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The Quadrantid meteoroid complex

Paul Wiegert [*], Peter Brown

Department of Physics and Astronomy, The University of Western Ontario, London, Ontario N6A 3K7, Canada

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Abstract

The Quadrantids, one of the more active of the annual meteor showers, is unusual for its strong but brief maximum within a broader background of activity. It is also notable for its recent onset, the first observation having been likely made in 1835. Until recently, no parent with a similar orbit had been observed and previous investigators concluded that the stream was quite old, with the stream's recent appearance and sharp peak attributed to a fortuitous convergence of meteoroid orbits. The discovery of the near-Earth Asteroid 2003 EH1 on an orbit very similar to that of the Quadrantids has probably unveiled the parent body of this stream [Jenniskens and Marsden, 2003. 2003 EH1 and the Quadrantids. IAU Circ. 8252]. From simulations of the orbit of this body and of meteoroids released from it at different intervals in the past, we find that both the sharp peak and recent appearance of the Quadrantids can most easily be explained by a release of meteoroids from 2003 EH1 near 1800 AD. This is supported by three lines of evidence. First, the evolution of the observed solar longitude of the Quadrantids over time is consistent with release from 2003 EH1 approximately 200 years ago. Second, numerical simulations of meteoroids released from this parent body at this time match the basic orbital characteristics of the Quadrantid stream well. Finally, these simulations also reveal that the Quadrantid core is well reproduced by a single outburst at perihelion circa 1800, whereas earlier releases result in the shower's appearance in our skies significantly prior to 1835. These results apply to the concentrated central core of the stream: the extended background was likely produced at earlier times. In fact, we find that 2003 EH1 is in a state of Kozai circulation along with a number of other comets and NEAs which may form a larger Quadrantid complex. Using the current total duration of the broader background Quadrantid activity compared to our simulations, we suggest a minimum age of ~3500 years for the stream as a whole. This also represents the approximate lower limit for the age of the complex. We have further identified five comets as well as nine additional NEAs which may be part of the aforementioned complex, the latter all having Tisserand parameters less than three, further suggesting that the are extinct comet nuclei.

Keywords: Asteroids, 2003EH1; Meteors, Quadrantids

1. Introduction

The Quadrantids are among the strongest of the annual meteor showers. Unlike the Geminids and Perseids, however, the stream shows several peculiar features. Among these features are sharp, short-duration maxima and a very recent appearance in terrestrial skies (cf. Williams et al., 1979). The main activity of the stream is confined to a 12 to 14 h window near maximum, but some extended stream activity is visible for ∼ ±4 days centered around this date based on radar data. The central portion of the stream is certainly young based on its duration alone (as noted by Jenniskens et al., 1997), but the broader stream has a nodal spread most consistent with a much older stream (cf. Jones and Jones, 1993). Records prior to the early 19th century, (1835) do not show any evidence of Quadrantid activity (Quetelet, 1839) an observation previously interpreted as a consequence of the rapid evolution of the node of the stream (Williams et al., 1979). There are also hints that the strength of the shower may change from year-to-year (McIntosh and Simek, 1984), although some of this variability is likely the result of the short duration of the stream and differences in its visibility from any one location from year-to-year. Perhaps the most puzzling aspect of the shower, how-

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[*] Corresponding author. Fax: +1 519 661 2033.
E-mail addresses: pwiegert@uwo.ca (P. Wiegert), pbrown@uwo.ca (P. Brown).

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ever, has been the apparent lack of a clearly related parent body for the Quadrantids. Many attempts have been made to find a parent body association, and the shower has received extensive modeling attention over the last 25 years. Indeed, it has been suggested that the Quadrantid meteor shower is associated with Comet 96P/Machholz (McIntosh, 1990; Babadzhanov and Obrubov, 1992; Gonczi et al., 1992; Jones and Jones, 1993), although the difference their current orbital elements implies that the stream must have originated between 2000–5000 yrs ago. The Quadrantids have also been connected to Asteroid 5496 (1973 NA) (Williams and Collander-Brown, 1998), Comet C/1490 Y1 (Hasegawa, 1979; Williams and Wu, 1993) and Comet Liais [which split in 1860, Pokrovsky and Shaine (1919), cited in Fisher (1930)] among others [see Williams et al. (2004) for a discussion of the less likely candidates].

Past models of the stream have suggested it is part of a broader complex. In particular, the present location of the stream is in a dynamically "hot" zone, where close approaches to Jupiter may cause particularly rapid orbital evolution. Given sufficient time (of order millenia) orbital evolution may produce up to eight additional streams as noted by Babadzhanov and Obrubov (1992). The dynamical richness of the stream makes modeling interpretations particularly difficult.

Jenniskens et al. (1997) have argued for a much younger age of the stream (500 years) than past modeling efforts have suggested (2000–5000 years). It is important to emphasize that this suggestion applies to the central portion of the stream; the broader longer-lived background activity is likely much older. More recently, Jenniskens (2004) was the first to note that 2003 EH1 has an orbit much closer to the original stream orbit than past parent body suggestions. On this basis, he suggests that 2003 EH1 is the direct, recent parent of the central portion of the Quadrantid shower and provides an age estimate of 500 years based on comparisons with earlier modeling efforts constrained primarily by the observed width of the core of the stream.

Asteroid 2003 EH1 has an absolute magnitude $H = 16.8$ which corresponds to a diameter of 1.3–2.9 km for an assumed albedo of 0.2 (S-type) or 0.04 (C-type), respectively. Its mass is thus $1\text{–}30 \times 10^{15}$ g for a density of 1–2 $\mathrm{g\,cm^{-3}}$. This value is larger than previous estimates of the Quadrantid stream mass [$4.6 \times 10^{12}\text{–}1.3 \times 10^{15}$ g, Hughes (1974); Hughes and McBride (1989); Jenniskens (1994)], so in this regard 2003 EH1 is consistent with being the true parent of the stream rather than a fragment thereof.

Here we investigate the likely age for the association between 2003 EH1 and the Quadrantids through numerical integration of hypothetical meteoroids released from the proposed parent. We also present new radar data for the orbit of stream particles of mass $\approx 10^{-5}$ g. After investigating the complex orbital dynamics associated with the shower, we suggest that some smaller meteoroids may be trapped in the 2:1 mean-motion resonance (MMR) with Jupiter and display different nodal retrogression rates as a result. Close approaches to Jupiter are also a factor in the dynamics as the orbits have their aphelion close to that giant planet (see Fig. 1).

We propose a picture of the stream which is dominated by hierarchical fragmentation of the original parent body over the course of several millenia, with 2003 EH1 being just one fragment of this decay process. This is a scenario similar to that proposed for the Taurid meteoroid complex (Steel et al., 1991). The shower as a whole we suggest is close to 10 thousand years old based on the total spread of the nodes for broader Quadrantid activity when compared to previous modeling work. The central portion of the stream is much younger however, due to 2003 EH1 having been "activated" ≈200 years ago, in qualitative agreement with the scenario outlined by Jenniskens (2004). We also propose that the first visibility of the stream in the early 19th century is not the

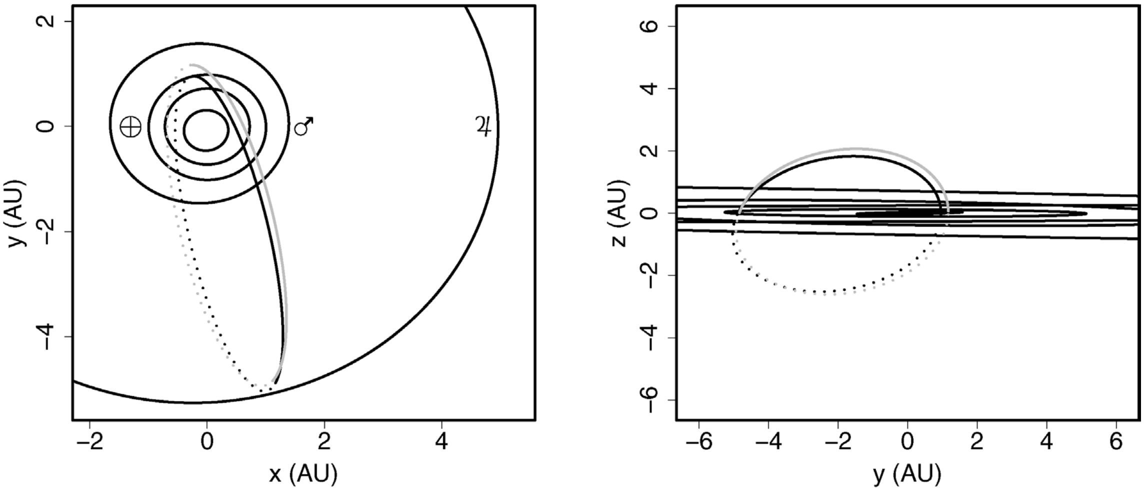

Fig. 1. A plot of the orbits of the Quadrantid shower (black) and 2003 EH1 (gray) in the standard coordinate system. The dotted lines indicate where the orbits pass below the ecliptic.

result of the stream's nodal evolution, but is representative of the epoch of injection of material from 2003 EH1.

2. Radar observations of the Quadrantids

Observational data related to the stream include extensive visual counts of the shower, which have provided flux information [see Rendtel et al. (1995) for a summary], as well as multi-station photographic and video observations (cf. Jenniskens et al., 1997) which have provided accurate orbits for larger stream members (mg to g size).

The Quadrantids have also been examined using radar since 1947 (Hawkins and Almond, 1952). Several major radar studies have been performed on the stream, most notably by Hawkins and Almond (1952); Millman and McKinley (1953); Bullough (1954); Poole et al. (1972); and McIntosh and Simek (1984). The location of the maximum for Quadrantids observed by radar has been measured in these and other studies, but with much scatter, and even differing interpretations from different years for the same radar systems [e.g. Poole et al. (1972) compared to Hughes and Taylor (1977)]. Fig. 2 is a compilation of reported locations of radar and visual maxima from past work. A least-squares fit to the nodal regression rate yields −0°.0034 ± 0°.0015 per year. This differs from the earliest assessments, which placed the slope at −0°.006 yr^{-1} (Hawkins and Southworth, 1958) or even steeper (Hines and Vogan, 1957), but is consistent with more recent determinations such as the −0°.0038 ± 0°.0014 of Murray (1982). Asteroid 2003 EH1's orbital evolution shows a best-fit slope of −0.004710 ± 0°.000086 yr^{-1} with a systematic offset of ∼ 0°.25 between it and the Quadrantids at the present day. There is significant scatter in these data; however, a simple order of magnitude calculation reveals that the difference in the precession rates (0°.0047 − 0°.0034 = 0°.0013) will open a gap of this size in 0°.25/0°.0013 yr^{-1} ≈ 190 yrs. This suggests that the core of the Quadrantid stream was formed only 200 years ago.

