The Astronomical Journal, 127:3018–3022, 2004 May

2003 EH_1 IS THE QUADRANTID SHOWER PARENT COMET

P. Jenniskens
SETI Institute, 2035 Landings Drive, Mountain View, CA 94043
Received 2003 December 11; accepted 2004 January 20

ABSTRACT

The Quadrantid meteor shower in early January is our most intense annual shower. Until now, the parent was thought to have evolved away from the observable part of an old, widely dispersed meteoroid stream. A few years ago, it was found from a small dispersion in a new set of precisely reduced Quadrantid orbits that the stream was only about 500 years old. It was predicted that the parent was still to be found among the meteoroids. I now find that the shower originated from 2003 EH_1, a minor planet discovered by LONEOS on March 6, currently passing 0.213 AU outside of Earth orbit in a high-inclination, comet-like orbit with a Tisserand invariant with respect to Jupiter of only 2.064. The orbit agrees with that of the Quadrantids. Small discrepancies in node ($\sim 0\overset{\circ}{.}3$) and perihelion distance ($\sim$0.23 AU) are consistent with the differential evolution of comet and debris that was released from 2003 EH_1 about 500 years ago into slightly longer orbits. I conclude that object 2003 EH_1 is an intermittently active comet. The large total mass in the shower ($\sim 10^{13}$ kg) is only consistent with a young age if the meteoroids were shed during a breakup. Comet C/1490 Y1 was observed in about the right time frame for such a breakup and might be a prior sighting when the Quadrantid meteoroid stream was created, but efforts to construct a common orbit that links 2003 EH_1 and comet C/1490 Y1 show that nongravitational perturbations or close encounters with Earth may need to be considered.

Key words: comets: individual (2003 EH_1) — meteors, meteoroids — minor planets, asteroids

1. INTRODUCTION

The Quadrantids are named after the now defunct constellation *Quadrans Muralis*, where the radiant was located during its discovery in 1835 (Fisher 1930; Sauval 1997). Its alternative name, the *Bootids*, refers to the modern constellation of Bootes. The Quadrantid shower is hard to observe because the radiant is in lower culmination at midnight. The peak zenith hourly rate is currently about 130 meteors per hour, which is the hourly rate for a visual observer under good circumstances, when there is no disturbing moonlight and the narrow peak of the shower is in the early morning when the shower radiant is high in the sky.

It is the only major shower with no known parent body. The debate in recent years has focused on the dramatic evolution of Quadrantid-like orbits, first discovered in the early modeling by Hamid & Youssef (1963) and confirmed by others using more rigorous planetary perturbation calculations (Williams, Murray, & Hughes 1979; Hughes, Williams & Murray 1979; Murray, Hughes, & Williams 1980). For a range of aphelion distances, the orbit rotates from a low inclination of $i \sim 13^\circ$ and low perihelion distance $q = 0.10$ AU about 1500–4000 years ago, to its current high value of $i \sim 71^\circ$ and $q = 0.78$. Based on its similar orbital evolution, McIntosh (1990) suggested that comet 96P/Machholz 1 (now with $q = 0.12$ AU and $i = 60^\circ$; Table 1) has a sibling relationship with the Quadrantid shower, part of a larger complex of dust including the daytime Arietid and southern Delta Aquarid showers that could have formed as recently as 2200 years ago (Jones & Jones 1993) as a result of the perturbing effects of close encounters with Jupiter. More recently, Williams & Collander-Brown (1998) concluded in that same vein that asteroid 5496 (1973 NA) is a more likely candidate (Table 1), even more likely than comet C/1490 Y1 (see below).

That old age was challenged by recent photographic observations of the 1995 Quadrantid shower by members of the Dutch Meteor Society, from which Jenniskens et al. (1997) demonstrated that the shower has a stratification of the meteoroid orbits consistent only with an ejection age on the order of 500 years. This shower age was derived by comparing the observed dispersion of all orbital elements with those in the model by Wiliams & Wu (1993). Jupiter's position near the aphelion of the stream, meeting some meteoroids in each orbit, causes a rapid dispersion over time.

