger than that of Quadrantids and Lovell (1954) already rejected its relationship with the shower, we return to this parent body candidate in the context of the findings by Wu & Williams (1995) that the Perseid meteoroid stream has dispersed into several strands, situated near the mean-motion resonances with the Jupiter and Saturn, which have considerably different mean semi-major axes than the mean semi-major axis of the main part of the stream near the orbit of the Perseid parent. Kaňuchová et al. (2005), who studied the evolution of the Perseid stream in more detail, revealed four stream filaments with the mean $\langle a \rangle$ from ≈3.3 to ≈4.5 AU, while the most recent semi-major axis of the parent comet, 109P/1992 S2 (Swift-Tuttle), equals 26.3 AU (Marsden & Williams 2003). This difference can be the precedent of a parent body on a different orbit than the associated meteoroid stream. Such precendent implies that the large difference alone, between a of C/1939 B1 and Quadrantids, does not discriminate C/1939 B1 as the parent of the stream.

Modelling the standard theoretical stream of C/1939 B1 and monitoring its dynamical evolution from the time of the modelling untill the present, we, however, find no relationship to the Quadrantids. At the present, no particle of the theoretical stream approaches the Earth's orbit closer than 0.24 AU. We regard this fact as a sufficient reason to reject the comet C/1939 B1 as the Quadrantid parent.

6.2. Asteroid 5496

Williams & Collander-Brown (1998) suggested that there is a strong case that can be made for an association of asteroid 5496 (1973 NA) and the Quadrantid stream (see also Williams et al. 2004). Applying the procedure described in Sect. 2 to model a standard theoretical stream of this asteroid, we cannot confirm such an association, however.

No particle approaches the Earth's orbit for about 1000 years after the time of modelling. Then the predicted population of the part approaching the Earth's orbit increases up to 99.4% of the entire modelled stream, in 1800 years after the modelling, and slowly disappears by 2800 years after the modelling. Another period of its increase begins in about 3400 years. At present, the predicted population seems to be closely after another culmination time and reaches 53.5% of the entire stream. The predicted meteor shower is quite compact having the orbital elements in the intervals: $q \in (0.72, 0.90)$ AU, $e \in (0.63, 0.66)$ (for a very small part $e \in (0.66, 0.71)$), $\omega \in (116°, 123°)$, $\Omega \in (100°, 109°)$, and $i \in (64°, 69°)$. So, the mean orbit is clearly different from the mean orbit of Quadrantids.

The prediction of the theoretical stream associated with the asteroid 5496 implies a possibility that this body could be the parent of another real meteor shower. In the IAU MDC photographic database (Lindblad et al. 2003), no single meteor orbit, however, matches the listed intervals. The asteroid had to be an inactive body several millenia ago. (Maybe, a more detailed study, comprehending the modelling for more recent dates (which exceeds the goal of this work) could predict a different corridor with some actually observed meteors.)

7. Conclusions

Our study of the dynamical evolution of theoretical streams associated with the comet 96P/Machholz and asteroid 2003 EH1 proves that one of these bodies or both are the parents of the Quadrantid meteor stream. This conclusion is supported by the remarkably high level of agreement between the predicted and observed mean orbital elements of Quadrantids. We thus confirm the original suggestions by McIntosh (1990) and Jenniskens (2004), and strenghten the proof by Babadzhanov & Obrubov (1992), concerning the comet 96P as the parent of Quadrantids.

A more certain conclusion about which body was dominant in the stream creation or whether the supply of meteoroids from both bodies was significant cannot be drawn because of the uncertainty in the determination of their orbits and the unknown non-gravitational effects. If we assume that the known, catalogue orbits of 96P and 2003 EH1 are the actual, extremly precisely determined orbits and that non-gravitational effects have been negligible during the studied dynamical evolution of large, photographically detectable, stream particles, then the following claims are possible.

Those meteor particles of the stream, impacting the Earth at the present time, which would have originated from 96P, would have been released from the nucleus of this comet earlier than about 3900 years ago. We demonstrated a long life-time of the particles inside the main corridor of the stream.

The asteroid 2003 EH1 could be a single parent of the stream, if the meteoroid particles were released, at a large rate, during a period around ≈4400 years ago, but later, during a period around ≈2700 years ago, the body was inactive. It could have become active again not much earlier than ≈500 years ago. During the period around ≈2700 years ago, the asteroid would have created a strand of stream approaching the Earth's orbit, which would be characterized, at the present, by a value of mean $\langle\Omega\rangle$ different from the actually observed mean $\langle\Omega\rangle$ of the Quadrantids. Such a stream is not observed. So, the idea that 2003 EH1 is the single Quadrantid parent does not seem to be acceptable. We would have to assume that 2003 EH1, being an asteroidal body today, was actively releasing the meteoroids more than 4 millenia ago, but the cometary body 96P was inactive during approximately the same period.