On the basis of the data in Fig. 2, previous workers have suggested a systematic shift in the location of the maximum between visual and radar-sized Quadrantid meteoroids (Hughes and Taylor, 1977). However, the scatter in these radar maxima positions and more recent global visual measurements (Jenniskens, 1994; Rendtel et al., 1995) which place recent visual maxima at approximately the same location as past radar data, namely near $\lambda = 282°2 \pm 0°1$ (J2000.0) cast doubt on the veracity of such mass segregation. Earlier visual data also need to be cautiously interpreted as the short duration of maximum for the stream produces heavy temporal biases for any one site; it is only the advent of combined global analyses of the Quadrantids in the last decade which have consistently yielded similar positions for shower maxima. Similar comments apply to many past radar analyses of the stream. We note, for example, that the radar analysis of the Quadrantids by Poole et al. (1972) who carefully corrected Quadrantid rate observations for the radar response function and produced an estimate for the radar maxima averaged between 1964 and 1971 at $\lambda = 282°26 \pm 0°03$ is in good agreement with the recent visual peak location. They also noted no variation in peak position with radar magnitude. Similarly, Brown et al. (1998) applied radar response corrections for the 1997

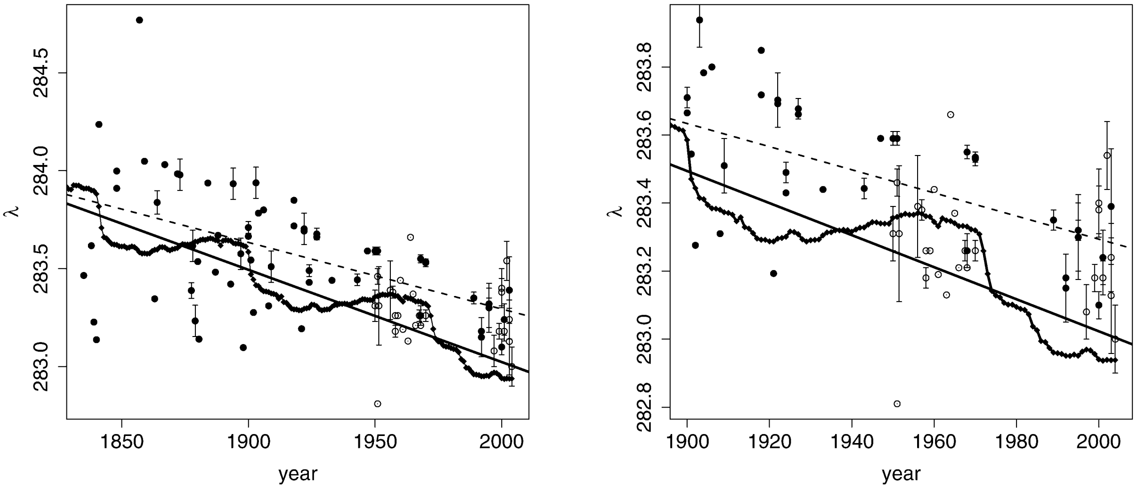

Fig. 2. The solar longitude (J2000.0) of the peak of the Quadrantid meteor shower versus time. The solid circles are visual determinations, the empty circles are from radar. The heavy lines are the longitude of the Sun as seen by 2003 EH1 as it passes close to the Earth's orbit at its descending node (equivalent to the longitude of its ascending node *Ω*) along with a linear-least squares fit. The dashed line is a weighted best fit to the observations. Observations without reported uncertainties have no error bars shown but were given uncertainties of ±1 degree. Visual observations are taken from the following sources: Quetelet (1839, 1842); Backhouse (1884); Denning (1888); Denning and Wilson (1918); Denning (1924); Fisher (1930); Prentice (1953); Hindley (1970, 1971); Poole et al. (1972); Roggemans (1990); Rendtel et al. (1993); Evans and Steele (1995); Langbroek (1995); Jenniskens et al. (1997); McBeath (2000, 2001, 2003); Arlt and Krumov (2001). Radio observations are from Hawkins and Almond (1952); Millman and McKinley (1953); Bullough (1954); Hines and Vogan (1957); Hindley (1971); Poole et al. (1972); Hughes (1972); Yellaiah and Lokanadham (1993); Shimoda and Suzuki (1995); Brown et al. (1998); McBeath (1999, 2000, 2001, 2003) as well as from unpublished data from the Canadian Meteor Orbit Radar.

Quadrantid return and found no evidence for sorting in the stream or any difference (within error) between the radar and visual maxima. The only long-term radar study of the stream by McIntosh and Simek (1984) also found no clear evidence for a systematic shift in the times of maxima between larger and smaller Quadrantids.

One likely cause for the large year-to-year variations in radar peak locations is an often rapidly changing radar collecting area associated with the shower. This is due to the fact that the radiant is circumpolar from mid-northern latitudes and any narrow beam radar system will be sensitive to the radiant for only a few hours at most. Even broad all-sky radar systems will show large changes in apparent sensitivity to the radiant on time scales shorter than the duration of the main part of the shower. Hence, any one location making radar observations in any one year is likely to record a peak time which is more a function of the radiant-beam geometry than the true shower flux. Convolving this sharply changing collecting area with the intrinsic sharp peak associated with the core of the Quadrantids makes measurement of true peak locations difficult from any one radar station, particularly if rapid changes in the shower mass-index (which affects the radar collecting area) occur at the same time. Rendtel et al. (1995), for example, present visual data of the shower which shows changes in the population index of 50% in intervals as short as 24 h near the peak. Jenniskens et al. (1997) also questioned the previous interpretations of mass sorting from earlier literature studies and suggested that some of the effect may have been due to variations in the mean magnitude of the shower meteors, which correlate with radiant elevation.

We have measured the orbits for radar-sized (average mass near 10^{-4} g) Quadrantid meteoroids using the Canadian Meteor Orbital Radar (CMOR) during the 2003 and 2004 returns [for details see (Webster et al., 2004)]. The CMOR radar, located at 43°.2 N, 80°.7 W near Tavistock, Ontario, measures approximately 2000 radar meteor echoes per day using time-of-flight measurements between two outlying stations and interferometric measurement at the main radar station. The sensitivity limit for CMOR is near radio magnitude +8 and at Quadrantid velocities we expect a minimum detectable mass to be 5×10^{-5} g. CMOR Quadrantid radar meteors were identified by their proximity to the known shower radiant. The radiant for the Quadrantids was identified using single-station radiant mapping techniques (cf. Brown et al., 1998). The radiant is visible in these single station data from $\lambda = 280$–$287°$ (J2000.0) in 2004, for a total duration of the outer/extended portion of the stream of 7° as shown in Fig. 3.

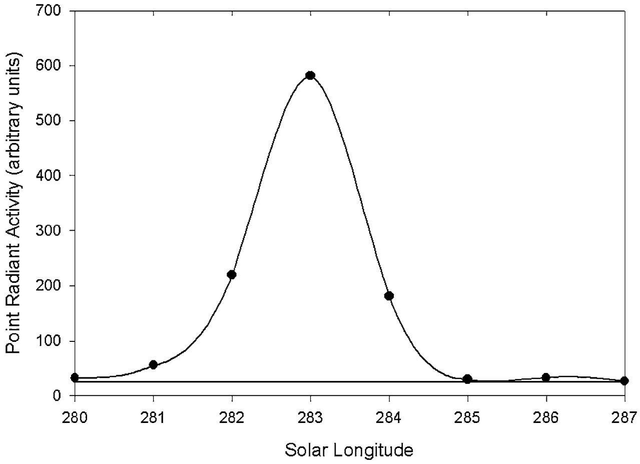

Fig. 3. The apparent radar strength of the Quadrantids as measured at 29 MHz using the single-station radiant technique [cf. Brown et al. (1998) for a description]. The observed radiant location on each date is within 1 degree in Dec. and RA of the expected location based on visual determinations of the drift as given by Rendtel et al. (1995). The horizontal line indicates the background activity level.

From these single-station radiant locations all potential radar meteor orbits with radiants within five degrees of the shower radiant were selected and this pool was further restricted to those with apparent velocities between 30–55 km s^{-1}. This wide interval was chosen to ensure all possible Quadrantids within 3 sigma of the shower velocity were counted. Here our error in an individual velocity measurement is approximately 4 km s^{-1}. A total of 384 probable Quadrantid orbits were recorded in 2003 and 823 in 2004.

To accurately measure the mean orbit for radar Quadrantids it is necessary to ensure that the effects of deceleration in the atmosphere are minimized. To demonstrate the significance of this effect on our sample of radar Quadrantids, Fig. 4 shows the mean measured velocities binned in 5 km height intervals for shower meteors for 2003. Note that the average height error for a single echo is ∼2 km (cf. Webster et al., 2004). It is clear that the average velocity falls as height decreases, as expected. Below 95 km in particular deceleration becomes significant, with the decrease in the measured apparent velocity being more than 2 km s^{-1} compared to higher altitudes. Previous radar orbit measurements for the Quadrantids have used fixed, height-independent estimated corrections for the decelerations (cf. Millman and McKinley, 1953), but it is clear that this effect is strongly height dependent. To attempt to minimize the effects of deceleration on the velocity measurements we have further restricted our analysis to only those Quadrantids detected above 95 km altitude and made no direct correction for deceleration, estimating this to be no more than ∼1 km s^{-1} for our sample.

In addition to the time-of-flight velocity measurements, a small proportion (about 10%) of Quadrantid echoes have had independent velocities measured using a hybrid Fresnel/pre-t_0 phase technique (cf. Hocking, 2000). This technique tends to isolate those echoes which show little or no evidence of fragmentation, and thus possess clear Fresnel oscillations [see Ceplecha et al. (1998) for a discussion of the Fresnel velocity measurement technique]. To ensure selection of only the very highest quality echoes experiencing very little deceleration we further limit our

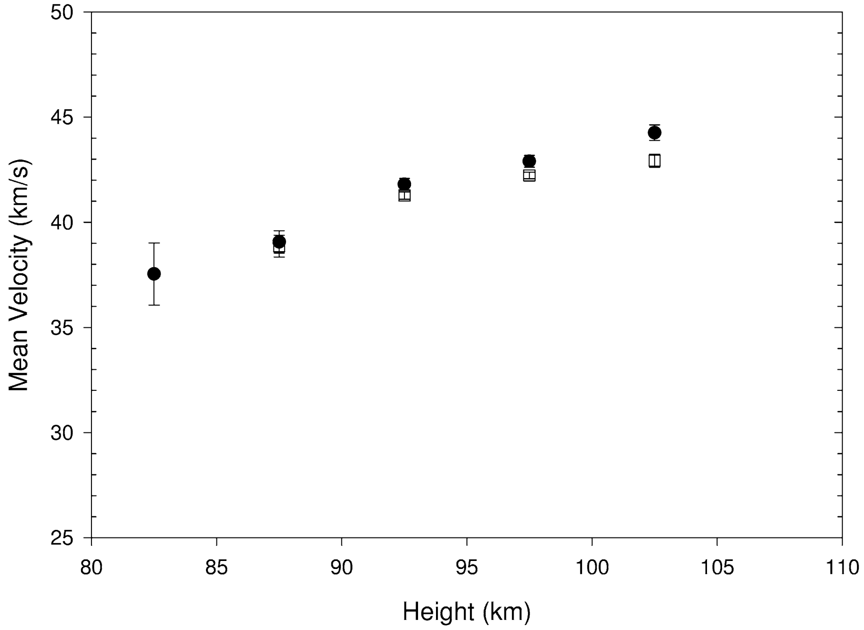

Fig. 4. The change in the average measured velocity for Quadrantid echoes as a function of height in 2003. These data are binned in 5 km height bins. The solid circles represent velocity measurements from the time-of-flight method while the open squares represent velocities independently measured using the hybrid-Fresnel technique (see text for details).

