Meteor Showers and their Parent Comets

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In recent years, it was discovered that meteor showers are younger than thought before. Meteor storms, such as the Leonids, are caused by dust grains (called meteoroids) ejected just a few revolutions ago. Meteoroids can be dragged along and ejected by the flow of (water) vapour, each time when the comet is near the Sun and the heat of the Sun evaporates ices. The most recent development is that many of our short-period annual showers also appear to have been created in the last one or two thousand years. In these cases, there is mounting evidence that the meteoroids were ejected during a comet fragmentation event, at random positions along the comet orbit.

1 Introduction

This article is a summary of some chapters of the book "Meteor Showers and their Parent Comets", which was published recently by Cambridge University Press and now available at book vendor sites such as `'amazon.com'` (Jenniskens, 2006). The book is an overview of the field of meteor astronomy, talking about the four dynamical classes of parent bodies, how these classes originate from different sources and how the streams evolve and manifest in different ways. It also talks about how our annual showers originated. The book contains many anecdotes of past meteor shower observing campaigns, including the Leonid MAC missions, in order to make the text more enjoyable to read and pass a sense of how we have gradually learned to understand and anticipate meteor showers. Even though dense with information, the text is intended to be read by amateur astronomers. It contains predictions for future meteor outbursts in the next fifty years, mostly from the work of Esko Lyytinen and Jérémie Vaubaillon.

2 Dynamical classes: long period type, Halley type, Jupiter-Family type, and Encke type

Predicting meteor showers is all about the past and future orbit of the meteoroids and their parent comet. The orbit is the path of the meteoroid around the Sun. This path mostly follows an ellipse with the Sun at one of the focal points. Important to realize is that the meteoroids move along that orbit like the cars in a roller coaster: when they are at their highest point, they move slowly, and when they are at their lowest point (nearest the Sun), they go very fast. The faster they go, the less time the meteoroids spend in the neighbourhood of Jupiter and the less the orbit changes.

Those orbits are changed continuously by the gravity of the planets, especially Jupiter. The ellipse is slightly elongated, or rotated, for example. The most important changes are: a) those that determine the position of the orbit near Earth's orbit and b) the changes in the orbital period, the time it takes to return after one orbit.

A meteor shower occurs only when the meteoroids hit the Earth. That happens when the meteoroid crosses the plane of the planets, called the ecliptic plane. When the meteoroid arrives from the North, this point is called the "descending node" of the orbit. And when the meteoroid arrives from the South, it is called the "ascending node".

Gravity has the peculiar effect of causing changes in the orbit independent of the mass of the orbiting object. Hence, the comet orbit is changed in much the same way as that of its meteoroids. Of course, the

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change depends on when the meteoroids are nearest to Jupiter's orbit (where is Jupiter at that moment). As a result, the orbital changes are somewhat different for meteoroids (and comet) at different positions along the orbit. Jupiter continuously moves around the Sun in an orbit of almost 12 years. Saturn, in an orbit of about 30 years, has also some influence, and together they cause a repeating perturbing pattern of 60-years (2 orbits of Saturn are about equal to five orbits of Jupiter).

Jupiter's dominant influence causes four different types of evolutions of the meteoroid orbits and the orbit of the parent comets:

1. *Long Period type*. The orbit is so long that the perturbations by Jupiter change the return date dramatically. When it takes more than about 250 years to complete one orbit, the particle will not remember where Jupiter was in the previous orbit. When the particle returns, Jupiter is at a random location along its orbit.
2. *Halley type*. The comet returns with a memory of where Jupiter was in the previous orbit. The orbit is long enough for the particles to move quickly by the planet Jupiter (typically between 12 and 250 years). As a result, the orbits are relatively stable.The perturbations are relatively small, especially if the nodes of the orbit are far from Jupiter's orbit or if the orbital period resonates with that of Jupiter (with Jupiter being always far from the node when the particle passes by).
3. *Jupiter-family type*. The furthest point of the orbit is close to the orbit of Jupiter. In a previous return, the meteoroid or comet was slowed down by Jupiter so much that when they return from their trip towards the Sun, typically every 5–7 years, they can barely make it out to Jupiter. They now move very slowly when in the neighbourhood of Jupiter's orbit and the perturbations are big.
4. *Encke-type*. The terrestrial planets can perturb a comet into an orbit much shorter than 5 years. In that case, the meteoroids do not come anywhere close to Jupiter and the orbits are more stable. They evolve more slowly due to precession from the distant effects of Jupiter's gravity.