With most meteoroids in the stream escaping close encounters with Jupiter, it is also likely that the parent body had only shallow close encounters with Jupiter since the creation of the stream. From that, Jenniskens et al. (1997) predicted that an asteroid-like object would be found among the meteoroids and provided an approximate orbit of this parent, assuming that the Quadrantid meteoroids trace its path (Table 1). The comet was predicted to return to perihelion around 2002.7, based on admittedly very uncertain reports of high Quadrantid rates in the past. The tables of newly discovered asteroids were examined periodically in search of the parent. The comet was discovered when it returned to perihelion on 2003 February 24 (2003.15).

2. ASTEROID 2003 EH_1

On 2003 March 6, the Lowell Observatory Near-Earth Object Search (LONEOS) telescope discovered near-Earth asteroid 2003 EH_1 in a high-inclination orbit (Skiff 2003). The first published orbit was unlike that of the meteor shower, but follow-up observations by other observers in the next 48 days changed the result considerably (Fig. 1). The refined orbit agrees well with the Quadrantid orbit given by Jenniskens et al. (1997). The aphelion of 2003 EH_1 is precisely at the peak of the meteoroid distribution. The orientation of the orbit is close to expected, with no significant discrepancy in the argument of perihelion and inclination, and only a slight offset in the rapidly evolving node. Indeed, the theoretical radiant

TABLE 1
ORBITAL ELEMENTS OF QUADRANTIDS (J2000) AND POSSIBLE PARENTS

Object	T (UT)	q (AU)	e	a (AU)	ω (deg)	Ω (deg)	i (deg)
2003 EH_1 (2003)	2003 Feb 24.5	1.1924	0.6188	3.1277	171.368	282.938	70.798
Uncertainty	...	±0.0022	±0.00035	±0.0030	±0.0030	±0.0037	±0.0021
Quadrantids[a]	...	0.979	0.69	3.14	171.2	283.3	71.05 + 72.7
Dispersion	...	±0.002	±0.03	<0.27	±2.1	±0.16	±1.0
2003 EH_1[a]	...	1.1979	0.6176	3.1320	171.19	282.952	70.68
1600 debris from 2003 EH_1[a]	...	1.157	0.628	3.114	173.38	283.08	71.24 + 72.4
Dispersion	...	±0.064	±0.020	±0.041	±1.20	±0.11	±0.56
Year of ejection to match dispersion (C.E.)	...	...	~1400	...	~1300	~1420	~1290
C/1490 Y1[b]	1491 Jan 8.9	0.761	1.000	...	164.9	280.2	73.4
2003 EH_1 (1491)[c]	(1491 Jan 8.9)	0.759	0.756	3.10	164.5	285.5	69.2
2003 EH_1 (1491)[d]	1491 Jan	0.580	0.812	3.10	163.7	286.5	65.7
96P/Machholz	2002 Jan 8.6	0.1241	0.9582	2.969	14.596	94.609	60.186
5496 (1973 NA)	2003 Sep 28.0	0.8829	0.6373	2.435	118.124	101.109	68.003

[a] Epoch 1995 January 4.15; Jenniskens et al. 1997.
[b] Hasegawa 1979.
[c] The most probable common orbit based on the evolution of 2003 EH_1–like orbits in the 1600–2003 time frame.
[d] A typical result from B. Marsden (2003, private communication), this one for initial epoch 2003 December 27.0 TT (=JD 2,453,000.5), $a = 3.1340203$ AU, $e = 0.6194604$, $\omega = 171^\circ.36251$, node = $282^\circ.93072$, and $i = 70^\circ.80067$.

and geocentric speed for a shower from 2003 EH_1 (R.A. = $229^\circ.9$, decl. = $+49^\circ.6$, $V_g = 40.21$ km s^{-1} at $\lambda_0 = 282^\circ.938$; J2000) fall in the middle of those measured for the Quadrantids. Only if the age of the shower is very young may we expect to find the parent still among the meteoroids.