Table 1
Average orbital elements for radar-observed Quadrantid meteoroids

	a (AU)	e	q (AU)	i (deg)	Ω (deg)	ω (deg)	V_g (km s^{-1})
This paper	3.34 ± 0.20	0.672 ± 0.01	0.977 ± 0.01	71.0 ± 0.3	283.3 ± 0.81	171.0 ± 0.6	40.7 ± 0.2
Millman and McKinley (1953)	3.74	0.738	0.98	70.3	283.46	173	40.9 ± 0.5
Sekanina (1970)	3.064	0.682 ± 0.009	0.974 ± 0.001	70.3 ± 0.4	283.01 ± 0.1	168.1 ± 0.7	40.5
Cook (1973)	3.08	0.683	0.977	72.5	282.7	170.0	41.5

analysis to only echoes whose time-of-flight velocities and hybrid velocities agree to within 3%. The final total number of Quadrantid orbits meeting these stricter criteria from 2003 and 2004 combined is 83 (from a total of 1147 orbits originally identified). The mean orbital elements and standard errors for these highest quality Quadrantid orbits is given in Table 1 along with a comparison from other radar sources. Note that extrapolation of the geocentric velocity out of the atmosphere based on the average decelerations observed in Fig. 4 is within the standard deviation of the geocentric velocities measured with these Quadrantid radar echoes. Fig. 5 shows the spread in semi-major axes for these 83 Quadrantid orbits along with comparisons with Super-Schmidt, small camera and video data. The observed radar spread is qualitatively similar to that seen for video Quadrantids reported by Jenniskens et al. (1997), which are only slightly larger in mass than our radar-measured Quadrantids. Our orbital element dispersions are twice that observed for photographic Quadrantid meteors (Jenniskens et al., 1997). We also note that our average semi-major axis for the stream is identical to the photographically measured average found in Jenniskens et al. (1997).

3. Past evolution of 2003 EH1

At the time of writing, 2003 EH1 had an observed orbital arc of 306 days, allowing an accurate orbit to be determined. The orbital elements of 2003 EH1 are presented in Table 2. We should note however that the mean shower orbit as seen from Earth does not necessarily reflect the mean orbit of the Quadrantid meteoroids, rather only that of the portion of the stream that intersects our planet's orbit. The match between 2003 EH1 and the nominal Quadrantid orbit is quite good, the largest difference being in the perihelion distances: 2003 EH1 has a perihelion distance significantly outside that of the Earth, while the mean Quadrantid stream is slightly inside. This difference is large enough to suggest that 2003 EH1 is unlikely to be *currently* producing the Quadrantid meteoroids observed at this epoch. It is however completely consistent with its past evolution (see Figs. 8 and 12). Any meteoroids released from 2003 EH1 in the past but evolving dynamically at a slightly slower rate would be currently crossing the Earth's orbit.

The evolution of 2003 EH1 was examined by integrating it backward along with 99 clones. The clones are generated by selecting orbital elements from a Gaussian distribution

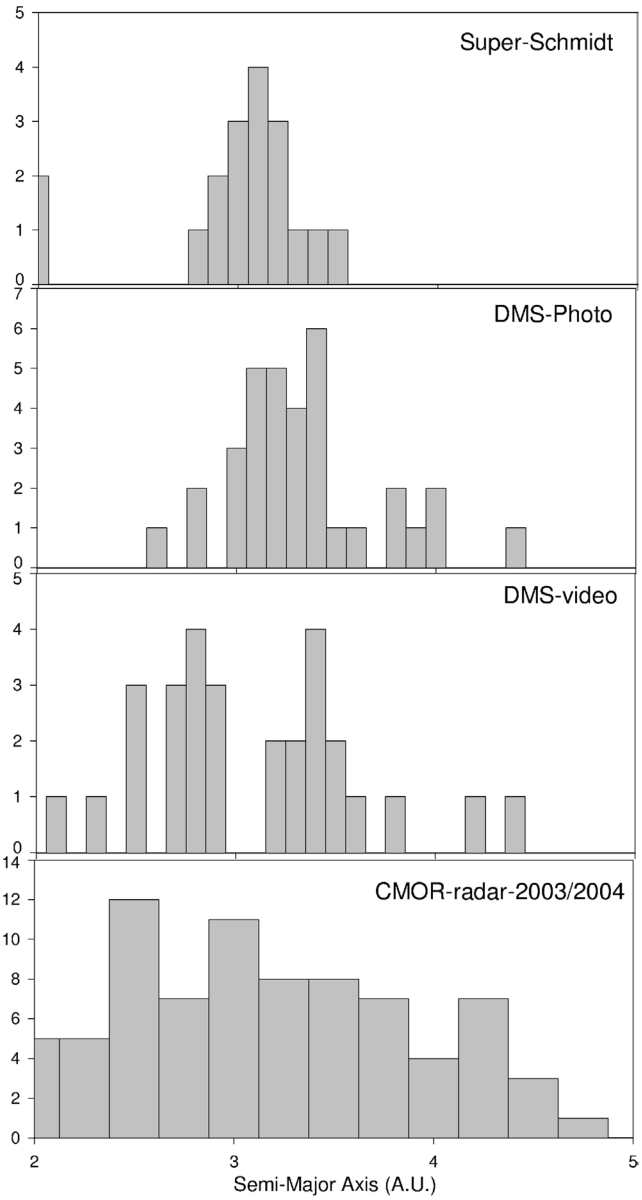

Fig. 5. The measured semi-major axis distribution of Quadrantid meteoroids. DMS-photo and video are observations from the Dutch Meteor Society (Jenniskens et al., 1997) and the Super-Schmidt data from the IAU Meteor Database.

centered on the nominal values for 2003 EH1 and with a standard deviation given by the magnitude of the elements' uncertainties, as shown in Table 2. The particles are released in a single outburst at perihelion. Although the orbit is well known, the frequency of encounters with Jupiter means that the asteroid's evolution is very sensitive to small uncertainties. The behavior of this suite of clones allows us a broader statistical view of the past evolution of 2003 EH1.

Simulations of 2003 EH1 and its meteoroid stream were performed with a Wisdom–Holman (Wisdom and Holman, 1991) style integrator modified to handle close approaches symplectically by the hybrid method (Chambers, 1999). A time step of 1 day was used. Short-term simulations (<1000 yr) were checked with the RADAU integrator of Everhart (1985), a high-order non-symplectic integrator; the results were qualitatively identical. In all simulations, the eight major planets (except Pluto) are included and they interact fully with each other and any asteroids or meteoroids, these latter being treated as test particles due to their negligibly small mass. Initial planetary positions and velocities were extracted from the DE 405 ephemeris (Standish, 1998).

The semi-major axis a (Fig. 6) of 2003 EH1 puts it near, but not currently in, the 2:1 mean-motion resonance (MMR) with Jupiter. The Quadrantid stream has long been known to be located near this resonance (Hughes et al., 1981). The width of the 2:1 MMR varies with e and i and is known to be very wide at large values of these quantities (Moons and Morbidelli, 1993; Morbidelli and Moons, 1993; Roig et al., 2002), but has not been investigated to our knowledge for the particular values of Asteroid 2003 EH1. Simulations of particles on orbits identical to that of 2003 EH1 except for their semi-major axis a reveal that the resonance extends from 3.18 to 3.38 AU (indicated in Fig. 6 by the horizontal dashed lines) at the current position of 2003 EH1. The extent of the resonance will vary as the other orbital elements of 2003 EH1 change, so while 2003 EH1 was in this range of a in the past, plots of the resonant argument $\sigma_{2:1}$ of the 2:1 MMR, given by $\sigma_{2:1} = 2\lambda_J - \lambda - \varpi_J$ (cf. Murray and Dermott, 1999), where λ is the mean longitude and the subscript J indicates Jupiter's values, show that neither the nominal orbit of 2003 EH1 nor its clones are in the 2:1 MMR during the simulations shown.

Although the relationship of 2003 EH1 to the 2:1 MMR is evolving and complex, even when in a non-resonant state the proximity of this resonance has a strong influence. The orbital elements show a periodicity with a roughly 59 yr period, which has also been observed in simulations of the Quadrantid stream (Hughes et al., 1979). This periodicity was analytically determined to be associated with the 2:1 resonance by Murray (1982). A Fast Fourier Transform of $\sigma_{2:1}$ of the clones reveals a strong signature at 59 years, confirming Murray's result. The resonance may have further effects on the Quadrantid stream, as particles ejected from 2003 EH1 could find themselves within this resonance. Meteoroid orbits trapped in resonance may have markedly different precession rates than those outside (Hughes et al., 1981).

The subsequent plots show the orbital elements (J2000.0) including the past eccentricity e (Fig. 7), perihelion distance q (Fig. 8), inclination i (Fig. 9), longitude of the ascending node Ω (Fig. 10), argument of perihelion ω (Fig. 11) and the heliocentric distances to the nodes (Fig. 12). A heavy triangle indicates the values computed for Comet C/1490 Y1 by Hasegawa (1979), converted to J2000.0. The other proposed parent bodies (cf. Table 2) have elements typically well off the figures presented, due to the afore-mentioned relatively large differences in their orbits. Because of these differences, we conclude it is unlikely that Comet 96P/Machholz or Asteroid 5496 are directly related to the narrow core of the

Table 2
The orbits of the Quadrantid shower (Cook, 1973) along with previously proposed candidates for its parent body (J2000.0)

	2003 EH1	Quadrantids	Machholz	5496	Liais	C/1490 Y1
a (AU)	$3.12619 \pm 8.5 \times 10^{-5}$	3.08	3.014	2.435	∞	∞
e	$0.618406 \pm 9.4 \times 10^{-6}$	0.683	0.959	0.637	1.0	1.0
q (AU)	1.1929 ± 0.0001	0.976	0.124	0.884	1.20	0.761
i (deg)	70.785 ± 0.00011	72.5	60.13	68.0	79.7	73.4
Ω (deg)	282.950 ± 0.00015	283.4	94.60	101.1	326.0	280.2
ω (deg)	171.369 ± 0.00091	170.0	14.59	118.1	209.7	164.9
ϖ (deg)	94.319 ± 0.00093	92.7	109.2	219.2	175.7	84.4
D	0.230	–	2.03	2.21	1.08	0.397
D'	0.113	–	1.08	0.87	0.432	0.228
H_0	16.67	–	–	15.73	–	–
d (km)	1–2	–	–	2–4	–	–
T_J	2.063	2.026	1.940	2.531	–	–

Notes. H_0 is the asteroidal (rather than cometary) absolute magnitude. Comet orbits are from Williams (1999) while the orbit and uncertainties of 2003 EH1 are from the NeoDys website (http://hamilton.dm.unipi.it/neodys/). Note that for Comets 1490 Y1 and Liais, a parabolic orbit was assumed. The values of the orbital similarity parameters D (Southworth and Hawkins, 1963) and D' (Drummond, 1981) are with respect to current Quadrantid stream orbit, while T_J is the Tisserand parameter with respect to Jupiter.