3 Dynamical classes of parent bodies

Long Period and Halley-type comets originate in the Oort cloud, which is located all around the solar system out to about 1/3 the distance to the nearest star. They come from random directions, almost half from directions opposite to the motion of the planets. Their orbits tend to be steeply inclined and very elongated.

Long Period comets tend to not survive more than five returns to the Sun. They fall apart easily. Most "new" comets have orbital periods of the order of 100 000 years, but the comets that cause our meteor showers tend to have orbital periods in the range 250 to 10 000 years. In that case, the dust is not dispersed too much along the orbit for us to recognize the shower. Five long-period comets are known to have meteor showers:

C/1983 H1 (IRAS-Araki-Alcock) - eta-Lyrids
C/1861 G1 (Thatcher) - April Lyrids
C/1911 N1 (Kiess) - Aurigids
C/1739 K1 (Zanotti) - October Leonis Minorids
C/1852 K1 (Chacornac) - eta-Eridanids

Only the first three associations are well established. The latter two comets have unknown orbital periods. Several other associations have been proposed, but are even less certain. All comets have been seen only once.

There are also five Halley-type comets that have associated meteor showers:

1P/Halley - Orionids and eta-Aquariids
109P/Swift-Tuttle - Perseids
55P/Tempel-Tuttle - Leonids
8P/Tuttle - Ursids
C/1917 F1 (Mellish) - December Monocerotids

All but one of these Halley-type comet has been observed during multiple returns. Only 109P/Swift-Tuttle and 55P/Tempel-Tuttle pass close to Earth's orbit at this time.

Jupiter-family comets and Encke-type comets originate from the Kuiper Belt, in particular the scattered disc component, which is located just outside of Neptune's orbit. The comets move in the same direction as the planets and usually in orbits that are not very steeply inclined to the plane of the planets. Seven comets are known to have caused meteor showers in the past two hundred years:

7P/Pons-Winnecke - June Bootids

21P/Giacobini-Zinner - Draconids

26P/Grigg-Skjellerup - Pi-Puppids

73P/Schwassmann-Wachmann 3 - tau-Herculids

3D/Biela - Andromedids

D/1819 W1 (Blanpain) - Phoenicids

D/1978 R1 (Haneda-Campos) - October Capricornids

Some others are expected to create showers in the near future, e.g. 15P/Finlay, 45P/Honda-Mrkos-Pajdusakova, 103P/Hartley 2, and P/2004 CB (Linear). Jupiter family comets tend to break on occasion at random points along their orbit. Most recently, 73P/Schwassmann-Wachmann 3 broke in 1995. Three comets (Biela, Blanpain, and Haneda-Campos) were lost after their first (series of) sightings.

Encke-family comets tend to be much less active than expected for Jupiter family comets, some are dormant most of the time. Examples associated with meteor showers are:

2P/Encke - Taurids

107P/Wilson-Harrington -September Sagittariids

3200 Phaethon - Geminids

Some, such as Phaethon, are in an asteroid-like orbit. Most decoupled Earth-crossing comets are expected to have orbital periods in the range 2.8 to 3.7 years.