Asteroid 2003 EH_1 is now passing relatively far outside of Earth orbit. The minimum distance between comet orbit and Earth (0.213 AU) is larger than typical for other annual showers (<0.04 AU). However, backward integration of the orbits using the JPL Horizons software shows that the orbit of 2003 EH_1 evolved in the recent past from a much smaller perihelion distance in the same manner as found for typical Quadrantid orbits by authors in the past (Hughes, Williams, & Fox 1981). In doing so, the asteroid spends little time near Earth orbit, where its perihelion is located. Encounters with Jupiter are brief as a result of the high inclination, and relatively shallow. The precise orbital evolution of 2003 EH_1 is complicated by those close encounters with Jupiter.

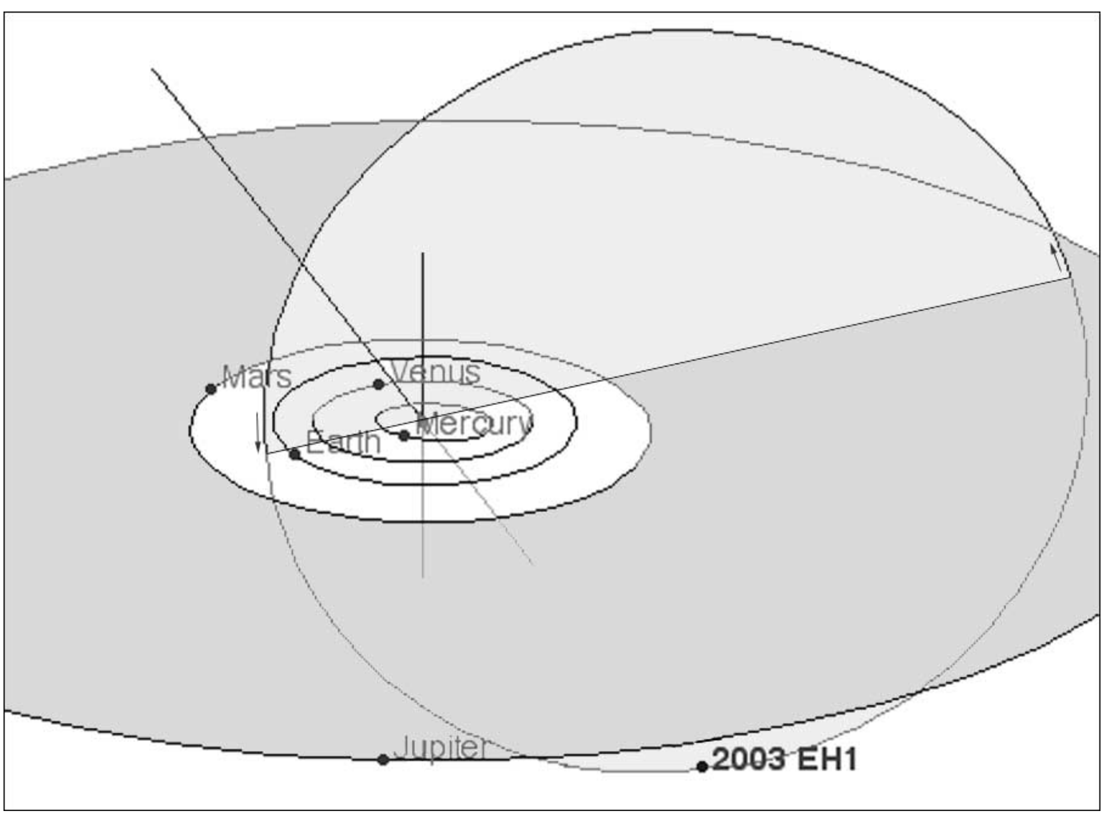

FIG. 1.—Orbit of 2003 EH_1 and position on 2004 January 4

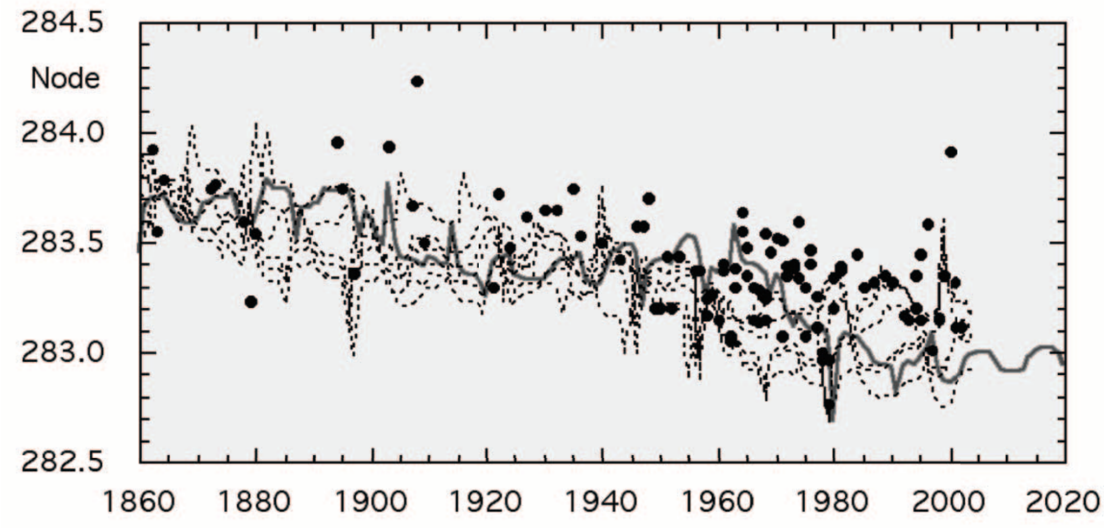

FIG. 2.—Shift in the node of the Quadrantid shower, 2003 EH_1 (*solid line*), and model orbits ejected in 1600 (*dashed lines*). Points are the observed shower peak times (MacKenzie 1980, p. 6; McIntosh & Šimek 1984; Jenniskens 1985; Rendtel, Koschack, & Arlt 1993).

Backward integration of the Quadrantid meteoroids is even more uncertain, because they have a relatively large uncertainty in their semimajor-axis values. Even small variations in the semimajor axis can introduce chaotic motion and will cause quite different encounters with Jupiter (Gonczi, Rickman, & Froeschlé 1992). The overall pattern of a rapidly increasing perihelion distance and decreasing node is consistent with results found by others for orbits that cover a relatively wide range in semimajor axis. Only if the meteoroids librate about the 2:1 (or 9:4) mean motion resonance with Jupiter does the stream as a whole avoid such close encounters and maintain its narrow structure for a very long period of time. In that case, however, the annual shift of the node reverses sign and becomes positive. Moreover, the perihelion distance does not advance in the same manner in the absence of close encounters with Jupiter.

