METEOR SHOWERS FROM BROKEN COMETS

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ABSTRACT

Even though comets have been observed to break, there was no strong evidence until now that the meteoroids generated in these discrete and relatively rare events accounted for meteoroid streams detected as meteor showers on Earth. That has changed now minor planet 2003 EH_1 and other such inactive (dormant) and weakly active comet nuclei are found still intimately associated with known meteoroid streams. More and more of such minor bodies are now identified. The meteor showers that are likely from the fragmentation of comets rather than from Whipple-type ejection by water vapor drag now include the Quadrantids, Daytime Arietids, delta-Aquariids, Capricornids, Taurids, Andromedids, Phoenicids, and Geminids, representing most of our strongest annual showers. This makes the breakup of dormant comet nuclei an important mechanism to replenish the zodiacal cloud.

1. ASSOCIATION OF MINOR BODIES WITH METEOROID STREAMS

When Whipple [1] discovered a mechanism to accelerate meteoroids by the drag of water vapor in 1951, the old idea of meteor showers originating from comet breakup went into remission. Meteoroid streams were thought created by the gradual ejection of meteoroids during the comet's sublimation of ice.

Our meteor showers tell a different story. Until recently, most showers had no known active parent comets, even those that have short orbital periods and frequently should have their parent body in the Earth's neighborhood.

It was surmised, that those parent bodies had now evolved into orbits quite different from the meteoroids that we now see on Earth as a meteor shower.

Traditionally, minor bodies have been associated with meteoroid streams using the D-criterion, a measure of the similarity of orbits based on the integrals of motion. Especially when the orbit of the stream was similar to that of asteroids, many potential parents were thus identified in orbits different from that of the meteoroids. The best example being the Taurid Complex of minor bodies associated with comet 2P/Encke [2]. All of the originally proposed objects investigated since have asteroidal colors and, therefore, in all likelihood are unrelated to the Taurid shower.

In 1983, Fred Whipple recognized that minor planet 3200 Phaethon orbits among the very short-period ($P \sim 1.59$ yr.) and unusually small perihelion distance ($q = 0.14$ AU) meteoroid stream responsible for the Geminid shower [3]. Due to the uncommon orbit, the probability of this good an association by chance is only about 1 in 2 million, depending on the actual number of objects in this still sparsely sampled population. However, the reflectance properties of the minor planet (taxonomic type B) made the nature of this object as an extinct comet nucleus uncertain. The small perihelion distance heated the surface to above 700 K and sintered the Geminid meteoroids enough to change their morphology. It has since been shown that the Geminids appear to have been created close to perihelion, more typical of comet ejection than asteroidal collisions [4].

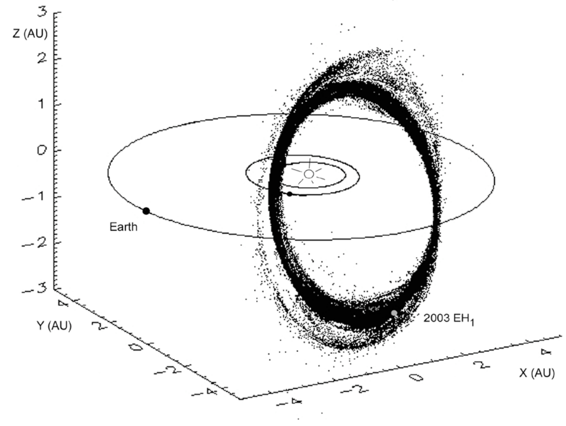

Fig. 1: 2003 EH_1 and the Quadrantid meteoroid stream, in a model by Jerémié Vaubaillon.