4 Dynamical classes of meteoroid streams

A meteoroid stream is formed when the ejected meteoroids complete one orbit around the Sun (Figure 1). Initially, they hang around the comet nucleus as a dust cloud, called the dust coma. All meteoroids follow their independent orbit around the Sun, typically making a slightly wider orbit than the comet due to the slight push from solar radiation. As a result, they tend to come back later. It just takes longer to complete one orbit. Some particles take a lot longer, depending on the direction and speed of ejection.

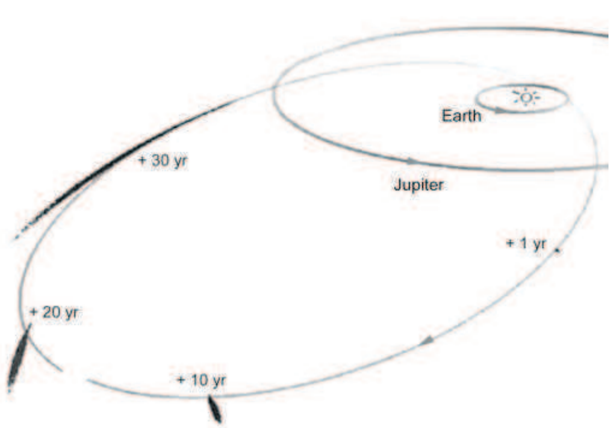

Figure 1 – Graph showing the formation of a meteoroid stream, from calculations by Jérémie Vaubaillon. This particular case is for the Leonid meteoroid stream from comet 55P/Tempel-Tuttle.

An observer at Earth sees a continuous stream of meteoroids. That stream is very thin, perhaps five times the diameter of Earth, the width determined by the ejection conditions. Most of the time, that stream of dust sits just outside of Earth orbit. Only when the Sun and planets steer the dust into Earth's orbit do we see a meteor shower.

A different evolution of the meteoroid streams causes different manifestations of the meteor showers on Earth:

a) *Long Period*. Only the one-revolution dust trail causes recognizable meteor outbursts. The trail is perturbed only on the way in, after it was formed (Figure 1). The position of the trail near Earth's orbit follows more or less the Sun's reflex motion. This is the motion of the Sun's center of mass around the barycenter of the solar system. The barycenter of the solar system is the point where the Greek god Atlas would have kept his finger to keep the solar system in balance. The Sun's reflex motion is easily calculated, making it possible to predict the next return of a meteor outburst. That happens usually only once or twice every 60 years. Expect meteor outbursts only when the comet passes less than 0.012 AU from Earth's orbit, which is the amplitude of the Sun's reflex motion. Annual showers may occur over a slightly wider region and tend to be very old.

b) *Halley type*. Orbits evolve slowly and dust is deposited over many returns, creating dense streams in a large volume of space. The current comet orbit may well be far from Earth's orbit (over 0.1 AU, for example). When the comet does pass close to Earth's orbit, such as in the case of the Leonids and Perseids, there may be dust trail crossings from recently ejected dust. Multiple trails are present, slightly displaced from each other because of the evolution of the parent comet. As a result, more than one meteor storm can happen when Earth travels through the forest of trails. Trails stay together for long periods of time. For example, the 45-revolution dust trail of comet 8P/Tuttle was observed to cause a meteor outburst in 2000. Annual showers tend to be old. The biggest comet that passes Earth frequently is 109P/Swift-Tuttle and this comet has a big cloud of dust that is located just outside Earth's orbit. The Perseids have been around for a very long time. The core of the stream is about 5000 years old, while the tail of dust seen in July could date back as much as 160 000 years ago.

c) *Jupiter-family type*. The orbital evolution of dust trails is now strongly affected by Jupiter. The spreading along the trail is mostly due to planetary perturbations (by changing the orbital period of the orbit), rather than due to comet ejection speed, and the cross section of a trail depends on where the particles were ejected along the comet orbit. Dust trails are chopped up, but those parts that avoid close encounters with Jupiter can persist for extended period of time as "trailets". The dust trail position at Earth orbit changes rapidly from one orbit to the next and meteor storms are typically only observed on a few occasions in between two close encounters of the parent comet with Jupiter.

