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Models for the origin of the Quadrantids

Received: date

Abstract  We present two scenarios for production of the Quadrantid stream based on two different models for its origin: the extinct model in which 2003EH1 was an active comet that released the dust particles during past 5000 years, stopping its activity abruptly in AD 1488; and the split model; in which a catastrophic disruption of an asteroid at AD 1488 released a large number of dust particles in a single event. We calculate the orbital evolution of test particles released in both cases and derive the resulting size distribution of surviving meteoroids in the current Quadrantid stream in the form of $s^{-\alpha} ds$, where $s$ denotes the radius of a meteoroid. We find $\alpha = 3.1$ in the extinct model and $2.0$ in the split model. In addition, the radius of the surviving meteoroids is derived as $s > 10\mu m$ in the both models. We propose, based on
our estimation of the infrared color ratio for the Quadrantid stream derived from both models, that infrared observations of the Quadrantid stream may determine which origin model is more reasonable.

**Keywords** 2003EH1 · Quadrantids · dust trail · color ratio

1 Introduction

The Quadrantid shower, one of the major meteor showers, was first observed in January 1835 [Kronk, 1988]. However the parent body has not been determined, and debate continues. Hasegawa (1979) suggested the parent body was comet C/1490Y1, which was observed in China, Korea, and Japan. The orbital elements of C/1490Y1 were assumed to be parabolic, but as the position of C/1490Y1 had not been observed in detail at that time, the orbital elements of the C/1490Y1 included some uncertainty. Williams and Wu (1993) found that the orbital elements of the Quadrantids and C/1490Y1 were in good agreement with each other in AD 1491, if that comet had an eccentricity of 0.77, rather than 1.

Another proposed candidate for the parent body of the Quadrantid stream is the comet 96P/Machholz1. Gonczi et al. (1992) found that dust particles ejected with a forward ejection velocity $10\text{ms}^{-1}$ from 96P/Machholz1 could form the present observable Quadrantid stream.

On 6 March 2003, the asteroid 2003EH1 was discovered by the Lowell Observatory Near-Earth Object Survey (LONEOS) telescope [Skiff, 2003]. Based on a comparison of the orbital elements of asteroid 2003EH1 with those of the Quadrantids (see Table 1), 2003EH1 was proposed to be strongly related to the Quadrantids [Jenniskens, 2004]. 2003EH1 is not now an active comet.

We examine two models with different mechanisms for producing the dust: one, that 2003EH1 is an extinct comet and another, that a split of an asteroid produced the Quadrantid stream.

The parent body of the Geminids is the asteroid 3200 Phaethon, which should be classified as a comet rather than an asteroid [Mason, 1988]. 3200 Phaethon shows no cometary activity and is considered an extinct comet. After the parent body stopped releasing dust particles, the dust particles survived in the meteor stream. In Model I, we assume that 2003EH1 was an active dust-producing comet until AD 1490. These particles are responsible for the Quadrantid stream. In this model, 2003EH1 was observed as C/1490Y1 and became dormant after AD 1490.

In Model II, the source of the dust particles is a split of a small solar system body. In fact, the fragmentation of 73P/Schwassmann-Wachmann 3 produced a large amount of dust particles and formed a dust trail [Sitko, 2006]. We predict that a small body split, due to impact or fragmentation, and produced the Quadrantid stream about 520 years ago. In this model, we may regard 2003EH1 and C/1490Y1 as components of fragments produced by the split.

In this paper, we examine the dynamical evolution of the dust particles based on these two models. From the orbital evolution of these test particles, we can estimate the size distribution in the Quadrantid stream in the present.
We calculate the infrared color ratio of the dust cloud from the size distribution, and infrared observations of the trail, in conjunction with this work, will provide a clue to the origin of the Quadrantids. In this paper, we refer to the present Quadrantid stream as the "dust trail".