For long, this object was our "Pluto" in the context of the long-undiscovered Kuiper Belt. Then, in 2003, I identified a minor planet 2003 EH_1 in the high-inclination orbit of the Quadrantids [5]. Due to the rare high inclination of the orbit (i ~ 72°), the probability of this good a match by chance alone was again only about 1 in 2 million. This time, the cause of the stream must have been a breakup. The Quadrantids are a massive stream (Fig. 1), containing a thousand times more mass than typically ejected by an active Jupiter-family comet over one orbit. The minor planet passed outside of Earth orbit, but the stream evolved rapidly due to

Proc. 'Dust in Planetary Systems', Kauai, Hawaii, USA.
26 -- 30 September 2005 (ESA SP-643, January 2007)

perturbations of Jupiter at aphelion (and at the ascending node), quickly changing the perihelion distance of the meteoroids affected. The measured dispersion of meteoroid orbits [6] implied that the stream is not older than about 500 years. In such a short period of time, 2003 EH$_1$ could not have created the stream in normal Whipple-type ejection if the now extinct comet would have been active in the past. Instead, a discrete breakup event is implicated. The comet C/1490 Y$_1$, seen in early 1491, may have been the manifestation of that breakup [7].

Following this identification, I discovered that 160-meter sized 2003 WY$_{25}$ traces back to comet D/1819 W$_1$ (Blanpain), associated with the Phoenicid shower [8]. Blanpain was not seen again after the 1819 sighting. 2003 WY$_{25}$ has angular elements within 0.2° from those of Blanpain at that time. Subsequently, David Jewitt discovered from past images taken on March 10, 2004, that 2003 WY$_{25}$ is on occasion an active comet [9], the smallest known comet nucleus at this time, creating dust at a rate of only 0.01 kg/yr. At this rate, this comet fragment could not have generated the Phoenicid meteoroid stream.

Blanpain's activity in 1819 suggests that 2003 WY$_{25}$ is much smaller than Blanpain, and could indeed only have been a fragment of a breakup. Esko Lyytinen and I investigated whether this breakup could have occurred at or just before 1819, with Blanpain being the manifestation of the immediate aftermath. We demonstrated that the dust generated in a breakup in 1819 would have wandered in Earth's path in 1951 and 1956, and does account for the time of the strong 1956 Phoenicid outburst. Since that time, the trail has not been in Earth's path at the time when Earth was at the node. Hence, the 1956 Phoenicids were likely the debris from the breakup of comet Blanpain in or shortly before 1819 [8].

The history of other meteoroid streams have now also come into focus. The Marsden group of sunskirting comets was found to have a short orbital period [11], making it more than likely that whatever was responsible for this large family of comet fragments is also responsible for the Daytime Arietids, a meteoroid stream with a short perihelion distance and an orbit very similar to that of the Marsden group. The Arietids are associated with the Kracht family of comet fragments and with other meteoroid streams, especially the delta-Aquariids of July. All of these are found further evolved along a nutation cycle.

Table 1. Some of our best examples of meteor showers and associated (mostly) dormant comet nuclei. The parent body orbits have been adjusted to intersect Earth's orbit [10].

Shower/comet	**Epoch**	**a**	**q**	**i**	**ω**	**Node**	**T_J**	**H_N**	**Formation**
Andromedids		2.90	0.777	7.5	242.7	225.5			
3D/Biela	(2004)	3.49	0.798	7.5	236.2	213.8	+0.78	> +7.1	AD 1840
Phoenicids		(3.05)	0.985	15.9	358.2	74.1			
2003 WY$_{25}$	(1956)	3.07	0.991	09.6	360.1	74.4	+0.51	> +8.5	~ AD 1819
Quadrantids		3.14	0.979	72.0	172.0	283.3			
2003 EH$_1$	(2006)	3.13	0.979	70.8	171.4	283.0	+3.89	+17.7	~ AD 1490
Daytime Arietids		1.75	0.094	27.9	29.5	78.7			
Marsden-group	(2004)	3.33	0.0483	26.8	23.2	81.5	~ +1.8	> +18	≥ AD 1059
Geminids		1.37	0.141	24.0	324.4	261.5			
3200 Phaethon	(2005)	1.27	0.140	24.2	325.3	262.5	+4.51	+14.6	~ AD 1030
Northern Taurids		2.12	0.350	3.1	294.9	226.2			
2004 TG$_{10}$	(2005)	2.24	0.315	3.6	298.4	223.9	+2.99	+19.5	~ AD 600
Capricornids		2.62	0.602	7.7	266.7	128.9			
2002 EX$_{12}$	(2005)	2.60	0.605	7.6	266.0	128.8	+2.89	+26.5	~ AD 10