Jones & Jones (1993) revealed a dynamical relationship between the Quadrantids and small-q showers Daytime Arietids and Southern δ-Aquarids. All these streams should have a common parent body. Under our assumption based on known orbits, the asteroid 2003 EH1 could have produced the Quadrantid stream in the period around ≈500 years ago, but it would not have simultaneously produced the small-q streams, during this period. Therefore, another body would have had to be required for all the mentioned streams to be observed.

Under the above mentioned assumptions, the comet 96P/Machholz would certainly have to be the parent body of the Quadrantids. Asteroid 2003 EH1 could contribute to the stream. This contribution could have been released from its surface either during a period 4 millenia ago, when it could perhaps have been an active comet, or during a period not very distant from the time of 500 years ago. In agreement with Williams & Collander-Brown (1998), we can conclude that a large population of the Quadrantid stream had to be released from a parent (or parents) at least few millenia ago. If the Earth is also impacted with younger, several-century-old particles, these originate from the asteroid 2003 EH1. However, this young population can represent only a fraction of the entire Quadrantid-shower population. (Since this asteroid was not known in the time of Williams & Collander-Brown's work, they suggested a splitting of a single parent into 96P and another fragment which evolved with Quadrantids, possibly the comet C/1490 Y1.)

We also studied the relationship between the comet 96P and asteroid 2003 EH1. Within our study, it appeared that 96P could have been, several millenia ago, on the orbit on which 2003 EH1 was on, if the current 96P's orbit were known for a fact and not changing due to the non-gravitational effects. Even a very small change in the catalogue orbit of 96P can lead to a quite different orbit (though always in the Quadrantid-orbital-element phase space) in the past. All this is also valid vice versa: asteroid 2003 EH1 could have been, in the past, on the orbit of 96P. Therefore, our conclusions based on the perfectly precise and unchanging orbits are valid, but they cannot be related to the first or second specific body.

The just mentioned fact that 96P could have been, in the past, on the orbit of 2003 EH1 and/or vice versa means that we found some routes supporting the idea that 96P and 2003 EH1 originated from a common progenitor, which split sometime in the past. In other words, we found a few explanations how the orbits of both bodies can be very similar and the positions of the bodies on these orbits were almost identical in the identical times. However, our result cannot be regarded as proof that the split did actually happen. In the common orbital-element phase space, controlled by Jupiter, the found orbital and position proximities can be a matter of a random coincidence. For actual proof, we should obtain a single convergence of the orbits and positions at a single time no matter which investigation is used. Such a convergence did not, however, occurred in our procedure. To prove or disprove the common origin of 96P and 2003 EH1, an inclusion of a comparative study of the physical properties of these bodies seems to be necessary.

To better document an exceptionality of 96P and 2003 EH1 as the parent bodies of the Quadrantids, we also investigated two another Quadrantid-parent candidates suggested by other authors: comet C/1939 B1 (Kozik-Peltier) and asteroid 5496 (1973 NA). According our results, the comet C/1939 B1 cannot be the parent of any meteoroid stream crossing the Earth's orbit. The asteroid 5496 could produce an Earth-orbit-crossing stream, but we found no single meteor in the photographic meteor-orbit database matching the predicted intervals of orbital elements. It implies that 5496 is likely an inactive body, not associated with any meteoroid stream.

Because of the poor orbit determination, we did not investigate the comet C/1490 Y1 (old designation: 1491 I) as the parent of the Quadrantids. It was obviously a body on an orbit within the corridor of the stream associated with 96P. We can expect that the uncertainty of the orbit is large enough for a demonstration of some routes supporting the ideas suggested by other authors earlier: (i) C/1490 Y1 contributed, at least in a certain period, to the Quadrantid stream (Hasegawa 1979), (ii) it separated from a common progenitor of 96P, C/1490 Y1 (Williams & Collander-Brown 1998), and, possibly, 2003 EH1, (iii) 2003 EH1 is the extinct nucleus of C/1490 Y1 (Jenniskens 2004). None of these ideas could, however, be properly proved by an exclusively dynamical study taking into account the available data.

Our study brings strong evidence about the comet 96P/Machholz and, possibly, asteroid 2003 EH1 as the Quadrantid-stream parent bodies. Though there is no longer a need for another parent body or bodies, we, however, still cannot exclude the existence of such, still unidentified, bodies contributing to the stream. The comet C/1490 Y1 might be one of them. Other possibilities were indicated by Wu & Williams (1992), who also used radar data in their study of a fine structure of the Quadrantids which revealed five substreams. Therefore, a search for other Quadrantid-parent candidates as well as a study of the stream fine structure still remain to be done.

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