2 Models

2.1 Extinct model

When we investigate the orbital evolution of a meteor stream, it is needed to proceed integration of the equation of motion as long as possible. JPL’s ephemeris DE408 provides the planetary coordinate and velocity correctly from 10000 B.C. to A.D.10000. [Standish,2005] In our extinct model (Model I) we consider the time scale of dust production as beginning 5000 years ago, we obtain the coordinates of the planets and Moon at all times during the integration from JPL’s ephemeris DE408 and proceed with a backward integration of the orbit of 2003EH1 from AD 2005 to 2995BC (Fig. 1). We found that the orbital elements of 2003EH1 were close to those of C/1490Y1 around AD 1490. This similarity permits us to assume that the asteroid 2003EH1 was active around AD 1490. In our simulation, test particles were ejected from the nucleus at each perihelion passage between 2995 BC and AD 1488, and no particles were released after AD 1488. Here, we suggest that AD 1488 was the nearest perihelion passage time to AD 1490 when C/1490Y1 was observed in China, Korea and Japan. 2003EH1 had returned to perihelion 892 times, from 2995 BC to AD 1488. McNaught and Asher (1999) predicted the time of maximum activity of the Leonid meteor shower to within ~ 10 min. In their simulation, test particles are released at 55P/Tempel-Tuttle’s perihelion only, although a comet releases dust particles when its heliocentric distance is smaller than 2-3 AU. Two test particles are ejected forward and backward relative to the direction of motion of 55P/Tempel-Tuttle’s perihelion. To produce the range of orbital elements of meteors, we set the direction of ejection as forward and backward at the 2003EH1’s perihelion.

The solar radiation pressure force is the main factor contributing to dust particles escaping from the dust stream. Figure 2 shows that smaller dust particles have a lower survival rate in the dust stream. The velocity \( V(m/s) \) relative to the parent body of the ejected dust particles depends on the heliocentric distance, particle size, and radius of the parent body. Gustafson (1989) gives the ejection velocity \( V(m/s) \) of dust particles from comets as a function of the heliocentric distance \( q \) (AU)

\[
V = 10R_c^{0.5} \sqrt{\frac{A}{mq^{9/4}}} - 0.1R_c \tag{1}
\]

where \( R_c \sim 0.9(km) \) is the supposed radius of 2003EH1 [Williams,2004], and \( q(AU) \) is the heliocentric distance of the comet. \( A(cm^2) \) is the projected surface area of the dust particle perpendicular to the gas stream from the nucleus and \( m(q) \) is the mass of the particle. \( \beta \) represents the ratio of solar radiation pressure force to solar gravity. We assume the test particle is
a spherical silicate dust particle whose density is 2.4 (g/cm$^3$) [Draine,1984] because Koten et al (2006) found that the properties of the Quadrantids meteor showed cometary and asteroid origins. We calculate orbital evolution in the case of $\beta = 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}$ and $10^{-2}$. We simulate the motion of the released test particle under the gravitational influence of the Sun, the six planets (from Mercury to Saturn), and the Moon, as well as under solar radiation pressure forces. Poynting-Robertson effects are also considered [Burns,1979].

We integrate the equation of motion by using RADAU [Everhart,1985]. Integration periods run from the time of each ejection to AD 2005 January 4.

Southworth and Hawkins (1963) used the orbital similarity criterion $D$ to investigate the relationship between two planetary bodies. $D$ is a generalized measure of distance between two orbits in the five-dimensional space of the conventional orbital elements $q$ (perihelion distance), $e$ (eccentricity), $i$ (inclination), $\omega$ (argument of perihelion), and $\Omega$ (longitude of ascending node):

$$D^2 = (e_2 - e_1)^2 + (q_2 - q_1)^2 + (2 \sin \frac{I_{21}}{2})^2 + \left( \frac{e_2 + e_1}{2} \right)^2 \left( 2 \sin \frac{\pi_{21}}{2} \right)^2$$

where

$$2 \sin \frac{I_{21}}{2} = (2 \sin \frac{i_2 + i_1}{2})^2 + \sin i_1 \sin i_2 (2 \sin \frac{\Omega_2 - \Omega_1}{2})^2$$

$$\pi_{21} = \omega_2 - \omega_1 + 2 \sin^{-1} (\cos \frac{i_2 + i_1}{2} \sin \frac{\Omega_2 - \Omega_1}{2} \sec \frac{I_{21}}{2})$$

and

$$I_{21} = \cos^{-1} (\cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos(\Omega_2 - \Omega_1)),$$