Asteroid 2003 EH_1 moves in an orbit just below the 2:1 mean motion resonance. The observed nodal displacement of the Quadrantid shower is negative, identical to that of 2003 EH_1 (Fig. 2). This argues that the meteoroids were ejected recently with small enough velocities to not have had time and energy to get trapped in a mean motion resonance.

In order to investigate the general distribution of orbital elements for a stream created from object 2003 EH_1, its orbit was integrated back to 1600 C.E. and forward-integrated for a range of initial orbits with slightly higher semimajor axis $\Delta a = +0.0000$ to $+0.0124$ AU (and adjusted eccentricity). Such orbits represent meteoroids of $\beta = 1 \times 10^{-4}$ ejected in a forward direction of motion at perihelion with ejection speeds of -2.0 to $+10.7$ m s^{-1}. Here β is the traditional ratio of the forces from radiation pressure and gravity on the particle. These initial conditions are similar to those used for recent successful Leonid storm predictions (e.g., Lyytinen & Van Flandern 2000).

The resulting orbits show a progressive scatter as a function of time since ejection (as in the models by Williams & Wu 1993) but, overall, follow the evolution of 2003 EH_1, as required for this object to be associated with the stream (Fig. 3). The dispersion relative to the current orbit of 2003 EH_1 accounts in sign and order of magnitude for the observed differences between 2003 EH_1 and the Quadrantid shower at the present time (Table 1). By calculating the dispersion since 1600, and comparing with the observed dispersion from our photographic observations (Jenniskens et al. 1997), I confirm that the estimated time of release of the particles is a few hundred years prior to 1600 C.E. (Table 1).

