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THE CORE OF THE QUADRANTID METEOROID STREAM IS TWO HUNDRED YEARS OLD

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Abstract. The Quadrantids are one of the most active annual meteor showers and have a number of unusual features. One is a sharp brief maximum, 12–14 h in length. A second is the Quadrantids, relatively recent appearance in our skies, the first observation having likely been made in 1835. Until recently no likely 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 recent fortuitous convergence of meteoroid orbits. The recent discovery of the near-Earth asteroid 2003 EH1 on an orbit very similar to that of the Quadrantids has almost certainly uncovered the parent body of this stream. From the simulations of the orbit of this body and of meteoroids released at intervals from it in the past, we find that both the sharp peak and recent appearance of the Quadrantids can most easily be explained assuming meteoroids were ejected in substantial numbers near 1800 AD.

Keywords: asteroids, 2003 EH1 – meteors, Quadrantids – meteor showers

1. Introduction

The Quadrantids, which peak in early January, constitute one of the strongest (ZHR $\backsim$ 120) meteor showers of the year. It is different from other strong showers like the Perseids, Geminids and Leonids in a number of ways. First, it appeared quite recently in our skies, circa 1800 (Williams et al., 1979) (though the Geminids also turned on in the early 19th century (Rendtel et al., 1995)). Second, it has a very sharp maximum (12–14 h) with extended low-level activity over ± 4 days. The duration of the central portion of the stream implies it is young as noted by Jenniskens et al. (1997), but the weak broader stream has a nodal spread most consistent with a much older age (cf. Jones and Jones, 1993). Third, it has had no known parent body until very recently: Jenniskens (2004) showed that 2003 EH1 is on an orbit very similar to that of the Quadrantid stream. At the high eccentricity and inclination of the Quadrantid orbit, very few of the more than 2000 recently-discovered near-Earth asteroids are present. As a result, it is very unlikely that the similar orbits of the stream and 2003 EH1 are just coincidental given their proximity in phase space. We note that, though the closeness of the orbits implies a connection between the two, 2003 EH1 hasn't been observed to display cometary activity yet and may be asteroidal.

On the basis of new Quadrantid orbits, Jenniskens et al. (1997) proposed that the stream was much younger (500 years) than previous studies had suggested. Note that this suggestion relates to the stream's narrow core rather than to the broader extent of the stream, which is likely to be much older. More recently, Jenniskens (2004) proposed that, given the proximity of their orbits, the Quadrantids were likely to be a direct recent product of the near-Earth object 2003 EH1, suggesting an age of 500 years based on comparison with earlier models.

2. The Quadrantid Stream and 2003 EH1

Here we propose that the core of the Quadrantid stream is associated with the parent 2003 EH1, but is even younger than has been proposed in the past. We present three lines of argument suggesting that the peak of the stream originated only 200 years ago. First, we show that the location of the observed maximum of the Quadrantids and the point at which 2003 EH1 crosses the ecliptic differ by an amount consistent with 200 years of differential evolution. Second, we integrate thirteen high-accuracy photographic Quadrantid meteor orbits backward along with 2003 EH1 and show that their evolution is consistent with the recent origin we propose here. Third, we simulate hypothetical meteor streams released from 2003 EH1 at various times in the past and show that, for releases prior to 1800, the appearance of the shower in Earth's skies would occur too soon. Taken together, we suggest that these points are most readily explained if the core of the stream is composed of meteoroids released circa 1800, though ejection times as early as 1750 would not be inconsistent with these points generally. We wish to emphasize that the strongest evidence in favour of this interpretation is the lack of Quadrantid observations before about 1830. We note that many other streams of comparable or weaker activity have extensive older records showing clear activity (Perseids, Leonids, cf. Zhuang (1977)) hence this lack of activity is a true feature of the shower.

The overall scenario we propose involves the progressive fragmentation of the original parent body. This process would take several millennia and result in many daughter objects, of which 2003 EH1 is only one. Steel (1991) has put forward a similar hypothesis regarding the Taurid complex. The broad portion of the Quadrantid stream is of order 10^4 yrs old based on its duration, with the central part being much younger due to a release event from 2003 EH1 in circa 1800.