and where the suffixes 1 and 2 refer to the two orbits being compared. In this paper, suffix 1 indicates the orbital elements of the present Quadrantids and suffix 2 denotes that of the test particle. Southworth and Hawkins derived a threshold value of $D$ of 0.2. A meteor stream is a collection of many orbits, and so it is difficult to define the representative orbital elements. Dutch Meteor Society (DMS) determine the 39 Quadrantid meteor orbits by photographic observations [Jenniskens,1997]. Two test particles are ejected forward and backward relative to the direction of motion of 2003EH1, in one revolution. We calculate two $D$ values from two (forward and backward) test particles in the same perihelion passage and one of DMS’s Quadrantid orbital elements. We substitute DMS orbital element for suffix 1, and the orbital elements of test particles for suffix 2 of equation (2)-(5). we determine the survival rate $r_i(s)$ of dust particles with radius $s$ released is

$$r_i(s) = \frac{0.2 - D_{\text{min}}^{(i)}}{D_{\text{max}}^{(i)} - D_{\text{min}}^{(i)}}, (i = 1 \text{ to } 39)$$

where $D_{\text{min}}^{(i)}$ is the lower limit and $D_{\text{max}}^{(i)}$ is the upper limit of the $D$ value range. The index $i$ designates the number of DMS’s Quadrantid orbit. If
$D_{\text{min}}^{(i)} > 0.2$, the survival rate $r_i(s) = 0$, and if $D_{\text{max}}^{(i)} < 0.2$, the survival rate $r_i(s) = 1$. 39 survival rates $r_i(s)$ are determined in one revolution, and these 39 survival rates $r_i(s)$ are averaged. We determine the average of 39 survival rates is the survival rate $r^{(j)}(s)$ for the particles released in a given revolution (Fig. 2). The index $j(j = 1 \to 892)$ denotes the number of the revolution of 2003EH1.

2.2 Split model

The nucleus of comet Shoemaker-Levy9 (SL9) was assumed to have been split by Jovian tidal forces. The split produced a large number of dust particles, and an increase in brightness, due to sunlight scattering of these dust particles led to SL9’s detection. The possibility exists that C/1490Y1’s brightness increased due to the splitting of a minor planet, as with SL9. The source of the split would be tidal force, thermal stress, or collision with another small body. In this split model, a test particle is released in AD 1488 when 2003EH1 passed the perihelion closest to AD 1490. The test particle is a spherical silicate, as was used for the ”extinct model”. 100 test particles with radii in the range of $10\mu m - 2.2 \times 10^4 \mu m$ are evenly spaced on a logarithmic scale. Though the sub-nuclei of SL9 had relative velocities of the order of 0.1 m/s, smaller dust particles have larger initial velocity, arising from chaotic collisions [Sekanina, 1994]. In split model, the initial velocity of ejection is 1.0 m/s independent of dust radius and heliocentric distance. We estimate the survival rate $r(s)$ of test particles by the same method of extinct model, in each particle size. We find that small test particles ($\sim 10\mu m$) can survive in the dust trail (Fig. 3).

3 Size Distribution

From the simulation of orbital elements in Section 2, the fraction of dust particles that survive is determined, at each size. The size distribution of dust particles is expressed in the form of $s^{-\alpha}ds$. It is necessary to determine the original $\alpha_0$, due to estimate the current size distribution. In usual comet, the original index $\alpha_0$ is 3.5 [Fulle, 2004]. The dust particles in SL9’s coma were produced by the collapse of cometary nucleus, because no gas emission was detected from any observation of SL9. Sekanina et al (1994) concluded that the size distribution in SL9’s coma is $\alpha = 1.0 - 4.0$. In the split model, we determined the $\alpha_0 = 2.5$ as the average of 1.0 and 4.0.

From the ”extinct model”, we estimate the number ($N(s)$) of surviving dust particles of radius $s$ as

$$N(s) = \sum_{j=1}^{892} r^{(j)}(s) \times C s^{-\alpha_0},$$

(7)

where $\alpha_0$ denotes original size distribution index, $\alpha_0 = 3.5$ and the index $j$ denotes the number of revolution. The relationship of the $\beta$ value to dust radius $s(\mu m)$ is [Mukai, 1982]
\[ \beta = 0.16s^{-1.2}(s \geq 0.6 \mu m). \] (8)

\[ \beta = 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} \text{ and } 10^{-2} \text{ treated in the "extinct model" correspond to test particle radii of } 2.2 \times 10^3 \mu m, 3.2 \times 10^3 \mu m, 468 \mu m, 68 \mu m \text{ and } 10 \mu m, \text{ respectively.} \]

In the split model, we estimate the number of surviving dust particles of radius \( s \)

\[ N(s) = Cr(s)s^{-\alpha_0}, \] (9)

where \( r(s) \) is the survival rate of test particle of radius \( s \), \( \alpha_0 = 2.5 \) is the original size distribution index and 100 sizes of test particles are given. The constant \( C \) is set to be normalized for the number of dust particles with a radius 100 \( \mu m \) (see Fig.4). The relative number of dust particles of each size is estimated by equation (7) and (9). The index \( \alpha \) is determined from the inclination of the fitting line (Fig. 4) for both models. Table 2 summarizes the results of our simulations.