In particular, the distribution of perihelion distances increases rapidly and stretches shortward of the present position of the comet (Fig. 3). The reason for this is that the comet itself had a close encounter with Jupiter in 1972, while meteoroids elsewhere along the orbit were much less perturbed and saw their perihelion distance increase less. The rapid dispersion of the perihelion distance accounts for why a shower as narrow in Earth orbit as the Quadrantids can be seen for a period of nearly two centuries (Wu & Williams 1992). That dispersion can be measured by historic Quadrantid shower peak rates. Figure 4 (*right*) shows the variation of the reported peak rate versus the heliocentric distance of the node of 2003 EH_1 over time. Earth is currently located near the peak of that dust distribution. Ejection of dust in 1600 from an orbit with $q = 0.775$ AU tends to put most meteoroid nodes outside of Earth orbit (Fig. 3), suggesting that ejection was earlier in time (as implied by the shower dispersion) or that

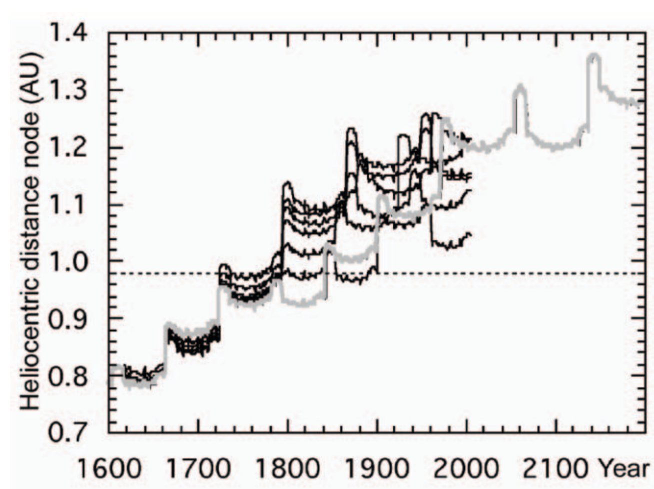

FIG. 3.—Evolution of the heliocentric distance of the node of 2003 EH_1 (same as evolution of the perihelion distance) and representative meteoroids ejected from 2003 EH_1 in 1600 January.

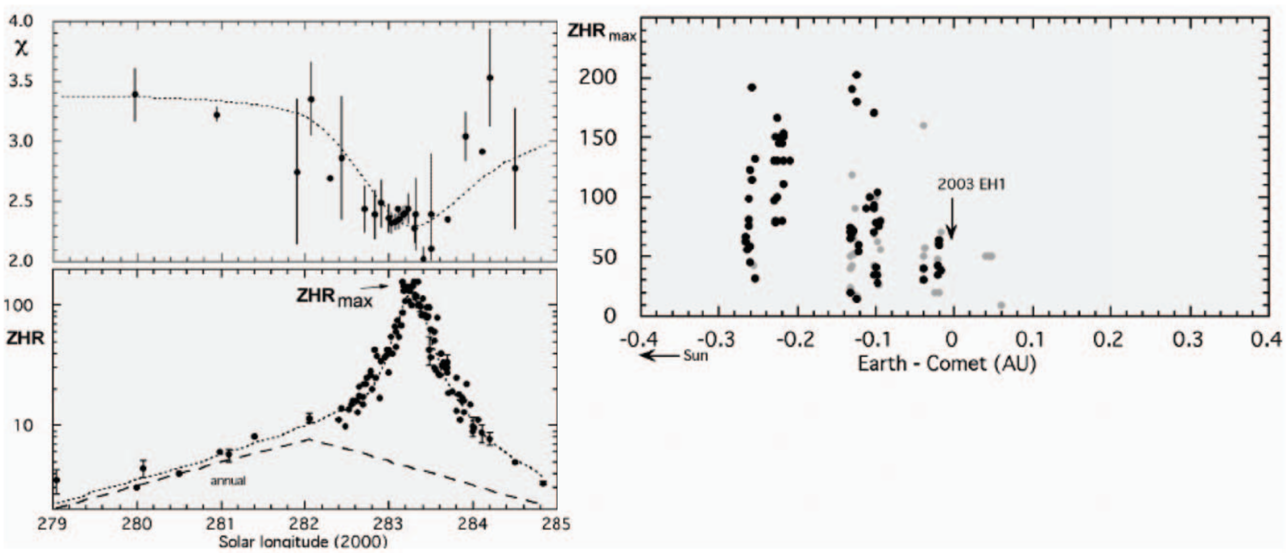

FIG. 4.—Distribution of dust in the Quadrantid meteoroid stream, expressed in units of zenith hourly rate (ZHR). *Left*, in Earth's path; *right*, along the heliocentric direction that is perpendicular to Earth's path. The quantity χ is the magnitude distribution index $N(m + 1)/N(m)$. "Annual" refers to a broader component of fainter meteors underlaying the main annual Quadrantid peak.

the comet was perturbed to a smaller perihelion distance at that time.