2. THE GIANT COMET HYPOTHESIS

The idea that the fragmentation of comets is a source of meteoroids causing meteor showers on Earth was first proposed following the 1872 and 1885 Andromedid storms, which occurred after the breakup of lost comet 3D/Biela in 1840, and the continued fragmentation of the comet observed in the returns of 1846 and 1852 [12]. Although the meteor showers were spectacular, they were not more intense than the more recent Draconid storms of 1933 and 1946, thought to have been caused by comet 21P/Giacobini-Zinner through normal Whipple-type comet dust ejection through water vapor drag [10]. Even though the Andromedid storms can be traced to dust trails in the Earth's path dating from 1846 and 1852, when the comet was in breakup, there were no dust trail encounters in other years that could have proven that normal activity of 3D/Biela wasn't capable of creating similar showers.

A recent incarnation of this idea is the *Giant Comet Hypothesis* of Clube, Napier, and others [2], which accounts for the massive and very dispersed Taurid stream, and a host of minor planets called the Taurid Complex (including one active comet 2P/Encke), as the product of the breakup of a 43-km sized comet about 20,000 years ago. Unfortunately, all of the implicated minor bodies studied to date, with the exception of 2P/Encke, have since been proven to be asteroids rather than extinct comet nuclei [10]. Their spectral taxonomic type is either S or O, typical of differentiated asteroids, or asteroids with metamorphic surfaces.

2.1 Introducing 2004 TG$_{10}$

Comet 2P/Encke, alone, can not account for the Taurid stream, there being too large a range in longitude of perihelion. Other fragments are implicated and an ongoing progressive fragmentation. Until now, candidates of such fragments only included objects with $q > 0.41$ AU (mostly around $q \sim 0.55$ AU), while the Taurids have $q \sim 0.35$ AU. I am introducing here the first Taurid Complex candidate with small enough perihelion distance, found when searching for objects matching the Northern Taurids. Minor planet *2004 TG*$_{10}$ matches this stream well (Table I). This is a better match than that of comet 2P/Encke with the southern Taurids, the former having a higher inclination.

Does this finally validate the Giant Comet hypothesis of Clube and Napier? The fragment is about 0.88 km in size (assuming an albedo of 0.04 and density 1 g/cm^3). If there are 20 other cometesimals like this and if I include the dust in the northern Taurid stream, then the parent body would have measured about 5.5 km across, about the same size as 2P/Encke. Both objects could be part of an earlier breakup. If, at best, twenty such objects existed, then this initial "giant" comet measured a mere 15 km in diameter, the size of comet Halley. No "Giant" comet. Nevertheless, a few hundred sub-km sized fragments could still exist among the Taurids, which are indeed an impact hazard to Earth.

3. COMET FRAGMENTATION

Active Jupiter-family comets are known to frequently break and shed a series of 10-m to 1000-m sized fragments. Examples are the 1840 breakup of 3D/Biela and the 1995 breakup of 73P/Schwassmann-Wachmann 3 [13]. Both comets used to, or will in the future, pass by Earth orbit. During those fragmentations, meteoroids are created that spread out after one orbit and that can lead to temporary meteor showers on Earth when the resulting dust trails are steered in Earth path. If the amount of dust is substantial, fragmentations can lead to prominent annual showers, such as the Geminids and Quadrantids, when the streams evolve into elongated structures that cross Earth's path.

One of the more interesting results from comparing mass estimates of the comet fragments and the meteoroid streams of these Jupiter-family comet parents [7] is that the streams represent a mass no more than that of a single fragment [8]. In contrast, the disruption of long-period comet C/1999 S4 (Linear) was thought to have created as much as 200 times more mass in dust than the sum of fragments combined [14]. Hence, the fragmentations in question are not necessary wholesale, but could pertain to the release of just a small number of cometesimals from their parent comet, in the process brightening the comet by a few magnitudes from the release of fine dust and gas.