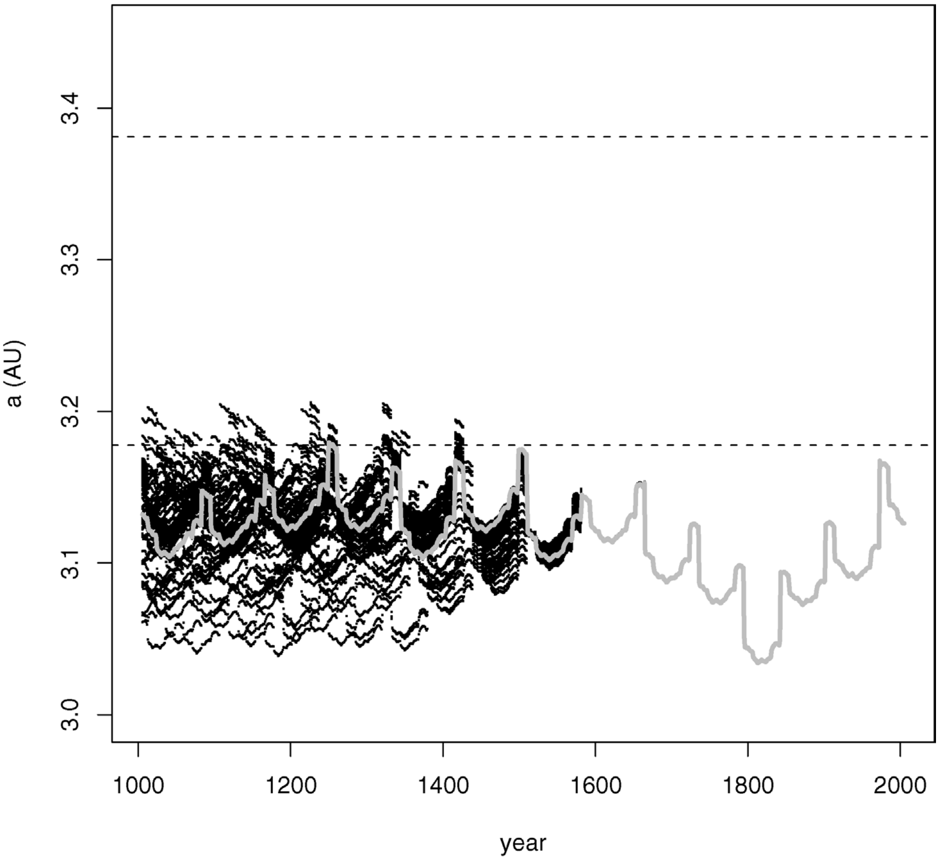

Fig. 6. The past orbital evolution of the semi-major axis of 2003 EH1 (solid line) and its clones. The dotted lines are an estimate of the width of the 2:1 resonance at the e and i of 2003 EH1.

Quadrantid stream, although we will show later than Machholz may be part of a broader Quadrantid complex. The other two most probable candidates, Liais and C/1490 Y1, deserve a fuller discussion.

The orbits of C/1490 Y1 and 2003 EH1 coincide almost exactly in q but differ by 2° in ω, and by less than 10° in i and Ω. Given that the assumed parabolic orbit is derived from ancient sources and that only six observations are available (Hasegawa, 1979), the match is quite good and it seems reasonable that 2003 EH1 may be either C/1490 Y1 or a genetically related fragment. We note however that Williams et al. (2004) find that 2003 EH1 appears too low in the sky to be C/1490 Y1. An additional check could be provided by a determination of the position of 2003 EH1 within its orbit:

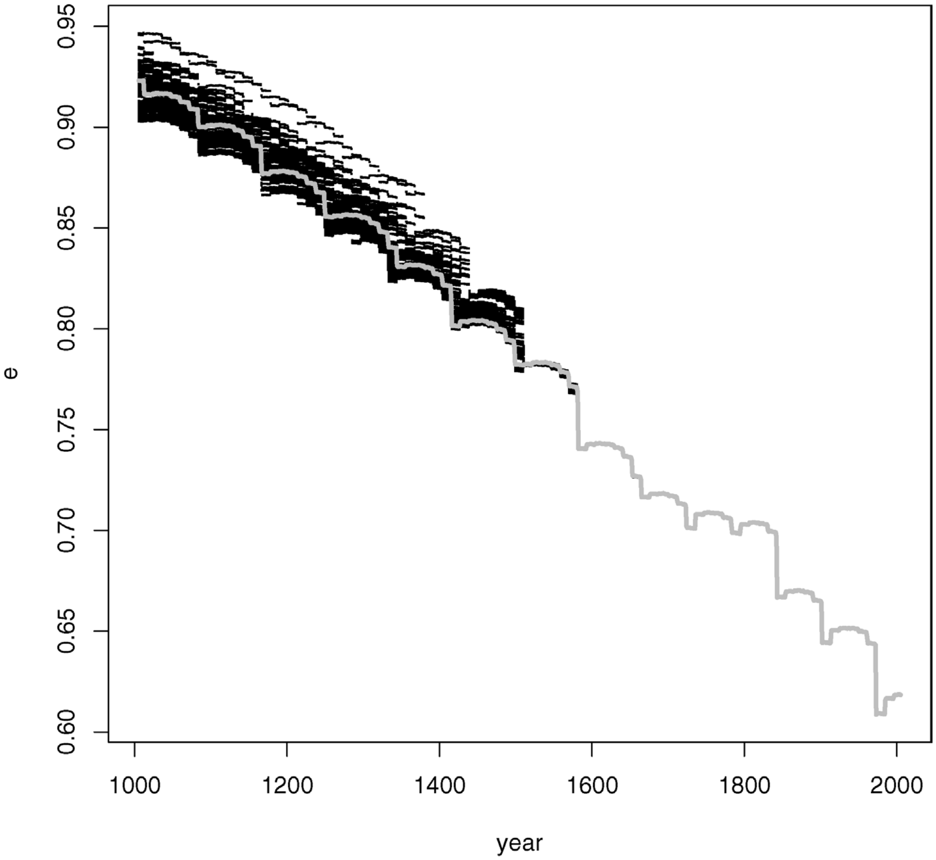

Fig. 7. The past orbital evolution of the eccentricity of 2003 EH1 (solid line) and its clones.

if it were at perihelion on the date in question, namely Jan. 8.9, 1491. Unfortunately the sensitivity of the true anomaly to small changes in the orbital elements does not allow this determination to be made. The time scale for chaos for NEAs and Jupiter family comets is typically 50–100 yrs (Tancredi, 1998) and we do not expect to be able to compute the position of bodies within their orbits beyond a few times this interval. Note that this "weak chaos" is largely confined to the true anomaly; thus the shape of the orbit can be computed reliably over much longer time scales than can the body's position within the orbit. In fact, on the date in question the clones are distributed around the orbit in a way consistent with their orbital eccentricity (i.e. largely at aphelion) and so, as expected, no conclusion can be drawn by comparing times of perihelion passage.

Another possible parent object for the Quadrantids is Comet Liais C/1860 D1 [Pokrovsky and Shaine (1919) cited in Fisher (1930)]. Its elements Ω and ω differ from those of the Quadrantid stream by about 30 degrees each, but the assumed parabolic orbit was computed based on only three observations (Williams, 1999). The comet was seen to be double when discovered in 1860 (Kronk, 2003), although this splitting event was too late to have been the source of the Quadrantids. The time interval between the present and 1860 is acceptable, although border-line, vis-à-vis the chaotic time scale. Intriguingly, when 2003 EH1 and its clones are integrated backward to the computed perihelion passage time for Comet Liais (Feb. 17, 1860), they are all at $6 \pm 1°$ (e.g., within about a month) of perihelion. Given the uncertainty in Liais' orbit this is an interesting coincidence, although the large difference in their longitudes of perihelion makes it unlikely these two are the same object.

4. Long-term behavior

In the longer-term, the behavior of 2003 EH1 is similar to that previously deduced for the Quadrantid stream, characterized by large variations in e and i. These have been seen by a number of investigators, starting with Hamid and Youssef (1963). The large oscillations are similar to those associated with the Kozai resonance (Kozai, 1962; Kinoshita and Nakai, 1999). In fact, the evolution of 2003 EH1 and its clones exhibit Kozai-type circulation in that their swings in e and i approximately conserve a and $\Theta = \sqrt{1-e^2}\cos i$ (Fig. 13) a situation often seen in sun-grazing comets (Bailey et al., 1992). However, their evolution does not conserve the nominal Kozai energy integral $C = ((2 + 3e^2)(3\cos^2 i - 1) + 15e^2 \sin^2 i \cos 2\omega)$ as given by Kinoshita and Nakai (1999). A plot of the evolution of 2003 EH1 against the curves of constant C is shown in Fig. 14. The breaking of the strict Kozai behavior could be caused by

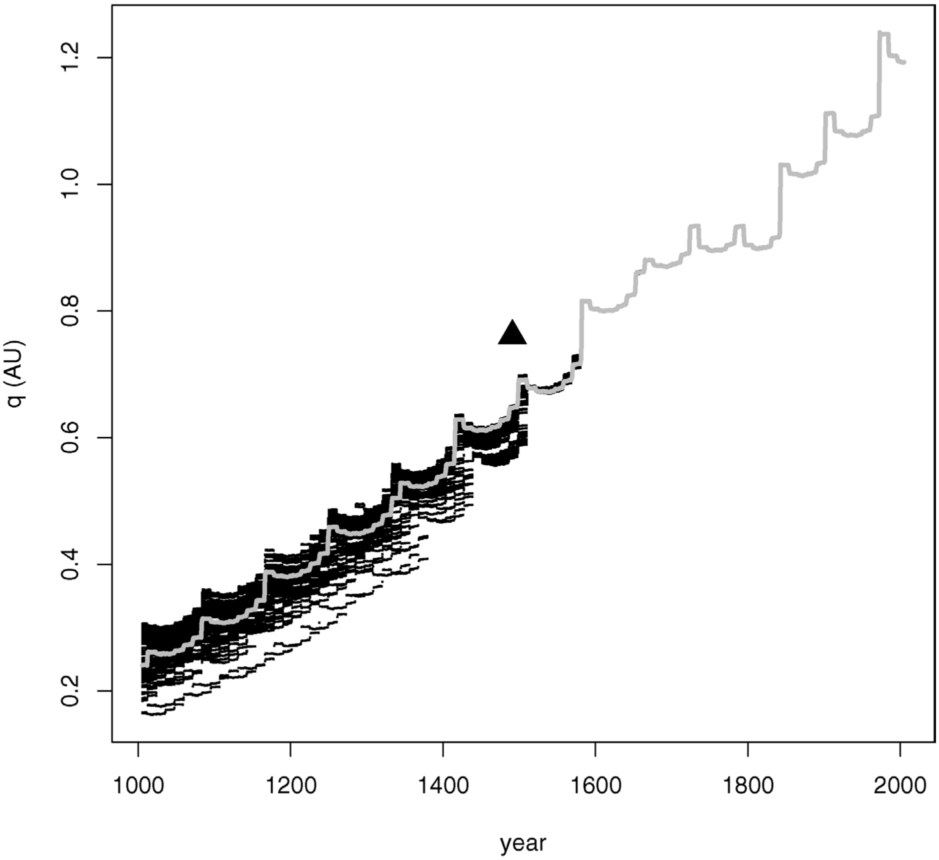

Fig. 8. The past orbital evolution of the perihelion distance of 2003 EH1 (solid line) and its clones. The computed values of Hasegawa (1979) for C/1490 Y1 is indicated by a triangle.

the proximity of the 2:1 resonance, frequent encounters with Jupiter or the action of the ν_5 resonance (none of which are accounted for in the Kozai formalism) as discussed below.