Despite the fortuitous agreement between predicted and observed return of the object, there is no hard evidence that the dust density increases near the comet position. The dust appears to have dispersed well along the orbit. Together with the distributions shown in Figure 4, this defines the distribution of dust in the stream in three dimensions. From that, a mass of about 1×10^{13} kg is calculated for grains in the range 10^{-6} to 10^{3} g (Jenniskens 1994). This compares with earlier estimates of a factor of 10–100 less (Lovell 1954; Hughes 1974; Hughes & McBride 1989), on account of a wider dispersion in q. That is significantly more dust than lost from a typical Jupiter-family comet in a single return ($\sim 10^{10}$ kg). If ejected in a normal manner, this would imply a deposition for a period of about 1000 yr, which is inconsistent with the young age of the Quadrantid stream. Hence, I conclude that the stream was created during the breakup of a comet nucleus. Object 2003 EH_1 is a remnant representing about 6×10^{12} kg (albedo 0.04), comparable to the mass in the shower. Other such fragments may exist in similar orbits to that of 2003 EH_1 but at a different anomaly.

The Quadrantid meteoroids are cometary in nature, given that they appear to be fragile with numerous flares from the sudden release of small fragments and their shallow penetration in Earth's atmosphere (Jacchia, Verniani, & Briggs 1967). The meteors end at altitudes similar to those of Perseids (from 109P/Swift-Tuttle) and the Lyrids, from C/1861 G1 (Thatcher). They do not penetrate as deep as the higher density Geminid meteoroids, cometary dust that has been sintered in a low-q orbit and is thought to be more representative of compact asteroidal dust (Fig. 5).