The cause of those fragmentations remains unknown. The breakups do not typically occur at perihelion and the objects may have lost much of their ices, which excludes thermal stresses as the most likely cause [15]. Tidal forces also appear to be excluded, with tidal forces from the Sun usually exceeding those of Jupiter at the time of breakup. Other possible scenarios that could trigger such an event are the impact of large meteoroids and spin-up. Spin-up can occur by outgassing in preferred directions and even by irregular heating of the surface. Large meteoroid impacts may heat trapped subterranean gasses that can lead to sufficient pressure buildup to gently break off cometesimals, even though such impacts contain a relatively small amount of kinetic energy.

3.1 The Deep Impact mission and Tempel 1

An experiment to study the effects of such a meteoroid impact was the Deep Impact mission [16]. Unfortunately, the Deep Impact probe hit 9P/Tempel 1 in terrain dotted by impact craters that had clearly weathered similar events in the past. The approach images did not immediately show the breaking off of a fragment.

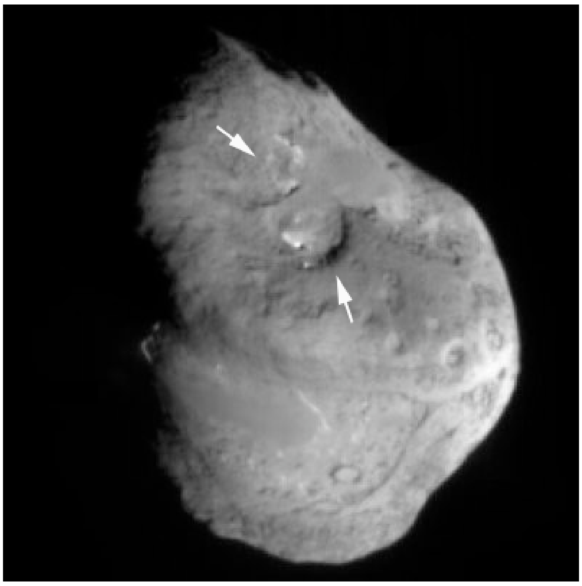

Fig. 2: Deep Impact target 9P/Tempel 1. Arrows mark areas that might be the scars from recent fragmentation. Photo: NASA/JPL/Deep Impact.

The mission did provide detailed images of the comet surface that should have revealed the scars of any past fragmentation history. The comet does appear angular in shape, as expected from cometesimals breaking off. Depressions in the topography are covered by smooth terrain with little albedo variation (Fig. 2). That flat terrain can have resulted from dust fallen back to the comet, if that accumulated at the bottom of the bowls. It is not clear, however, if that dust was created during a disruption, or was the result of normal Whipple-type ejection of meteoroids by the drag of water vapor instead.

The surface shows some areas with steep ridges that contain spots of high albedo terrain and that do not show the smooth dust covering of other depressions (arrows in Fig. 2). Rather than impact craters, these structures could perhaps be the site of spill-off of cometesimals in the recent past. There is a sparcity of close-by image data for this region, which makes this interpretation speculative. If so, at least two 0.5-km sized fragments were lost from the comet, perhaps now responsible for a meteor shower on Mars.

4. IMPLICATIONS

Many ecliptic meteoroid streams have now associated inactive minor bodies that are still in very similar orbits (Table 1). This implies that discrete fragmentation through the spill-off of boulders, loss of cometesimals, or catastrophic disruption is a common phenomenon among the population of dormant comet nuclei in the inner solar system. It is, in fact, their main mass-loss mechanism.

Even though a single breakup generates a relatively small amount of dust, combined these breakups add much mass to the zodiacal cloud. If each breakup adds about 1,000 billion kg of dust, then a steady state of about 300 000 fragmentation events over the cause of 20,000 years could account for the current mass of dust in the zodiacal cloud. That amounts to 15 fragmentation events per year over the whole cloud of comets in all forms in the inner solar system. To produce our about 105 known antihelion streams [10], this would demand that a fraction of about 105 / 300,000 = 0.04 % of those breakups evolved dust into Earth's path if the streams survive (at high enough dust density) for 20,000 years, or 0.4% if the streams survive for only 2,000 years. Those are reasonable numbers.

In that case, it is also likely that the zodiacal dust bands are the product of recent comet fragmentation. Although the observed inclination of the bands is difficult to reconcile with known active Jupiter-family comets, there is a wealth of potential associated minor bodies that are now dormant.

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