University of Ljubljana
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Meteors and their streams

Seminar

Figure 1: Leonid meteor storm in 2001. [6]

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Abstract

Probably the most fascinating phenomena that can be observed in the night sky with a naked eye is a bright shooting star dash across part of the sky. This of course is not really a star at all, but is a small piece of cosmic material called a meteoroid, which burns up during its passage through the Earth's atmosphere producing the streak of light which we call a meteor. The event itself can not be predicted, but yet we can say when we can expect higher or lower meteors, how fast meteoroids are, and where is this material originate from.

Contents

1. Introduction

A meteor, sometimes called a "shooting star," can be the brightest object in the night sky, yet meteoroids are the smallest bodies in the solar system that can be observed by eye. Wandering through space, as debris left behind by a comet, meteoroids enter the Earth's atmosphere, are heated by friction, and for a few seconds streak across the sky as a meteor with a glowing trail.

On almost any night a few meteors an hour will be seen from any one place. However, periodically there are meteor showers, with hundreds of meteors emanating from the same apparent spot in the sky. These showers typically last from a few hours to several days. They are usually associated with comet paths, and are caused by debris expelled by the comet.

2. Terminology

2.1. Meteoroid

A meteoroid is a small sand to boulder-sized particle of debris in the Solar System. The current official definition of a meteoroid from the International Astronomical Union is "A solid object moving in interplanetary space, of a size considerably smaller than an asteroid and considerably larger than an atom or molecule." The Royal Astronomical Society has proposed a new definition where a meteoroid is between 100 μm and 10 m across. [15]

2.2. Meteoroid stream

Meteoroid stream is a trail of solid particles released from a parent body such as a comet or asteroid, moving on similar orbits. Various ejection directions and velocities for individual meteoroids cause the width of a stream and the gradual distribution of meteoroids over the entire average orbit.

2.3. Meteor

A meteor is the visible event that occurs when a meteoroid or asteroid enters Earth's atmosphere and becomes brightly visible.

Figure 2: Fireballs during Leonid meteor shower in 2001. [7]

2.4. Fireball

A fireball is a very bright meteor. The International Astronomical Union defines a fireball as "a meteor brighter than magnitude -4".

2.5. Meteorite

A meteorite is a portion of a meteoroid or asteroid that survives its passage through the atmosphere and impact with the ground without being destroyed. Meteorites are sometimes, but not always, found in association with hypervelocity impact craters; during energetic collisions, the entire impactor may be vaporized, leaving no meteorites.

3. Comets origin

A comet is a small body in the Solar system that orbits the Sun and (at least occasionally) exhibits a coma (or atmosphere) and/or a tail — both primarily from the effects of solar radiation upon the comet's nucleus, which itself is a minor body composed of rock, dust, and ice. Comet's orbits are constantly changing: their origins are in the outer solar system, and they have a propensity to be highly affected (or perturbed) by relatively close approaches to the major planets. Some are moved into Sun-grazing orbits that destroy the comets when they near the Sun, while others are thrown out of the solar system forever. [1]

Figure 3: Comet 1P/Halley is the parent body of the most famous meteor shower, called Perseids, witch are active every year in mid August.[5]

3.1. Oort cloud

The Oort cloud is an immense spherical cloud surrounding the planetary system and extending approximately 3 light years from the Sun. This vast distance is considered the edge of the Sun's orb of physical, gravitational, or dynamical influence. Within the cloud, comets are typically tens of millions of kilometers apart. [2] They are weakly bound to the sun, and passing stars and other forces can readily change their orbits, sending them into the inner solar system or out to interstellar space.

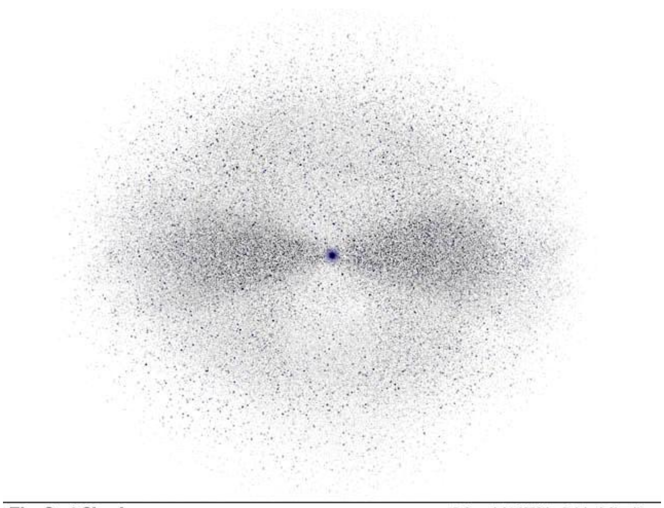

Figure 4: The structure of the Oort cloud is believed to consist of a relatively dense core that lies near the ecliptic plane and gradually replenishes the outer boundaries. The radius of the cloud is approximately 30 trillion kilometers, the Sun being the center point. Trillions of icy objects travel this region, ancient relics of the primordial Solar nebula from which the solar system was formed, and the source of future long-period comets to the inner Solar system.[2]