Nevertheless, this Kozai behavior provides us with a powerful diagnostic for membership in the Quadrantid complex. Particles splitting from a hypothetical original Quadrantid parent body, assuming they suffer only a small change in a, will move in e, i, ω space along the Kozai trajectories. Since different paths take different amounts of time to complete a cycle (cf. Kinoshita and Nakai, 1999), the particles end up smeared out along the trajectory, much as small differences in their mean rates of motion result in meteoroids spread out along the orbit of their parent body. In this case, however the spreading takes much longer (a Kozai cycle for 2003 EH1 takes ~7500 yrs, compared to 5.5 years for an orbital period). Our simulations indicate that it will take several cycles for particles to be perturbed away from these trajectories. Therefore bodies split from the Quadrantid parent over the last 50,000 years or so should still be near these paths, although their current values of e, i, and ω may be quite different from those of the Quadrantid stream. 96P/Machholz 1 may be such an object. The similarity of its oscillations in e and i to those of the nominal Quadrantid orbit lead previous investigators (McIntosh, 1990; Babadzhanov and Obrubov, 1992; Gonczi et al., 1992; Jones and Jones, 1993) to link it to the Quadrantid stream despite the dissimilarity of their current orbits, and indeed we find it quite close to the Kozai trajectory of 2003 EH1 (see Figs. 15 and 16 discussed below). We note that the possibility of “contamination” of such diagrams exists however, as any body that finds itself near such a Kozai trajectory will subsequently follow it, whether or not it has any connection to a hypothetical Quadrantid progenitor object. Similarly, close encounters with Jupiter are not treated by the Kozai formalism and can transfer particles away from the Kozai trajectories over time.

Figs. 15 and 16 display the numerically computed path of 2003 EH1 over the past 25,000 yrs, along with the current location of a number of comets, asteroids and meteor showers located nearby. Note that the trajectory does not close on itself perfectly, as it does get perturbed over time. Nonetheless, the motion is stably repeating for several cycles, of which three are shown in the figures. The comets and asteroids labeled lie near the Kozai trajectory on both the e–ω and i–ω plots. Our criteria for inclusion are based on a simple-minded distance function $\sqrt{\Delta\omega^2 + \Delta i^2} < X$ and $\sqrt{\Delta\omega^2 + \Delta e^2} < X$ where the angular quantities are taken in radians, and we have used $X = 0.25$ for the comets, and $X = 0.175$ for the better determined orbits of the NEAs. A list of objects meeting these criteria is presented in Table 3.

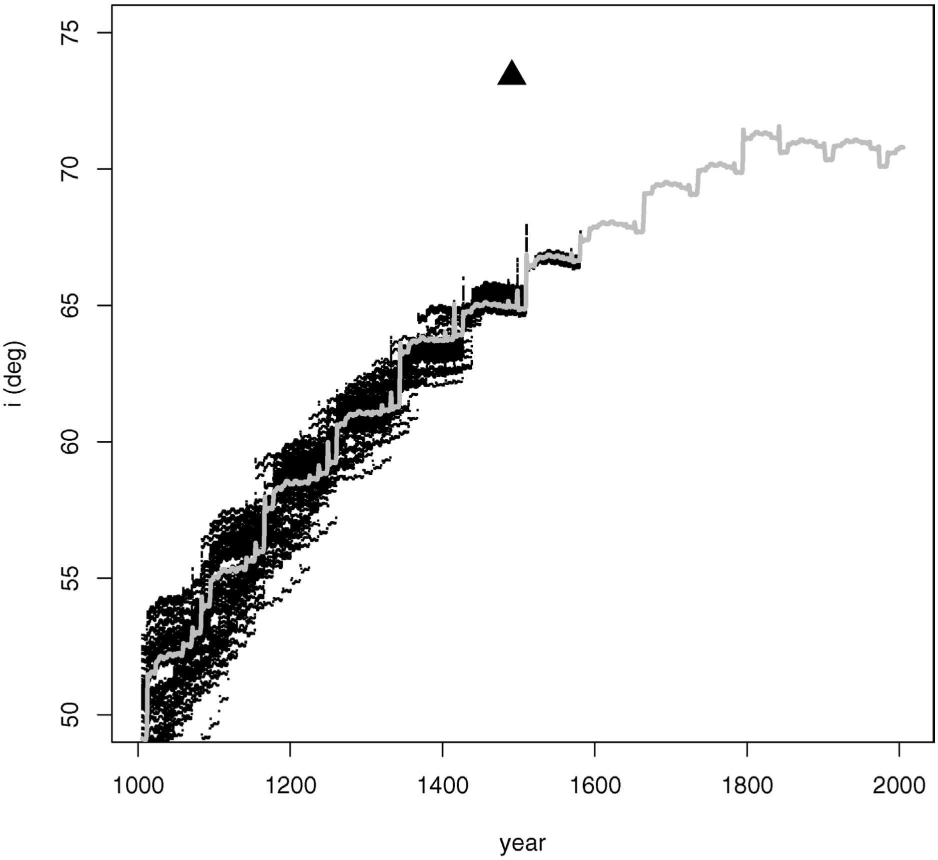

Fig. 9. The past orbital evolution of the inclination of 2003 EH1 (solid line) and its clones. A triangle indicates the value computed by Hasegawa (1979) for C/1490 Y1.

Table 3
Orbital elements of various comets, near-Earth asteroids and meteor showers that lie near the Kozai trajectory of 2003 EH1

Name	a (AU)	e	q (AU)	i (deg)	Ω (deg)	ω (deg)	T_J	Θ
D/1783 W1 (Pigott)	3.26	0.55	1.46	45.1	58.7	354.7	2.53	0.58
5D/1846 D2 (Brorsen)	3.10	0.81	0.59	29.4	103.0	14.9	2.47	0.51
D/1892 T1 (Barnard 3)	3.49	0.59	1.43	31.3	208.0	170.0	2.62	0.69
96P/1986 J2 (Machholz 1)	3.01	0.96	0.12	60.1	94.5	14.6	1.94	0.64
P/1994 P1 (Machholz 2)	3.01	0.75	0.75	12.8	246.1	149.3	2.71	0.14
1994 JX	2.76	0.57	1.18	32.2	52.5	193.5	2.89	0.69
1999 LT1	2.98	0.66	1.02	42.6	67.6	158.5	2.59	0.56
2000 PG3	2.83	0.86	0.40	20.5	326.8	138.6	2.55	0.48
2002 AR129	2.86	0.57	1.22	19.3	4.6	157.2	2.96	0.77
2002 KF4	2.89	0.58	1.22	37.1	78.0	193.6	2.77	0.65
2002 UO3	2.96	0.80	0.59	24.1	186.0	328.2	2.58	0.55
2003 EH1	3.13	0.62	1.19	70.8	282.9	171.4	2.06	0.26
2003 YS1	3.10	0.85	0.47	25.1	281.1	48.4	2.42	0.48
2004 BZ74	3.02	0.89	0.33	16.6	234.3	120.8	2.38	0.43
Arietids	1.6	0.94	0.09	21	77	39	3.60	0.32
South δ Aquarids	2.86	0.976	0.069	27.2	305	152.8	2.11	0.19

Notes. T_J is the Tisserand parameter and $\Theta = \sqrt{1-e^2}\cos i$. Data from Williams (1999), the NeoDys website and Cook (1973).

If the Kozai circulation was unperturbed, a criterion based on the Kozai Θ or C might be more natural, but this seems inappropriate in the present case. The past trajectory of 2003 EH1 changes little over a time scale of tens of thousands of years whereas the value of Θ changes substantially over a few thousand years (Fig. 13).

With the exception of the Arietids, orbits outside the range $2.75 < a < 3.5$ AU have been excluded (as the Kozai resonance proper conserves the semi-major axis), as have those with $e \geqslant 1$. True unbound comets are unlikely to be part of the Quadrantid complex. However, some poorly-observed objects have had parabolic orbits

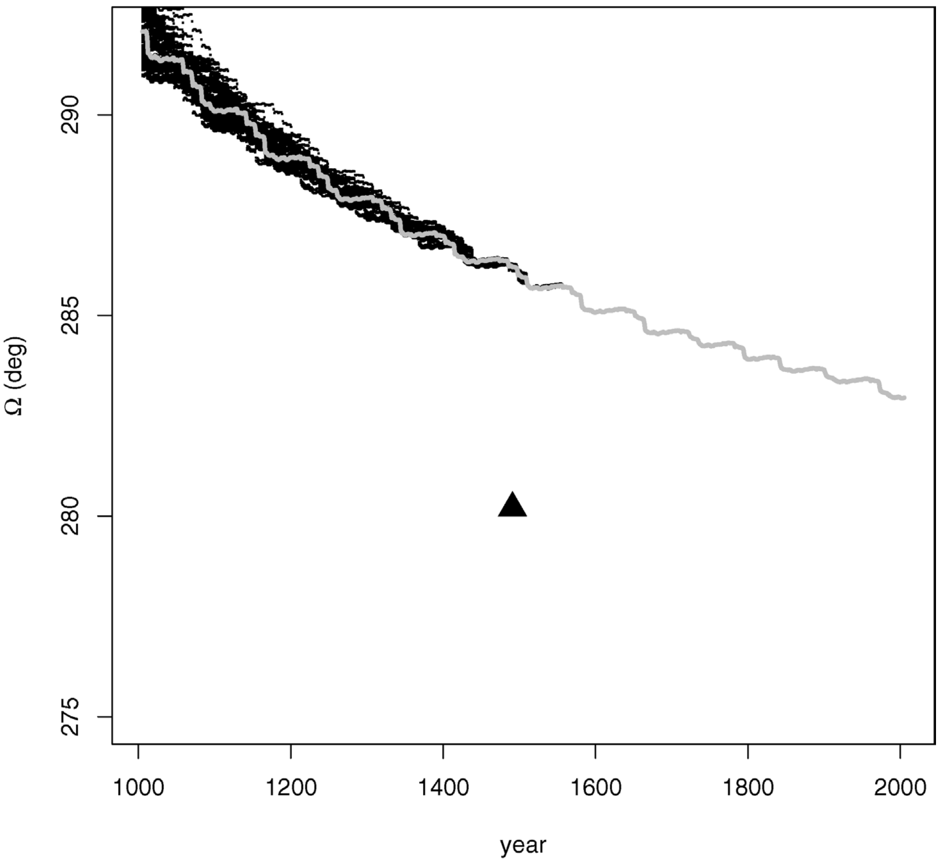

Fig. 10. The past orbital evolution of the longitude of the ascending node of 2003 EH1 (solid line) and its clones. The triangle represents C/1490 Y1 from Hasegawa (1979).

assumed, and since the Quadrantids' path covers a large fraction of the figures at e very close to one, this parameter provides a weaker criterion for determining membership in the Quadrantid complex. Thus we have excluded a number of comets that otherwise meet our criteria but have only parabolic orbits computed. These include Comet 1490 Y1, discussed earlier (Section 3) as well as Comets C/1785 A1 (Messier-Mechain), C/1798 G1 (Messier), C/1880 Y1 (Pechule), C/1898 R1 (Perrine-Chofardet), C/1903 H1 (Grigg), C/1953 X1 (Pajdusakova) C/1965 S2 (Alcock), C/1968 L1 (Whitaker-Thomas), C/1980 O1 (Cernis-Petrauskas), and C/1987 W1 (Ichimura). The nominal orbit for Comet Liais (C/1860 D1) does not match our criteria for inclusion above, although as noted earlier its computed orbit is based on a small number of observations. If we tighten our criterion to $X \leqslant 0.0875$ our sample is reduced to 96P/Machholz 1, 2003 EH1, 2000 PG3, and 2004 BZ74, making these nominally the best candidates to be part of a Quadrantid complex. Numerical integrations of their orbits over 25,000 years confirm that they all have similar oscillations in e, i, and ω. We note again however that this selection depends purely on orbital similarity and may contain genetically unrelated bodies. Fig. 15 also includes the daytime Arietid and southern δ Aquarid showers. They fall near the Kozai trajectory, supporting the conjecture of Jones and Jones (1993) that they are genetically linked to the Quadrantids, although the semi-major axis value of the Arietids (~1.6 AU) remains a difficulty.