d) *Encke-type*. These comets do not tend to be very active. Their dust trails are not as dense. Meteoroid streams are created by fragmentation of the comet nucleus (see next chapter). The meteoroid orbits evolve by precession, with some aspects of the orbit changing slowly (such as the direction of perihelion), while other aspects of the orbit change rapidly. Typically, the line that connects the two nodes of the orbit rotates rapidly in what is called a "nutation cycle". These nutation cycles turn out to be most important to understand the evolution of the resulting meteoroid streams.

5 Comet fragmentation as the dominant source of meteoroid streams

The most recent development in the field of meteor astronomy comes from the Near-Earth Object surveys that are underway. At this time, about 800 out of slightly over 1000 suspected bodies larger than 1 km in size have been discovered that pass within 0.2 AU from Earth's orbit. Most of these bodies are asteroids. Some are dormant comets.

In October 2003, I noticed that minor planet 2003 EH1 was moving in the steeply inclined orbit of the Quadrantids (Jenniskens, 2003). The orientation and size of the orbit was a match, while the perihelion

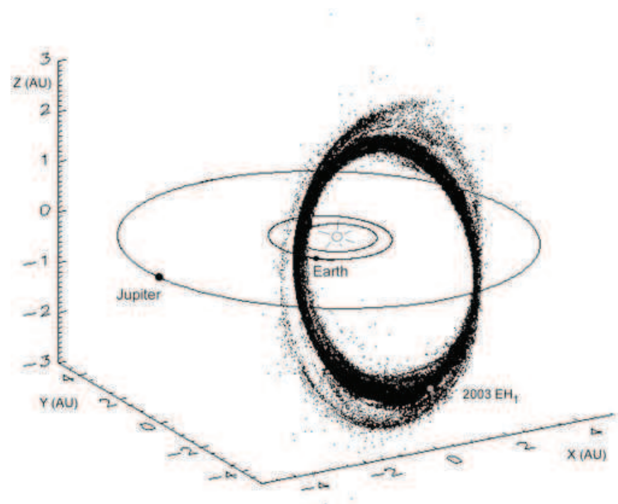

Figure 2 – Graph showing the Quadrantid stream as it would have developed from the breakup of 2003 EH1 in 1490, from calculations by Jérémie Vaubaillon. The position of 2003 EH1 in December 2003 is shown.

distance (nearest point to the Sun) was slightly larger than that of the meteoroids that hit Earth. It turns out that Jupiter changes the perihelion distance dramatically in close encounters and this object was perturbed to the outer regions of the stream only in the late 1960's. Based on Quadrantid orbit measurements by the Dutch Meteor Society, I had found earlier that the stream could not be much older than 500 years (Jenniskens et al., 1997). That excludes a mechanism of normal comet activity over an extended period of time. There is just too much dust in the stream. I now think that comet C/1490 Y1 may have been the manifestation of a discrete breakup that happened in 1490 or just before that, at which time the Quadrantid stream was created. It took until the end of the 18th century for the particles to evolve in orbits intersecting Earth. The center of the stream is now in Earth's path and will be so for some time in the future. However, the shower can vary in intensity from year to year due to the perturbations of Jupiter.

Since that time, more minor planets have been recognized to move among the meteoroids of a known stream. The cases where the orbit is strange are the most convincing. Chances of coincidence are only 1 in 2 million in the case of the Quadrantids. I now believe that 3200 Phaethon is a remnant of the breakup (in about 1030 AD) that led to the Geminid stream. Whipple (1983) had recognized that this minor planet moved among the stream, but for a long period of time it was thought by many to be an asteroid interloper. This is very unlikely, however, again one chance in about 2 million. The Geminid stream evolved in Earth's path at the end of the 18th century and will peak only in about 2050. At that time, the ZHR of the Geminids could be twice of that of today and the meteors could be brighter on average. More recently, Katsuhiro Ohtsuka (2005) recognized that 2005 UD moves among the Sextantids, another highly eccentric shower with a very short orbital period. Phaethon and 2005 UD are likely fragments of the same parent body that broke much longer ago.