4 Color Ratio

We assume that the number density of dust particles is uniform anywhere in the dust trail because the dust particles released from one revolution spread all over the Quadrantid orbit in 500 years [Jenniskens,2004]. The total thermal energy \( F_\lambda \) per unit area from the dust trail is given by the following [Mukai,1977],

\[ F_\lambda = \int_{l_1}^{l_2} dt \int_{s_1}^{s_2} ds N(s)Q_{abs}(s, \lambda)B_\lambda(T_g(s, r)), \] (10)

where \( l_2 - l_1 \) denotes the width of the Quadrantid dust trail in the line of sight direction, \( B_\lambda \) is a Planck distribution of grain temperature \( T_g \) and \( Q_{abs} \) denotes the efficiency factor for absorption derived from Mie theory as a function of grain radius \( s \) and wavelength \( \lambda \). \( N(s) \) is the total number of grains in unit volume \( V \). The numerical integration of equation (10) converges when the upper limit \( s_2 = 1.0 \times 10^5 \mu m \). We set the upper limit of integration at \( s_2 = 1.0 \times 10^5 \mu m \) and the lower limit of integration as the minimum radius dust particle \( s_1 = 1.0 \mu m \). The infrared astronomical satellite AKARI launched in 2006 by Japan Aerospace Exploration Agency(JAXA) carries a Far Infrared Surveyor(FIS) and InfraRed Camera(IRC). Since FIS’s observation wavelength range is 50 – 180 \( \mu m \) and IRC’s is 1.7 – 26.5 \( \mu m \), we estimate color ratio \( F_{100}/F_{52} \) and \( F_{18}/F_{11} \). Fig.5 shows that the color ratio is a function of the heliocentric distance.

5 Discussion and Conclusions

As Fig. 1 shows, the orbital elements of 2003EH1 varied periodically. Other results of the simulations of orbital evolution are consistent with our simulation [Williams,2004; Wiegert,2005].
Quadrantids show stable periodic variation in orbital elements by Kozai resonance. The eccentricity ($e$) and inclination ($i$) changed periodically (Fig. 1). In $-1,500$ years, the values of $e$ and $i$ differ widely from present values, i.e.: the inclination was very low and eccentricity was very high. Few test particles released in this period can remain in the dust trail. Some dust particles are constantly in and out of the Quadrantid stream, because these changes of the orbital element affect the D values in our models. The size distribution which we estimate in this work are in the present.

The total mass ($M_{\text{total}}$) of dust particles in the Quadrantid stream is nearly $1.0 \times 10^{13}$ g (for masses of $10^{-6} - 10^{3}$g) [Jenniskens,2006]. From our work, the total mass is given by the expression below.

$$1.0 \times 10^{13} = C \sum_{j=1}^{s_{\text{max}}} \int_{s_{\text{min}}}^{s_{\text{max}}} r^{(j)}(s) \left(\frac{4}{3}\pi s^3 \rho\right)s^{-\alpha_0} ds,$$

where $C$ is constant, $s$ is the radius of dust particle, $r^{(j)}$ is the survival rate of dust particles with radius $s$, the index $j$ is the number of revolution, $\alpha_0 = 3.5$ is the index of size distribution in extinct model, $\rho = 2.4g/cm^3$ is the density of dust particles, $s_{\text{min}} = 10\mu m$ is the smallest radius and $s_{\text{max}} = 4.6 \times 10^4 \mu m (\sim 10^3 g)$ is the largest radius. The original total mass of the dust particles ($M_0$) released in one revolution is represented by

$$M_0 = \int_{s_{\text{min}}}^{s_{\text{max}}} Cs^{-\alpha_0} ds$$

We can determine the constant $C$ from eq.(11). By substituting the constant $C$ in eq.(12), we can determine the original total mass $M_0$. 2003EH1 must release $M_0 = 9.8 \times 10^{13}$ g dust particles in one revolution while in its active phase. Jupiter family comets release a total mass of $10^{12} - 10^{13} g$ dust particles in one revolution [Reach,2000; Ishiguro,2007]. Thus, 2003EH1 must be 10-100 times more active than a typical Jupiter family comet, if 2003EH1 was once an usual comet.