The five comets of Table 3 include four that are now lost. Comet Pigott (D/1783 W1) was observed over the course of one month, Barnard 3 (D/1892 T1) over almost two months and Brorsen (5D/1846 D2) was observed during many returns before its final appearance in 1879 (Kronk, 1984). Soon after discovery, Machholz 2 (P/1994 P1) was observed to have multiple nuclei, indicating that it had split within the previous two decades (Asher and Steel, 1996; Sekanina, 1999). Although the less-well observed of these comets may have been lost simply due to insufficiently accurate orbits, their behavior is consistent with them all having the same structural properties, pointing to a common origin from a relatively fragile parent nucleus.

The possibility exists that these bodies are disintegrating and providing material for the presumably-older broader Quadrantid meteoroid distribution. Previous modeling efforts have not examined closely the spread in nodal longitude for the stream as a function of age. Our simulations suggest that the spreading in nodal stream width for the stream as a whole is of the order of 0.05–0.2 degrees in solar longitude per century, which equates to a minimum formation age of ~3500 years based on the seven-day radar duration of the shower (Fig. 3).

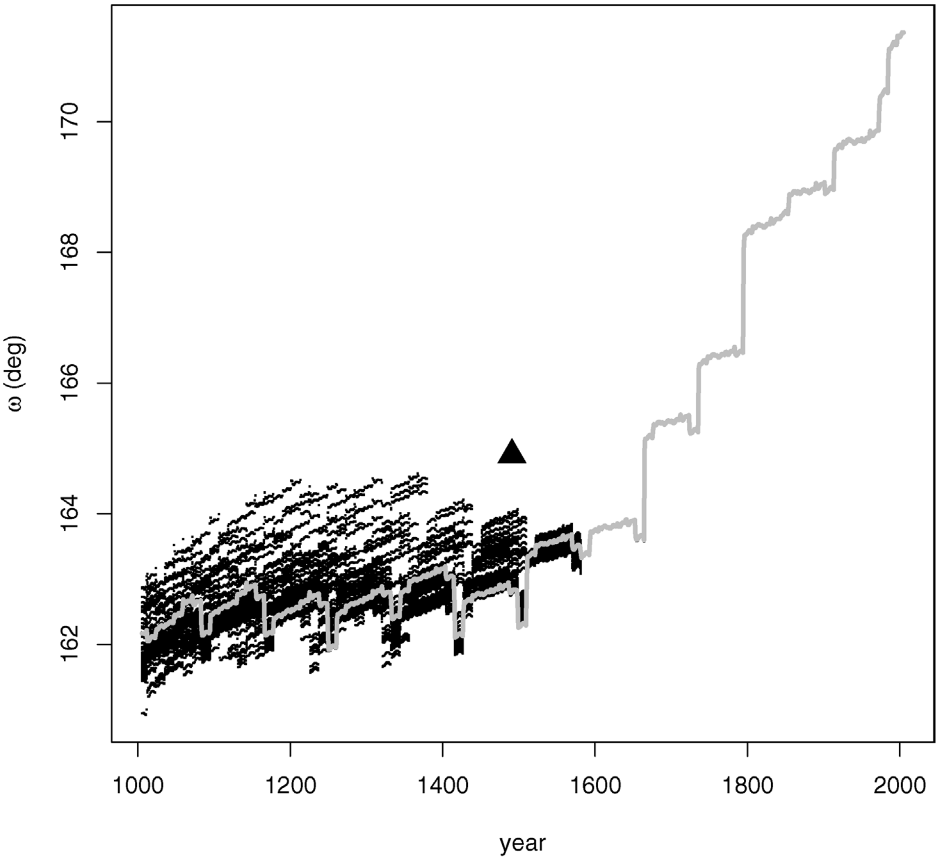

Fig. 11. The past orbital evolution of the argument of perihelion of 2003 EH1 (solid line) and its clones.

The NEAs listed in Table 3 all have Tisserand parameters in the range $2 < T_J < 3$ consistent with being Jupiter-family comets (Levison, 1996) although no comae have presumably yet been observed for any of them. Of these, only 2000 PG3 has published physical properties; it was found to have a low albedo (Fernandez et al., 2001) consistent with a cometary nucleus or a C-type asteroid. Whether 2003 EH1 is a comet or not remains unclear; it has yet to display cometary activity. It was detected by the LONEOS program at Lowell Observatory on March 6th 2003 when it was 1.2 AU from the Sun and heading outward toward aphelion, which it will reach in late 2005. Fig. 8 shows that its perihelion distance has been increasing in the recent past. A thousand years ago it would have had a small (<0.3 AU) perihelion distance, yet it was not discovered as a comet. This indicates that it must be a nearly exhausted comet with very low level activity if it is not indeed an asteroid, and that perhaps a collision or other mechanism (such as tidal disruption or Yarkovsky spin-up) produced the meteoroid stream.

4.1. Other resonances

Other resonances known to be important to objects in this region are the ν_5, ν_6, and ν_{16} secular resonances (Moons and Morbidelli, 1993; Morbidelli and Moons, 1993), associated with chaos and the clearing of the 2:1 Kirkwood gap, called the Hecuba gap (cf. Murray, 1986). Plots of the resonant argument show that 2003 EH1 and its clones are in the ν_5, but not the other two resonances. The existence of this resonance means that longitude of perihelion of 2003 EH1 is constrained to precess at the same rate as Jupiter's, or more precisely at the rate of the Solar System's g_5 secular eigenfrequency (cf. Murray and Dermott, 1999). A plot of $\sigma_5 = \varpi - g_5 t$ for 2003 EH1 is in Fig. 17. The resonance holds the longitudes of perihelion of the two bodies approximately 90° apart so that should 2003 EH1 encounter Jupiter, the planet will not be at perihelion. Since Jupiter's perihelion distance is 4.95 AU and the nodal distance of 2003 EH1 regularly reaches up to very near 5 AU, this may have some protective effect. However, since the size of Jupiter's Hill sphere ($R_{\text{Hill}} = 0.36$ AU) is larger than this "buffer zone" a strong encounter may still occur.

In extended simulations, some clones of 2003 EH1 are seen to have been in the 2:1 resonance in the more distant past, having left it approximately 20,000 years ago. This indicates 2003 EH1 may have resided in this resonance in the past, a state not uncommon for other comets as well (Vaghi and Rickman, 1982). However the uncertain nature of such long-term integrations under the influence of multiple close encounters with Jupiter does not allow us to conclude this firmly.

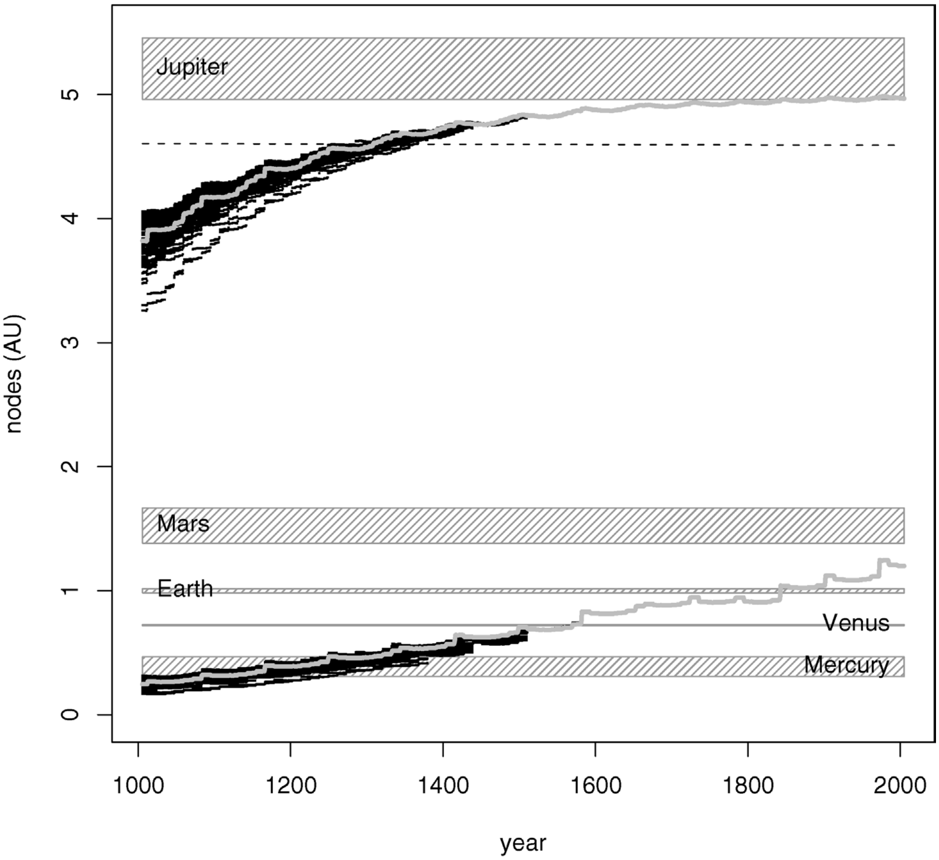

Fig. 12. The heliocentric distance to the nodes of 2003 EH1 and its clones. The shaded areas indicate the peri/aphelion distances of the planets. For Jupiter, an additional dotted line indicates its perihelion distance minus the radius of its Hill sphere.

5. Stream modeling

The Quadrantid meteor stream is recognized as being among the most narrow, which may be an indicator either of a young age or a confluence of meteoroid orbits at the current time. The latter model has been preferred prior to the identification of 2003 EH1, presumably since the association of the stream with 96P/Machholz would require a considerable time (2000–5000 yrs) for the two to have diverged to their current orbits. Jenniskens et al. (1997) proposed a much younger age for the stream based on their determination that it was highly structured, with little dispersion in mass and speed and on this basis made a prediction that an object (like 2003 EH1) would eventually be found.

If 2003 EH1 is indeed the parent of the core of the Quadrantid stream, then its age may be determinable from a study of hypothetical meteoroids ejected from this body at earlier times. We investigated the hypothesis that the peak of the Quadrantid stream was released in a single burst at perihelion passage either in 1800 AD [as suggested by the difference in the nodes (Section 2)], 1600 AD [suggested by Jenniskens (2004)] or 1491 AD (corresponding to the time of perihelion passage of C/1490 Y1). The small dispersion of the clones in Figs. 6–12 confirm that the present-day nominal orbit of 2003 EH1 is representative of the past evolution of 2003 EH1 over the last several hundred years. Thus we will use the nominal orbit as the basis of our simulated meteor streams.

Each injection of meteoroids into the stream was simulated by an ensemble of 4000 particles. These were divided into eight sets of 500, and each set had an ejection velocity from the nucleus of 10, 30, 50, or 100 $\mathrm{m\,s^{-1}}$ and β of 0 or 5×10^{-3}. The ejection directions were chosen randomly on the sphere. These meteoroids were subsequently integrated forward under the influence of the planets and Poynting–Robertson drag. The multiplicity of parameters provides reasonable coverage of the expected β and velocities of meteors ejected from a comet without being overly dependent on any one parameter. The range of beta was chosen to cover from the largest particles down to those of around 50 μm, close to the peak detection range for patrol radars. The velocities were derived from the formulae of Whipple (1950, 1951). A 50 μm particle released from a 2.9 km nucleus at 1 AU may have an ejection velocity of 79 $\mathrm{m\,s^{-1}}$, although Whipple argues the smallest particles ejected would have velocities of 4/9 the average thermal gas speed, or 239 $\mathrm{m\,s^{-1}}$ at $T = 273$ K. A maximum of 100 $\mathrm{m\,s^{-1}}$ seems a reasonable compromise. Also, ejection velocities at 1 AU using the Jones (1995) model for low density meteoroids (0.1 to 0.5 $\mathrm{g\,cm^{-3}}$) for a cometary nucleus the size of 2003 EH1's produce speeds in the 50–100 $\mathrm{m\,s^{-1}}$ range.