In the same way, I identified the tiny 2003 WY25 as a fragment of comet D/1819 W1 (Blanpain) and Esko Lyytinen and I showed that a breakup in 1819 could have created the meteoroid stream that caused the 1952 Phoenicid outburst (Jenniskens & Lyytinen, 2005). No other outbursts would have been expected since. After this discovery, it was found that 2003 WY25 was weakly active when at perihelion (Jewitt, 2006).

By searching along the nutation cycle of the stream, 2002 EX12 was found to move among the alpha-Capricornids by Paul Wiegert of the University of Western Ontario and myself, independently. Shortly after this identification was made, Brian Warner at the Palmer Divide Observatory in Colorado discovered in images taken on the 29th of July, 2005, that the object suddenly showed cometary activity.

In the course of writing the book, I also found that 2004 TG10 was a better match to the northern Taurids than comet 2P/Encke. Encke is now in a higher inclined orbit with a node at Mercury, instead of the Earth. Both objects likely originate from a larger precursor body that broke about 5 000–20 000 years ago. The Taurid shower has many freshly ejected fragments in it, from the continued disintegration of the dormant comets.

Finally, David Seargent (in Kracht et al. 2002) pointed out that the Daytime Arietids are likely associated with the family of comet fragments called the Marsden group of Sungrazers (or Sun skirters). These are small pieces left over from the breakup of the comet some time in the first millennium. The fragments are detected as comets when they pass the field of view of the SOHO satellite, in wide field cameras designed to study the atmosphere of the Sun. Since, Sekanina and Chodas (2005) investigated the evolution of comet fragments in the Marsden and Kracht group of sunskirters and found that a breakup in AD 710, 530, 340, or 170, but certainly before AD 950, followed by a close encounter with Jupiter in AD 1059, could explain the dispersion of fragments along the nutation cycle. In this scenario, I conclude that the Arietids originated after 1059, when some fragments continued to disintegrate. Comet 96P/Machholz 1 is part of this "Machholz Complex". The delta-Aquariids are also part of this complex, but further evolved along the nutation cycle. It is not clear if the Aquariids originate from the Kracht group of sunskirters, or from a different fragment yet. Even 2003 EH1 could have originated from this breakup, having had a very close encounter with Jupiter in 1059, which would have speeded up the evolution along the nutation cycle rapidly.

In just a few years, most of our strong annual showers have now associated (mostly dormant) comets. Because most of our annual showers belong to this category of objects, fragmentation has to be the main demise mechanism for comets that reside in the inner solar system, and the main source of large meteoroids (meteors brighter than magnitude +3) that hit the Earth annually.

6 The future

During the 2006 General Assembly in Prague, the International Astronomical Union has taken responsibility for naming meteor showers. It is our hope that this will result in a more certain list of meteoroid streams from the helion and antihelion directions, that can be compared to the newly discovered minor planets. This could greatly increase the number of identified dormant comets and understand their breakup history. Amateur astronomers can help identify meteor showers from orbital element surveys and single-station video surveys. Most meteors brighter than about magnitude +3 are expected to be part of (some highly distorted) meteoroid streams.

Among the fast meteors that arrive from the apex direction of Earth, meteor outbursts will continue to be a way to investigate the ejection of dust from comets and detect the presence of yet unknown Earth-threatening comets.

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Peter Jenniskens, his brand new book and Geert Barentsen in the bus towards the Westerbork radio telescope (photo Casper ter Kuile).

Peter Jenniskens, Arnold Tukkers, Bernd Gärhrken and Felix Bettonvil (photo Casper ter Kuile).