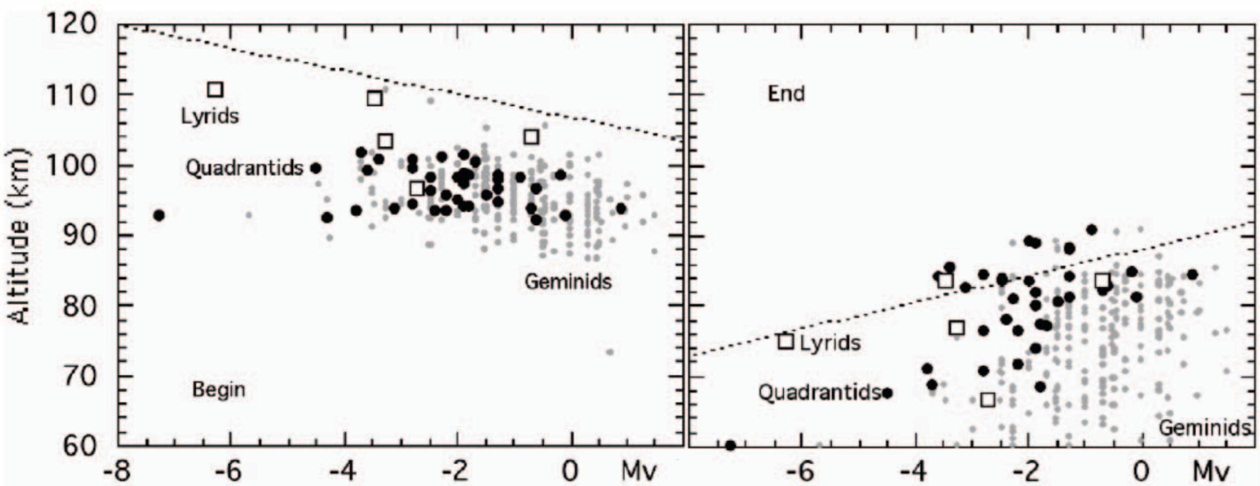

FIG. 5.—Beginning and ending height of Quadrantid meteors (*black circles*, $V_{inf} = 43$ km s^{-1}) vs. Geminids (*gray circles*; $V_{inf} = 36$ km s^{-1}) and Lyrids (*squares*; $V_{inf} = 49$ km s^{-1}). The dotted lines show the trend for Perseid meteors ($V_{inf} = 61$ km s^{-1}). The Geminids are thought to have a higher density (more typical for asteroidal material), possibly because of sintering in a low-perihelion orbit. All these photographic data are from the Dutch Meteor Society meteor orbit database (Betlem et al. 1998).

3. COMET C/1490 Y1

Hasegawa (1979) first pointed out the similarity of the Quadrantid orbital elements to those of comet C/1490 Y1, a bright comet observed from China, Korea, and Japan between 1490 December 31.5 and 1491 February 12.5 (Kronk 1999). Comet C/1490 Y1 passed perihelion on 1491 January 8, when Earth was near the node. The approximate information about the comet's position on the sky allows only a parabolic solution to its orbit. Williams & Wu (1993) first demonstrated that some backward-integrated Quadrantids have orbital elements consistent with C/1490 Y1 if that comet had an eccentricity of 0.77, rather than 1. Williams & Wu continued to propose that a close encounter with Jupiter in 1650 ejected this bright comet into a much different orbit (leaving the Quadrantid shower in place), in order to explain why the comet has not been observed since. The age of the shower was estimated at 5400 yr, based on earlier samples of meteoroid orbits that had a larger observational error (Wu & Williams 1992).

The comet was seen at about the time when the Quadrantid parent must have broken up. Efforts to find a common orbit between 2003 EH_1 and C/1490 Y1 are complicated by close encounters with Jupiter and Earth, which can change the result dramatically for very small differences in the initial orbit. By integrating 2003 EH_1–like orbits back to 1600 and searching for perihelion times that might agree with a past perihelion in January of 1491, I found that a common orbit may exist, but it tends to put the path in 1491 lower in the sky from the ideal trajectory deduced from the Chinese observations by Hasegawa, because of making q and i too small. B. Marsden of the Minor Planet Center (2003, private communication) arrived at the same result. Most of the potential solutions yield 0.5 AU $< q <$ 0.6 AU in 1491, and this is perhaps too small to fit the data used by Hasegawa. However, we both found that values in the more acceptable range 0.65 AU $< q <$ 0.75 AU are possible, certainly with the help of a close approach to Earth or—more likely—the presence of nongravitational forces. Hence, we cannot exclude the possibility that C/1490 Y1 was a prior sighting of the Quadrantid parent at the epoch when it created the shower. Further light could be shed on the problem by the recognition of precovery and/or recovery observations of 2003 EH_1.

Assuming an average geometric albedo for C- and S-type asteroids—0.04 and 0.20, respectively—the diameter of 2003 EH_1 is estimated to be only 2.9 or 1.3 km (Hahn 2003). Although comet brightness and nuclear diameter are not well related, the comet's absolute magnitude of $H_{10} = +5.4$ suggests a much larger nucleus, up to 12 km in diameter (Hughes 1990, 2002), or a mass of about 2×10^{14} kg. This is much more mass than is present in the Quadrantid shower. If C/1490 Y1 is a prior sighting of the Quadrantid parent body, then the comet became at least 3 mag brighter during the breakup, which suggests that this comet nucleus was still relatively rich in ice. Given the size of 2003 EH_1, it is likely that much of that ice remains, despite the absence of earlier sightings of this comet.

The identification of 2003 EH_1 as the Quadrantid parent is more than just a curiosity. NASA's *Deep Impact* mission is scheduled to visit comet 9P/Tempel 1 in 2005 July to probe the internal structure of that comet's nucleus. The discovery of a cometary nucleus fragment in the orbit of a meteoroid stream makes it possible to investigate the mineralogical and morphological properties of cometary dust originating from much deeper inside a comet nucleus than is typically observed in meteor streams. Moreover, the identification of 2003 EH_1 as an extinct comet nucleus provides a new target for future missions. No other proposed extinct comet nucleus has such a record of its recent history. This is a near-Earth object, perhaps with other similar kilometer-sized fragments in comparable orbits. The object has relatively fresh surfaces exposed and, unlike 3200 Phaeton, has remained at least 0.9 AU from the Sun since the breakup. Comet 2003 EH_1 provides a low-risk, dust-free environment for a sample-return mission. It would be of great value to compare the properties of a sample in hand with that derived from Quadrantid meteor observations. Future visits are perhaps possible with an assist of Jupiter when it is near the stream's aphelion in 2008 and 2019.