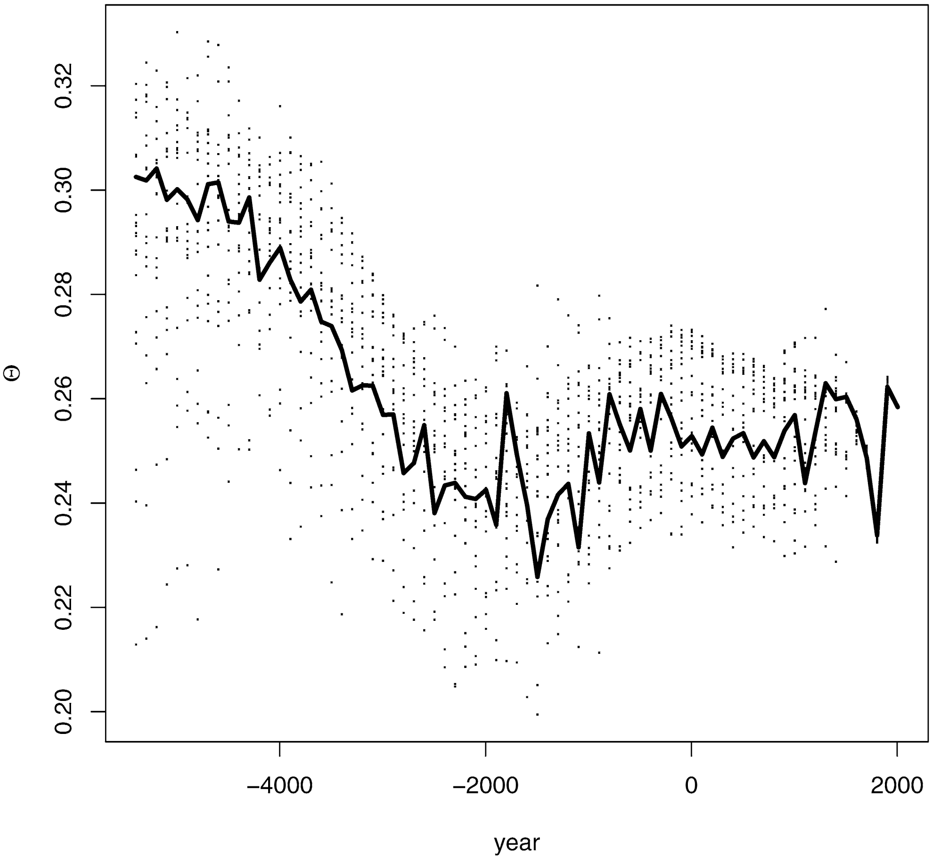

Fig. 13. The past orbital evolution of Θ for 2003 EH1 and its clones.

The distribution of the resulting orbits, in particular that of those intersecting the Earth, is compared with observations of the Quadrantid stream. The condition of intersection is implemented by including only those meteoroids whose nodal distance is within 0.01 AU of Earth's heliocentric distance, which is at $r = 0.983$ AU during the Quadrantid shower. Only these orbits are considered in comparing the simulations with observations.

When the meteoroids are released in 1491 (chosen to coincide the perihelion passage of C/1490 Y1), the stream develops two branches separated by over 2° in Ω: this does not correspond to the currently observed Quadrantid stream. The splitting arises because many meteoroids (in particular, many ejected at 100 $\mathrm{m\,s^{-1}}$) are placed directly into the 2:1 MMR with Jupiter. As noted earlier by Gonczi et al. (1992), this results in a different precession rate and a different orbital evolution for the resonant particles. This type of phenomena may be responsible for the creation of resonant meteoroid sub-streams with significantly different properties and which might appear and disappear at times different from those expected of the main stream. None of the particles ejected with up to 100 $\mathrm{m\,s^{-1}}$ random velocity at perihelion in 1600 or 1800 are seen to go into the 2:1 mean-motion resonance. This is most likely because the semi-major axis of 2003 EH1 is significantly smaller at this time (see Fig. 6) and a higher ejection velocity is required to put particles in the resonance at those epochs.

If the 100 $\mathrm{m\,s^{-1}}$ ejection velocity particles are ignored in the 1491 release scenario, the resonant sub-stream does not appear. Regardless, the remaining stream does not match the Quadrantids. The location and width of the stream would be roughly consistent with the observed values. However, the first appearance of this stream would be prior to 1600 for any of the chosen ejection velocity models, long before the first recorded observations. The flux is lower initially, but reaches its peak prior to 1700. On this basis alone, it is difficult to reconcile an origin for the core of the stream near 1491 and its first visibility only in the mid-19th century.

When the particles are released in 1600, a similar problem arises. The shower would first be observed in 1675 (with flux increasing to peak values around 1750). The meteoroids ejected at 10 $\mathrm{m\,s^{-1}}$ are the slowest-evolving meteoroids, but they reach the Earth prior to 1750. Although the location and width of the stream are again in fair agreement with observations, the early onset of the shower implied by this scenario makes it difficult to reconcile with observations. A few tests with 1 $\mathrm{m\,s^{-1}}$ ejection velocities show arrivals circa 1807, so very low ejection speeds might bridge the gap. However traditional outgassing related ejection is not expected to produce such low velocities so other mechanisms such as

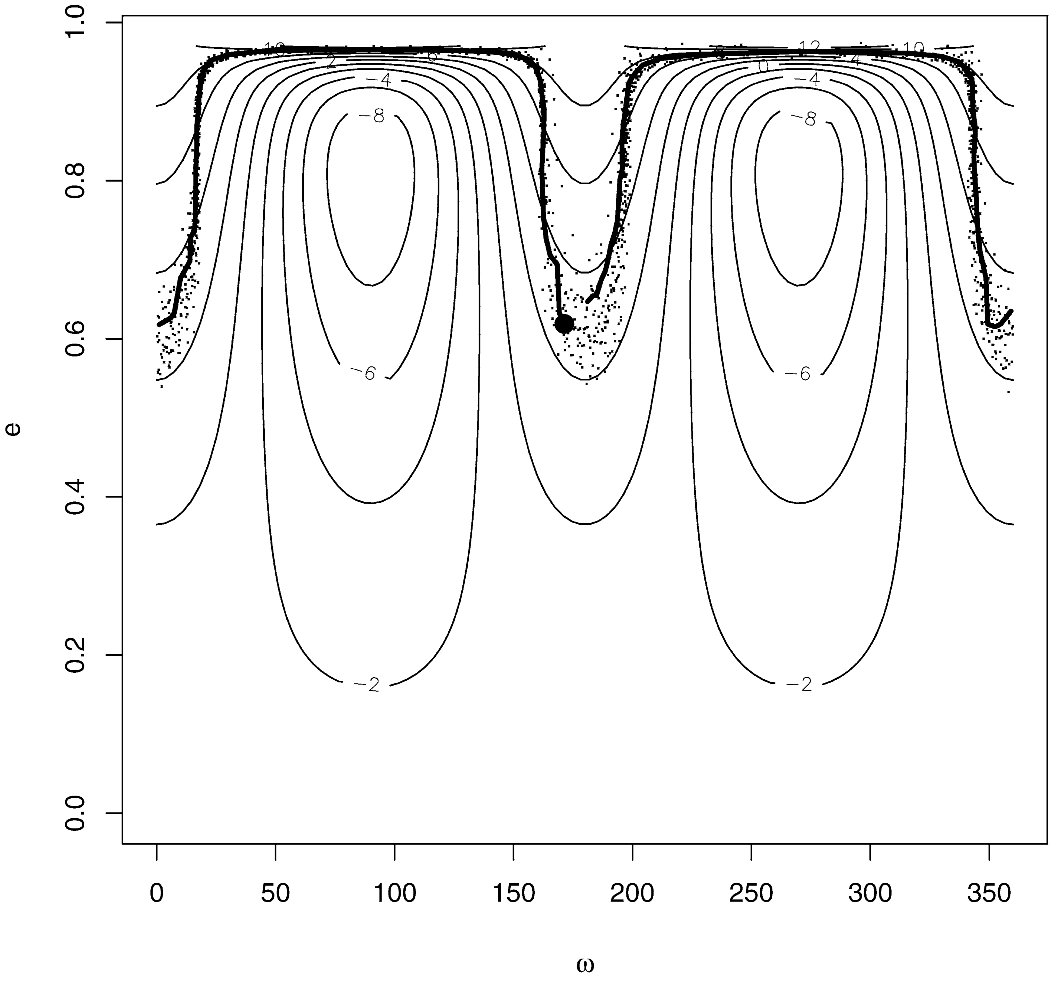

Fig. 14. The past orbital evolution of 2003 EH1 (solid line) and its clones (dots) across the lines of constant *C* for the Kozai resonance for the last 7500 years, or approximately one cycle. The current location of 2003 EH1 is indicated by the filled black circle.

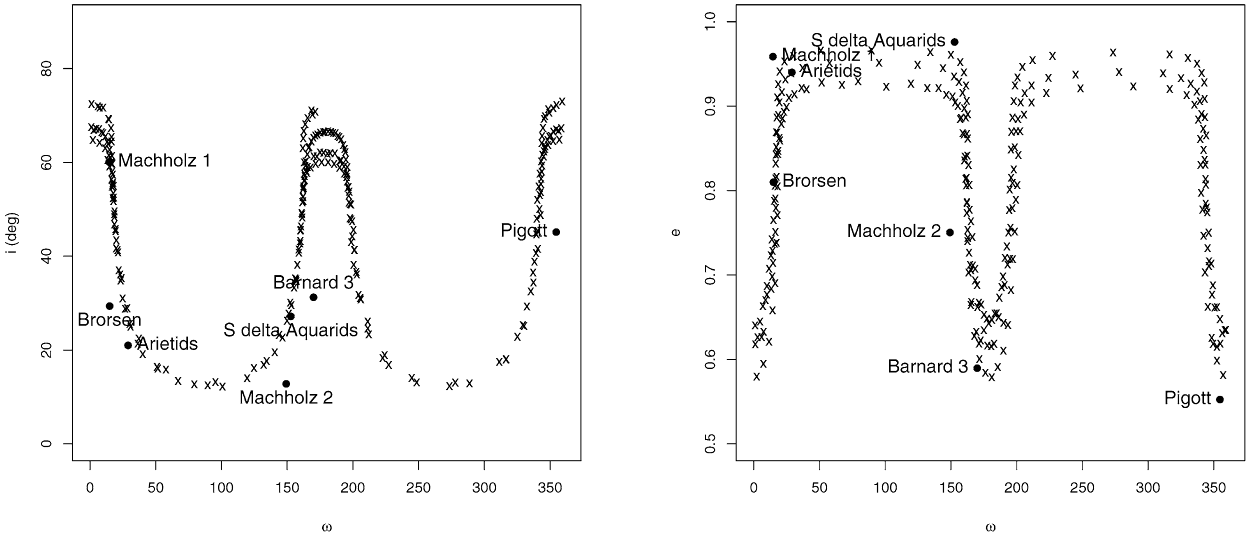

Fig. 15. The trajectories of 2003 EH1 over the past 25000 years (×) and the current location of some comets and meteoroid streams lying nearby (solid circles).