Jenniskens (2004) evaluated the magnitude distribution index $\chi = 3.5$ of the Quadrantid background component where it is rich in faint meteors. The magnitude distribution $\chi = 3.5$ corresponds to the size distribution $\alpha = 2.08$, it supports the "split model". Ishiguro et al.(2007) reported the particle radius range of some dust trails, : $1.0 \times 10^3 \mu m - 1.0 \times 10^4 \mu m$ (2P/Encke), $1.0 \times 10^3 \mu m - 1.0 \times 10^4 \mu m$ (22P/Kopff), and $1.0 \times 10^2 \mu m - 1.0 \times 10^3 \mu m$ (65P/Gunn). These results are consistent with neither model. Small dust particles are included in our model.

The color ratio increases with decreasing temperature because the dust particles are distributed uniformly throughout the dust trail. The color ratio is clearly different for each model.

Due to the large inclination ($\sim 71^\circ$) of the Quadrantid stream to the zodiac plane, AKARI can identify it very easily without confusing scattering light from the zodiacal dust which is dust in the ecliptic plane. Since FIS covers the simulation wavelength (52,100$\mu m$), we expect AKARI to detect the Quadrantid dust trail.
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References

Standish,2005. Private communication
Fig. 1 The computed orbital evolution of 2003EH1 in the last 5000 years. We integrated the present orbital elements for the past 5000 years. 2003EH1 moves in an orbit just below a 2:1 mean-motion resonance with Jupiter. Each element shows periodic variation. The filled triangle indicates the orbital element of C/1490Y1 in AD 1490.
Fig. 2 The result of the extinct model. The horizontal axis shows the time in years, where -5000 is 2995 BC. 2003EH1 had returned to perihelion 892 times in this period. The vertical axis is the percentage of surviving test particles in Quadrantid stream in AD 2005. \( \beta \) represents the ratio of solar radiation pressure force to solar gravity. Two test particles are released forward and backward at one perihelion passage. We estimate the survival rate from equation (6). The smaller dust particles are, the fewer they remain in the dust trail, due to solar radiation pressure force.
Fig. 3 The result of the "split model". Survival rate of the dust particles are produced by the split of a nucleus in AD 1488. 100 test particles are released with velocity $\pm 1\text{m/s}$ relative to the nucleus at perihelion. A solid line was fitted by the least squares method to the points, to obtain the surviving minimum dust radius. The minimum dust radius for survival is $s_{\text{min}} = 10.0\mu\text{m}$, as determined from the intersection with the $x$ axis. In top axis, $\beta$ represents the ratio of solar radiation pressure force to solar gravity in each size of dust particles.
The index \( \alpha \) of the size distribution of surviving dust particles in the dust trail. The upper panel shows extinct model results and lower panel shows split model results. The points plotted with error bars show the data obtained from our simulation. A solid line is fitted to the points, to obtain the index \( \alpha \) from its slope. The dashed line shows the original size distribution in each model. The relative number is normalized at the number of dust particles with a radius \( s \) of 100\( \mu \text{m} \), i.e., the coordinate \((s, \log_{10}N) = (100\mu\text{m}, 0)\) is on the dashed line in both models.
Fig. 5 The color ratios calculated from the size distribution in each model. The upper panel shows the color ratio expected at the observed wavelengths of $\lambda = 100$ and $52\mu m$, and the lower panel shows the color ratio expected at $\lambda = 18$ and $11\mu m$. The heliocentric distance is the range of the Quadrantid dust trail.
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<th>Orbital elements</th>
<th>Quadrantids(^a)</th>
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<th>96P/Machholz1(^c)</th>
<th>C/1490Y1(^d)</th>
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\(^a\) Williams (1998)  
\(^b\) Jenniskens (2004)  
\(^c\) Jenniskens (1997)  
\(^d\) Hasegawa (1979)  

**Table 1** Orbital elements of the Quadrantids parent body candidates
Model | Fitting ($\alpha$) | Original ($\alpha_0$)
--- | --- | ---
Extinct | 3.1 ($\pm$ 0.5) | 3.5
Split | 2.0 ($\pm$ 1.5) | 2.5

**Table 2** The index of differential size distribution in each model