I thank Brian Marsden for his help in exploring the possibilities for a common orbit with C/1490 Y1. I congratulate the Lowell Observatory Near-Earth Object Search for their successful program of minor-planet recoveries, and the observers of the Dutch Meteor Society (in particular Hans Betlem and Marc de Lignie) for their important photographic and video work. P. J. is supported by NASA's Planetary Atmospheres and Planetary Astronomy Programs.

REFERENCES

Betlem, H., ter Kuile, C. R., de Lignie, M., van't Leven, J., Jobse, K., Miskotte, K., & Jenniskens, P. 1998, A&AS, 128, 179
Fisher, I. W. 1930, Harvard Coll. Obs. Circ., No. 346
Gonczi, R., Rickman, H., & Froeschlé, C. 1992, MNRAS, 254, 627
Hahn, G. 2003, Data Base of Physical and Dynamical Properties of Near Earth Asteroids (Berlin: Inst. Planetenforschung)
Hamid, S. E., & Youssef, M. N. 1963, Smithsonian Contrib. Astrophys., 7, 309
Hasegawa, I. 1979, PASJ, 31, 257 (erratum 31, 829)
Hughes, D. W. 1974, Nature, 252, 191
———. 1990, in Asteroids, Comets, Meteors III, ed. C.-I. Lagerkvist, H. Rickman, B. A. Lindblad, & M. Lindgren (Uppsala: Uppsala Univ.), 327
———. 2002, MNRAS, 336, 363
Hughes, D. W., & McBride, N. 1989, MNRAS, 240, 73
Hughes, D. W., Williams, I. P., & Fox, K. 1981, MNRAS, 195, 625
Hughes, D. W., Williams, I. P., & Murray, C. D. 1979, MNRAS, 189, 493
Jacchia, L. G., Verniani, F., & Briggs, R. E. 1967, Smithsonian Contrib. Astrophys., 10, 1
Jenniskens, P. 1985, Radiant: J. Dutch Meteor Soc., 7, 118
———. 1994, A&A, 287, 990
Jenniskens, P., Betlem, H., de Lignie, M., Langbroek, M., & van Vliet, M. 1997, A&A, 327, 1242
Jones, J., & Jones, W. 1993, MNRAS, 261, 605
Kronk, G. W. 1999, Cometography: A Catalog of Comets, Vol. 1 (Cambridge: Cambridge Univ. Press)
Lovell, A. C. B. 1954, Meteor Astronomy (Oxford: Clarendon)
Lyytinen, E. J., & Van Flandern, T. 2000, Earth Moon Planets, 82–83, 149
MacKenzie, R. A. 1980, Solar System Debris (Dover: British Meteor Soc.)
McIntosh, B. A. 1990, Icarus, 86, 299
McIntosh, B. A., & Šimek, M. 1984, Bull. Astron. Inst. Czechoslovakia, 35, 14
Murray, C. D., Hughes, D. W., & Williams, I. P. 1980, MNRAS, 190, 733
Rendtel, J., Koschack, R., & Arlt, R. 1993, WGN: J. Int. Meteor Org., 21, 97
Sauval, J. 1997, WGN: J. Int. Meteor Org., 25, 21
Skiff, B. A. 2003, Minor Planet Electron. Circ., No. 2003-E27
Williams, I. P., & Collander-Brown, S. J. 1998, MNRAS, 294, 127
Williams, I. P., Murray, C. D., & Hughes, D. W. 1979, MNRAS, 189, 483
Williams, I. P., & Wu, Z. 1993, MNRAS, 264, 659
Wu, Z., & Williams, I. P. 1992, MNRAS, 259, 617