2.1. Differential evolution

There have been many observations of the Quadrantid shower since the first recorded instance in 1835 (Quetelet, 1839). Figure 1 is a compilation of reported locations of visual and radar maxima, as far as possible derived from the original sources. Early visual observations have uncertainties that are difficult to quantify, but are important in understanding the regression of the location of this stream, a fact which has been noted by previous authors (Hawkins and Southworth, 1958; Murray, 1982). Observations that do not quote an uncertainty in the peak location are given a value of ± 1 degree in solar longitude here. Given the narrowness of the peak, its unlikely that any visual observers would have seen the shower had they not observed it relatively close to the maximum.

A weighted least squares fit to the regression rate yields −0°0034 ± 0°0015 per year. Early studies of observed Quadrantid peak times found somewhat faster precession rates (Hines and Vogan, 1957; Hawkins and Southworth,

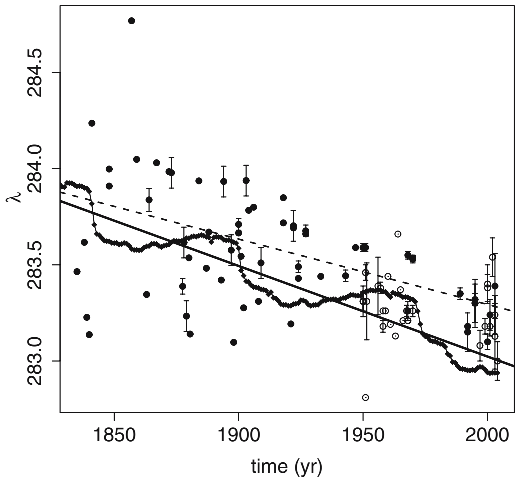

Figure 1. The solar longitude (J2000.0) of the peak of the Quadrantid meteor shower. The solid circles are visual (Quetelet, 1839; Quetelet, 1842; Backhouse, 1884; Denning, 1888; Denning and Wilson, 1918; Denning, 1924; Fisher, 1930; Prentice, 1953; Hindley, 1970; Hindley, 1971; Poole et al., 1972; Roggemans, 1990; Rendtel et al., 1993; Evans and Steele, 1995; Langbroek, 1995; Jenniskens et al., 1997; McBeath, 2000, 2001, 2003; Arlt and Krumov, 2001) determinations, the empty circles are from radar (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). The line marked with diamonds marks 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). The heavy line is a linear-least squares fit to the evolution of 2003 EH1; the dashed line is a fit weighted by the uncertainties to the observations. Points without reported uncertainties have no error bars shown, and were assigned uncertainties of ± 1 degree.

1958), but our value is consistent with more recent observational determinations such as that of $-0°0038 \pm 0°0014$ (Murray, 1982). Fitting a line to 2003 EH1's nodal evolution shows a best-fit slope of $-0.004710 \pm 0°000086$ yr^{-1}. It is also presently offset from the location of the Quadrantid shower by $\backsim 0°25$.

Differential precession should cause a separation of this size to arise in $0°25/0°00131$ yr$^{-1} \approx 200$ yrs. These data, particularly the older observations, contain substantial uncertainties. As well, the node of those orbits intersecting the Earth may not be the same as that of the stream as a whole, and some nodal dispersion may be due to the meteoroids' ejection velocities. Nevertheless, this analysis does suggest that the core of the Quadrantid stream was formed only 200 years ago.

2.2. Meteoroid orbits

A number of high-accuracy photographic orbits of Quadrantids have been obtained by Jacchia and Whipple (1961) and Hawkins and Southworth (1961). By integrating these orbits backward numerically, one can attempt to determine an approximate time of ejection. This was done by computing the proximity of the orbits of the meteors to that of 2003 EH1 (by means of a standard D parameter) as all objects were evolved backward in time (more detail on the algorithm in Section 2.3).

Figure 2 shows the mean values of the D (Southworth and Hawkins, 1963) and D' (Drummond, 1981) parameters of these thirteen meteor orbits

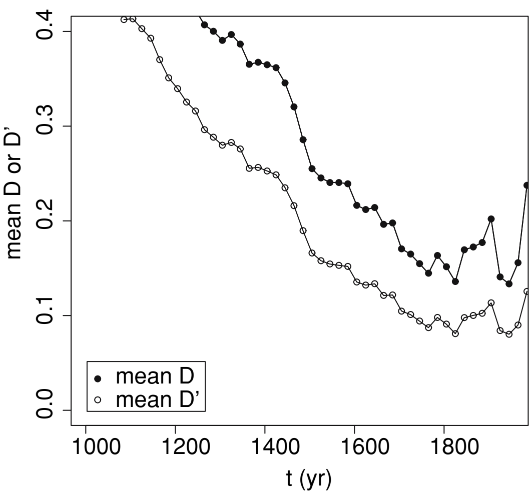

Figure 2. The mean D and D' values of 13 Quadrantid meteors relative to the instantaneous orbit of 2003 EH1 during the recent past.

