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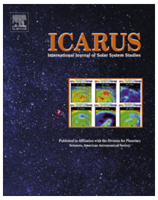

On the age and formation mechanism of the core of the Quadrantid meteoroid stream

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ABSTRACT

The Quadrantid meteor shower is among the strongest annual meteor showers, and has drawn the attention of scientists for several decades. The stream is unusual, among others, for several reasons: its very short duration around maximum activity (≈12–14 h) as detected by visual, photographic and radar observations, its recent onset (around 1835 AD Quetelet, L.A.J. [1839]. Catalogue des principles apparitions d'etoiles filantes) and because it had been the only major stream without an obvious parent body until 2003. Ever since, there have been debates as to the age of the stream and the nature of its proposed parent body, asteroid 2003 EH_1.

In this work, we present results on the most probable age and formation mechanism of the narrow portion of the Quadrantid meteoroid stream. For the first time we use data on eight high precision photographic Quadrantids, equivalent to gram–kilogram size, to constrain the most likely age of the core of the stream. Out of eight high-precision photographic Quadrantids, five pertain directly to the narrow portion of the stream. In addition, we also use data on five high-precision radar Quadrantids, observed within the peak of the shower.

We performed backwards numerical integrations of the equations of motion of a large number of 'clones' of both, the eight high-precision photographic and five radar Quadrantid meteors, along with the proposed parent body, 2003 EH_1. According to our results, from the backward integrations, the most likely age of the narrow structure of the Quadrantids is between 200 and 300 years. These presumed ejection epochs, corresponding to 1700–1800 AD, are then used for forward integrations of large numbers of hypothetical meteoroids, ejected from the parent 2003 EH_1, until the present epoch. The aim is to constrain whether the core of the Quadrantid meteoroid stream is consistent with a previously proposed relatively young age (≈200 years).

1. Introduction

The Quadrantids are among the most active meteor showers, reaching a peak activity of Zenithal Hourly Rate (ZHR) ~110 to 130 on 3–4 January each year (Shelton, 1965; Hindley, 1970; Hughes and Taylor, 1977), as determined by photographic, visual, video and radar techniques. The stream has recently been linked with asteroid 2003 EH_1 (Jenniskens, 2004).

The Quadrantid shower is unusual among meteoroid streams presently visible at the Earth for several reasons. Firstly, the Quadrantid meteor shower has a short duration of maximum activity, which we will call the 'core' or the "narrow structure" of the stream. The Full-Width at Half-Maximum (FWHM) of the core activity is ≈0.6 days (Shelton, 1965; Hughes and Taylor, 1977; Brower, 2006) for visual-sized particles, implying that this central portion is very young, while the shower as a whole has an overall duration of significant length ~4 days. Secondly, it has only become active recently, being first noted circa 1835 (Quetelet, 1839; Fisher, 1930). Moreover, the activity of the shower has changed dramatically over the last 150 years, from a very weak shower to among the strongest visible at the Earth (Jenniskens, 2006). Finally, recent radar observations (Brown et al., 2010b) suggest low level activity of the shower persisting for a few months (November to mid January), suggesting the stream has an older component as well.

Presently, the presumed parent body of the core of the Quadrantids is the *Near Earth Object* (NEO) 2003 EH_1. 6 Throughout this paper we will refer to it as asteroid 2003 EH_1. The object has been classified as an Amor type asteroid, although its nature is arguable based on dynamical criteria. Asteroid 2003 EH_1 has a short-period comet-like orbit, with a Tisserand parameter with respect to

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Jupiter of $T_J \approx 2.0$, but currently shows no evidence of cometary activity, suggesting that it is a strong candidate for either a recently dormant or extinct comet (Koten et al., 2006).

Prior to the discovery of 2003 EH_1, a few other objects with less similar orbits had been connected to the Quadrantid meteoroid stream, most notably comet 96P/Machholz (Jones and Jones, 1993; McIntosh, 1990; Babadzhanov and Obrubov, 1992) and comet C/1490 Y1 (Hasegawa, 1979; Lee et al., 2009; Williams and Wu, 1993; Williams and Collander-Brown, 1998). However, the relationship of these bodies to the Quadrantids remains unclear.

The earliest attempt to tackle the age of the Quadrantid meteoroids stream can be attributed to Hamid and Youssef (1963). The authors carried out a numerical secular perturbation analysis on the orbit of six doubly photographed Quadrantids and discovered large variations in the perihelion distance and the inclination of the stream orbit, with a period of 4000 years. Based on the backward secular solutions, the authors argued that the orbital elements of the six meteors were similar around 3000 years ago.

Williams et al. (1979) calculated the secular variations of the orbital elements of the mean Quadrantid stream and concluded that the Quadrantid meteoroid stream may have resulted from two major comet break-ups about 1690 and 1300 years in the past, where the resulting meteoroids converged into their present orbit around 200–150 years ago, explaining the recent appearance of the stream. Similar work was also performed by Hughes et al. (1979).