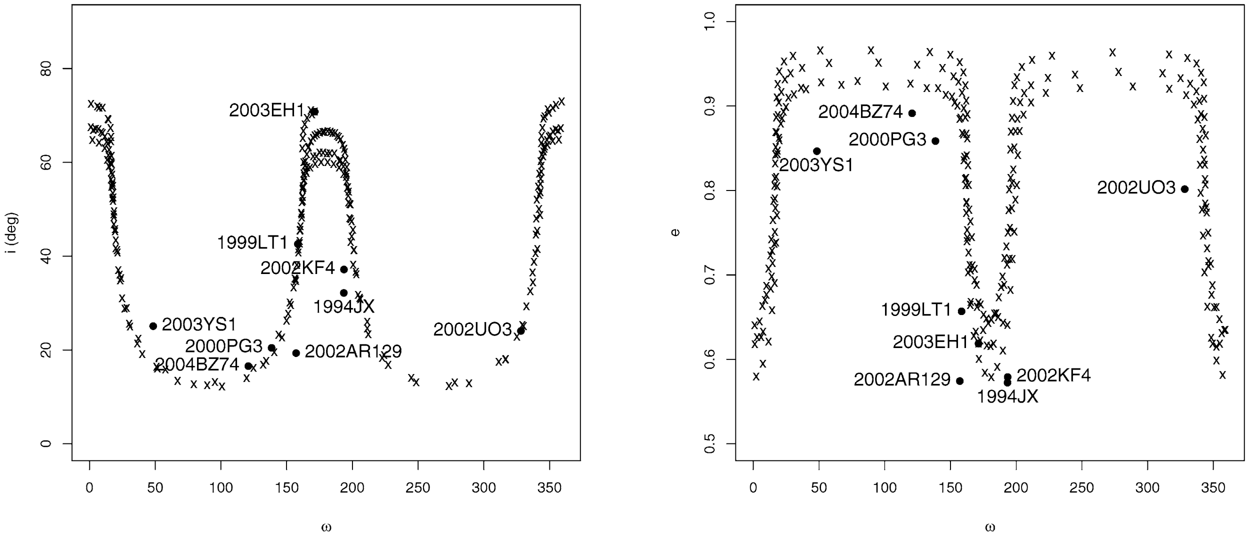

Fig. 16. The trajectories of 2003 EH1 over the past 25000 years (×) and the current location of some NEAs with a possible genetic linkage based on proximity to the trajectory of 2003 EH1 (solid circles).

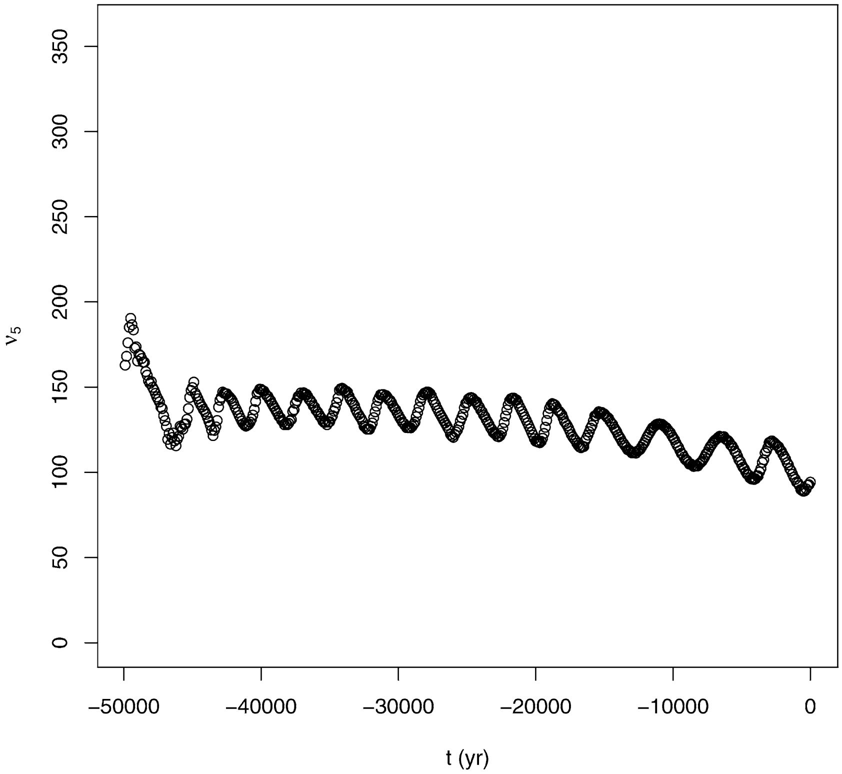

Fig. 17. The resonant argument for the ν_5 resonance based on the nominal orbit of 2003 EH1 over the past 5×10^4 yr.

Yarkovsky spin-up or tidal disruption would need to be invoked.

In the simulations where the particles are released in 1800, the first visibility of the Quadrantid shower occurs in approximately 1825. This is close to the first widely recognized observation of the Quadrantids, which occurred in 1835 (Quetelet, 1839). This simulated stream has a mean $\Omega = 282^\circ\!.93 \pm 0^\circ\!.19$ and the full width of the stream is 0°.3 at half-maximum, 0°.87 in total. These values are close to those observed: the current location of the Quadrantid node, taking the average of all post-1975 observations in Fig. 2 is $283^\circ\!.25 \pm 0^\circ\!.14$ and the stream width is ≈ 0°.5 at half-maximum [cf. Poole et al. (1972) and references therein]. These three are all consistent with the model within the uncertainties. Such a young stream might be expected to show considerable variability, but early determinations of Quadrantid activity were hampered by the short duration of the shower along with poor weather in the northern hemisphere

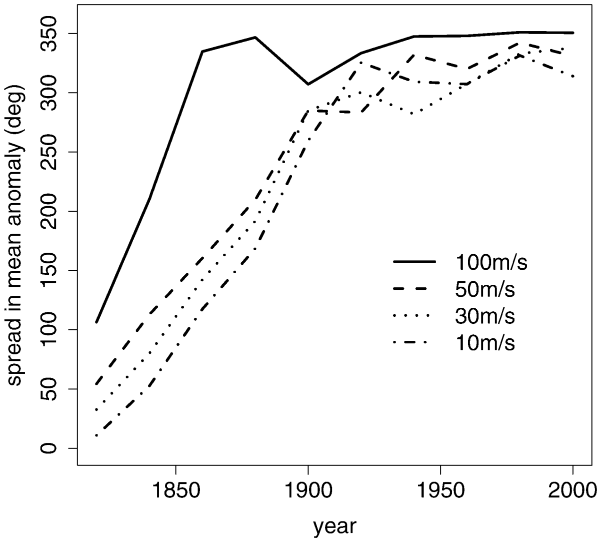

Fig. 18. The size of the smallest arc that contains all values of the mean anomaly of the 1800 outburst meteoroid stream components over time.

in early January. However, observations taken beginning in the early 20th century show a relatively stable stream. Determinations of the flux from the numerical simulations are complicated by the small numbers of particles actually intersecting the Earth's orbit. A plot of the spread in mean anomaly of the all the meteoroids in the stream is presented in Fig. 18. The streamlets at different ejection velocities are all essentially closed by the early 1900's, indicating the stream had achieved a certain amount of consistency by that point. The rapid fill-in of the stream, even for low ejection velocities, is a direct result of encounters with Jupiter. The location of the stream's aphelion near the giant planet's orbit ensures that the spreading meteoroids will receive strong perturbations within a few revolutions. These produce changes in the semi-major axis larger than those resulting from ejection processes, and accelerate the spreading of the stream. Our proposed 1800 ejection time just allows the stream to close before reliable observations begin to be taken, so its unlikely that the Quadrantids were created much later, though a slightly earlier time frame (circa 1750) could be accommodated.

The formation of the core of the Quadrantids 200 years ago is thus supported on three fronts: (1) the current location of Quadrantids is consistent with 200 years of differential evolution, (2) the 1800 release scenario produces a stream resembling the Quadrantids in all respects, and (3) most importantly, this scenario produces the correct onset time.

6. Discussion and conclusions

The picture which emerges from these integrations is of a multi-stage origin for the Quadrantids. The central core of the stream today probably originates with 2003 EH1 as first proposed by Jenniskens and Marsden (2003). We suggest that the most likely time period for the formation of the central portion of the stream is circa 1750–1800 AD. The separation of 2003 EH1 and the Quadrantid stream is most consistent with 200 years of differential precession. The rapid turn-on of the shower at the Earth argues in favor of formation in either a single event (a cometary disintegration) or over a short period of time (a few decades at most), perhaps the result of transient activity of the comet. Indeed, many of the other cometary bodies potentially associated with the stream (as suggested earlier) show this very behavior. This formation model produces a stream with orbital characteristics matching those of the Quadrantid shower, as well as naturally explaining the first appearance of the stream in records in the early 19th century—this is at or near the time of the actual formation of the core of the stream and hence the earliest any Quadrantid activity of note could have appeared in terrestrial skies. One difficulty with the origin of the stream with ejection circa the time of appearance of C/1490 Y1 is the inability to explain the sudden onset of strong Quadrantid activity in the early 19th century for virtually any choice of initial ejection velocity. Our integrations suggest that ejection ∼500 years ago would first produce noticeable, strong Quadrantid activity circa 1550 AD, which is the strongest point in favor of the late release hypothesis. For all these reasons we suggest the basic model having 2003 EH1 as the parent of the core of the stream is correct as proposed by Jenniskens (2004), but that the formation age is closer to 200–250 years ago, half his estimate of 500 years. In this interpretation, 2003 EH1 and C/1490 Y1 are potentially related, but not the same object.

The relatively large nodal dispersion for the outer portion of the stream (lasting more than a full week based on our radar observations) cannot be explained with an ejection origin of either 250–500 years in age. The outer portion of the stream must be much older, a minimum of 3500 years based on the spreading observed in our model of the stream. We suggest that the Quadrantid complex is the result of a continuing series of cometary disintegrations beginning with a large progenitor more than 5000 years ago which has subsequently produced a host of large and small bodies circulating in the Kozai resonance as discussed earlier. The larger members manifest in the form of both comets and asteroidal-like bodies, with the most recent injection of meteoroids accessible to the Earth being from 2003 EH1 roughly 200 years ago. Further support for this view comes from the modeling of Jones and Jones (1993) who find a connection between the Quadrantids and the strong Daytime–Arietids and South δ–Aquarid streams, assuming an origin time at least 2000 years in the past.

Thus it seems the Quadrantids have been present for several thousand years at least, but that the enhanced portion of the stream is only two centuries old. These earlier ejected Quadrantids have experienced substantially different orbital evolution than those in the core of the stream today. In particular, some would have experienced large excursions to small perihelia which should have baked (sintered) the meteoroids leading to stronger physical structure than meteoroids in the core population.

Although 2003 EH1 has an orbit that closely resembles that of the core of the Quadrantid meteoroid stream, we again emphasize that this does not necessarily mean it is the direct parent of the entire stream itself. The South Taurid stream, for example, has long been linked with Comet Encke ($D' = 0.094$). This association has persisted, with good reason, despite the discovery that two other bodies have D' values closer to the mean South Taurid orbit of Cook (1973), namely 5025 P-L ($D' = 0.086$) and 2003 UV11 ($D' = 0.054$). A small D' (or D) value is certainly strongly suggestive of membership in a common fragmentation hierarchy but not proof that a particular body is the primary precursor or source of a meteoroid stream.

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