calculated relative to the instantaneous orbit of 2003 EH1. Both quantities show a marked decrease in the recent past, with minima in the 1800's and a growing separation between the meteoroids and 2003 EH1 in the more distant past. These results must be interpreted with care given the frequent encounters of the bodies with Jupiter, and which results in the magnification of small uncertainties. As a result, we don't expect the simulations to show the meteoroids moving back to their precise launch points from the body in question. Nevertheless, these results suggest that the meteoroids are more likely to have originated from 2003 EH1 recently.

2.3. Stream modelling

The orbit of 2003 EH1, integrated numerically into the past, was used as the starting point for hypothetical meteor streams. An integrator of the Wisdom–Holman type (Wisdom and Holman, 1991) was used for all simulations. The algorithm was modified to handle close approaches symplectically by the hybrid method (Chambers, 1999). A time step of 1 day was used. The eight major planets (except Pluto) are included in all simulations. The asteroids and meteoroids are treated as test particles, in that they feel the planets' influence but not each others.

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 minimum in D' observed in Figure 2, 1600 AD suggested by Jenniskens (2004), or 1491 AD corresponding to the time of perihelion passage of c/1490 Y1, a comet which has been linked to the Quadrantids in the past (Hasegawa, 1979; Williams and Wu, 1993,). The nominal orbit of 2003 EH1, integrated backward, was used as the release point for the simulated meteoroids.

Each outburst was simulated by sixteen sets of 500 particles. Each set had an ejection velocity from the nucleus of 1, 5, 10, 30, 50, 100, 300 or 1000 m/s and β of 0 or 5×10^{-3}. The low (1 and 5 m/s) and high (300 and 1000 m/s) speeds represent the extreme physically probable lower and upper limits for ejection velocities. The ejection directions were chosen randomly over a sphere. The distribution of the resulting orbits, in particular those intersecting the Earth, is compared with observations of the Quadrantid stream. If a meteoroid's nodal distance was found to be within 0.01 AU of the Earth's orbit at a given time, it was considered to become visible as a meteor.

In all three cases the released meteoroids, once integrated forward to the current time, produce meteor showers with orbital elements similar to that of the Quadrantid stream (though with some small number of particles scattered onto quite different orbits). What differentiates most strongly between the different release times is the time of first appearance in Earth's skies. The 1491 release produces meteors at the Earth prior to 1600, and meteoroids at all release speeds begin to arrive persistently in large numbers by the early 1600's. The 1600 release produces a shower by the late 1600's that is persistent and rising in strength over time. The meteoroids with the smallest release velocities appear last, with those at 5 m/s arriving near 1775, and those at 1 m/s arriving in $\backsim$1800. If only very low release velocities are considered, the stream resembles the Quadrantids in orbit and onset time but material released even at 10 m/s arrives in significant numbers by the early 1700's. If the Quadrantid core did arise in 1600 then it must have originated from a very low velocity splitting event, with little of the few tens of meters per second ejection velocities typically expected of cometary out-gassing (Whipple, 1951). The 1800 release scenario produces meteors at the Earth in 20–30 years at all ejection speeds: the flux increases sharply from zero to a strong persistent shower over less than a decade or two. Since the first widely recognized observation of the Quadrantids occurred in 1835 (Quetelet, 1839) this scenario best matches the observed onset of the Quadrantid shower.

3. Conclusions

The sharp core of the Quadrantid stream is most consistent with a recent, relatively short duration release from 2003 EH1, as proposed by Jenniskens (2004). Our studies show that this release event is most likely to have occurred in approximately 1800, for three reasons. First, the separation between the maximum of the Quadrantids and the regression of the node of 2003 EH1 is consistent with 200 years of differential evolution. Second, integrations of high-accuracy meteoroid orbits backward shows minimum D and D' values that better agree with release scenario near 1800. Third, this scenario produces a modelled stream width, orbit, and (most importantly) time of onset completely consistent with the observed Quadrantid stream.

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