Hasegawa (1979), was the first to propose a potential parent body for the Quadrantids, noticing a similarity between the orbits of the mean Quadrantid stream and comet 1491 I (=C/1490 Y1), recorded in ancient Chinese observations. However, only a parabolic solution was assumed for the orbit of comet 1491 I, due to the low observational accuracy in the position of the comet. Based on the arguable similarity between the orbits of 1491 I and the Quadrantids, the authors concluded that 1491 I had been a periodic Jupiter-family comet, which suffered a very close encounter with Jupiter and was perturbed into a longer period orbit, where the orbital association with its meteoroid stream was lost.

Assuming that 1491 I was the actual parent of the Quadrantids using the calculated orbital elements of the comet, Williams and Wu (1993) concluded that the stream was created ~5000 years ago. Based on the hypothesis of a very shallow close encounter between comet 1491 I and Jupiter, Williams and Wu (1993) demonstrated that prior to the encounter with Jupiter, the eccentricity of the orbit of the comet must had been $e \approx 0.77$. The newly derived value for the eccentricity was used for backwards integration of the orbit of the comet to about 5000 years. Then, that epoch was used for the meteoroids ejection whose orbits were integrated forward until the present. The authors argued that the observed mean orbital elements of the stream is consistent with dust particle ejection ~5000 years ago. However, the lack of precise orbital elements for 1491 I, along with a hypothesized close encounter with Jupiter, renders the later conclusion uncertain. For a similar work, see also Lee et al. (2009).

Another possible parent of the Quadrantids is the comet 96P/Machholz (formerly P/1986 VIII). McIntosh (1990) calculated the secular precession of the orbital elements for the Quadrantids and comet 96P/Machholz and found that the long-term evolution of both orbits is strikingly similar, except for their precession cycles being shifted by a period of 2000 years. The author suggested that the stream was quite old and the phase shift in the precession cycles is due to the differential precession of the orbits of the stream and the comet. Moreover, the author argued that Quadrantids may be a part of a larger complex of meteoroid stream, belonging to comet 96P/Machholz.

Babadzhanov and Obrubov (1992) integrated the orbits of three test particles similar to that of comet 96P/Machholz for 8000 years back in time. Then 20 test particles were ejected from the nucleus of 96P at the epoch of 4500 BC and integrated forward until 3000 AD. For that period of 7500 years, the authors argued that meteoroids released by 96P can produce eight meteor showers on Earth within one precession cycle of the argument of perihelion ω of the meteoroids. Six of these showers have been identified as: the Quadrantids, the Ursids, Southern δ – Aquarids, daytime Arietids, Carinids and α – Cetids. That led the authors to conclude that 96P/Machholz is the parent of the Quadrantid meteoroid stream. For additional and more extensive work, see also Jones and Jones (1993) and Kaňuchová and Neslušan (2007).

Jenniskens et al. (1997) used ~35 doubly-photographed Quadrantids taken in 1995 by the *Dutch Meteor Society* (*DMS*) (Betlem et al., 1995), to argue that the age of the central portion of the Quadrantid stream is only ~500 years old and the parent may be hidden on a *Near Earth Object* (*NEO*) – like orbit. With the discovery of 2003 EH_1 in 2003 (Jenniskens and Marsden, 2003; McClusky et al., 2003), Jenniskens (2004) noted the striking similarity between the current orbit of the Quadrantids and the orbit of 2003 EH_1 and proposed a sibling relationship.

Wiegert and Brown (2005) estimated an approximate age of 200 years for the core of the Quadrantids, based on the nodal regression rate of the stream and forward integration of meteoroids, released by 2003 EH_1 circa 1800 AD. The authors concluded that meteoroids released prior to 1800 AD appear on the sky at much earlier times than the first reported appearance around 1835.

The main goal of this work is to estimate the most probable age of the central portion of the Quadrantid meteoroid stream and its mode of formation (e.g. cometary sublimation vs. asteroidal disruption). We seek to first constrain the approximate formation age assuming 2003EH1 is the parent by first performing backward integrations of high precision Quadrantid meteoroids to compare the orbital similarity between the meteoroids and 2003 EH_1. Having established an approximate age from backward integrations we then attempt to simulate the formation of the core of the stream forward in time using the formation epoch found from backward integration and compare with the characteristics of the stream. However, our intention is not to provide a complete and detailed picture of all physical characteristics of the stream, rather we aim to demonstrate whether the observed overall characteristics of the core of the stream can be explained by assuming a relatively recent (a few hundred years) formation age derived from backward integrations of individual meteoroids.

As a test of reliability of our backward integration estimate of the age and formation mode of the stream, we compare the following theoretical and observed characteristics of the stream:

1. The timing of the appearance of the stream on the sky (around 1835 AD).
2. The mean position and spread of the geocentric radiant of the stream.
3. The position of the peak of the activity profile of the core.
4. The width of the activity profile of the core (FWHM $\approx$ 0.6 days).

Throughout this work, we use an approach similar to that of Gustafson (1989). That author integrated backward in time the orbits of 20 high precision Geminids, along with the parent 3200 Phaethon, and compared the epochs at which the orbits of the Geminids and that of Phaethon intersected. Moreover, he calculated the probable meteoroid ejection speed and location on the orbit of the parent, and concluded that the Geminids are consistent with cometary sublimation that might have taken place on Phaethon around 600–2000 years ago. For an exhaustive description of the method see also Adolfsson (1996).