In addition to stellar perturbations where another star's Oort cloud passes through or close to the Sun's Oort cloud, are the influences of giant molecular[1] clouds and tidal forces. These are infrequently encountered, about every 300-500 million years, but when they are encountered, they can violently redistribute comets within the Oort cloud.

The total mass of comets in the Oort cloud is estimated to be 40 times that of Earth. This matter is believed to have originated at different distances and therefore temperatures from the Sun, which explains the compositional diversity observed in comets.

The Oort cloud is the source of long-period comets and possibly higher-inclination intermediate comets that were pulled into shorter period orbits by the planets, such as Halley and Swift-Tuttle. Comets can also shift their orbits due to jets of gas and dust that rocket from their icy surface as they approach the sun. Although they get off course, comets do have initial orbits with widely different periods, from 200 years to once every million years or more. Comets entering the planetary region for the first time, come from an average distance of 44,000 astronomical units[2]. [2]

3.2. Kuiper Belt

The Kuiper belt contains a vast number of objects in a flattened, ring-like volume beyond the orbit of Neptune[3] to approximately 55 AU from the Sun. These objects are collisionally processed relics from the accretion disk of the Sun and, as such,

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[1] A giant molecular-cloud (GMC) is an accumulation of cold hydrogen that is the birthplace of stars and solar systems. It is by far more massive than the Sun.

[2] Formal definition of Astronomical Unit (AU) is the radius of an unperturbed circular orbit a massless body would revolve about the sun in $2\pi/k$ days (i.e., 365.2568983.... days), where k is defined as the Gaussian constant exactly equal to 0.01720209895. 1 AU = 149,597,870.691 kilometers, witch is slightly less than semi-major axis of the Earth.

[3] Neptune's orbit is at about 30 AU from the Sun.

they can reveal much about early conditions in the Solar system. The Kuiper belt is the source of the Centaurs and the Jupiter-family comets. While most Kuiper belt objects are small, roughly a dozen known examples have diameters of order 1000 km or more, including Pluto and some other recently discovered giant Kuiper belt objects.

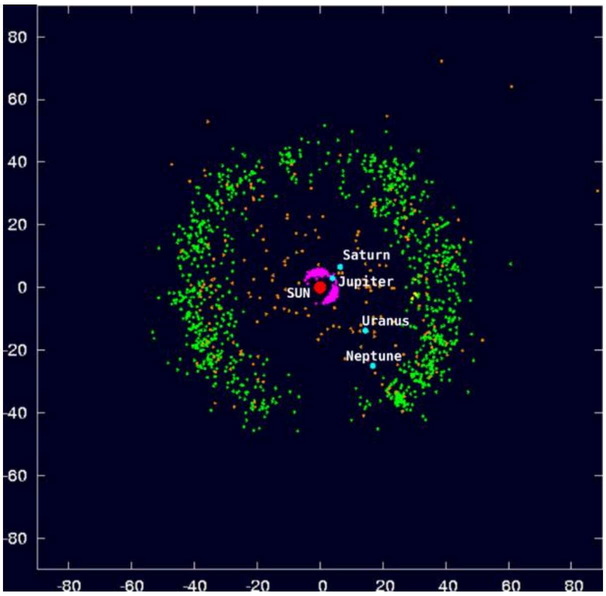

Figure 5: Known objects in the Kuiper belt, derived from data from the Minor Planet Center. Objects in the main belt are coloured green, while scattered objects are coloured orange.[14]

Jupiter-family comets behave strikingly different than those coming from the far reaches of the Oort cloud. Besides orbiting the Sun in less than 20 years (as opposed to 30 million years for an Oort member), the comets are unique because their orbits lie near the plane of the Earth's orbit around the Sun. In addition, all these comets go around the Sun in the same direction as the planets. [2], [3]

4. Meteoroid stream

Meteor streams are groups of meteoroids originating typically from dust grains ejected from comets. These small dust grains are distributed along the parent comet's orbit concentrated close to the comet nucleus with fewer grains farther away from the nucleus. By time, these grain particles are slowly distributed over the entire orbit due to the initial velocity and as well gravitational perturbations. Every time the Earth passes through such a stream of dust particles (i.e. meteoroid stream), we experience what is known as a meteor shower.

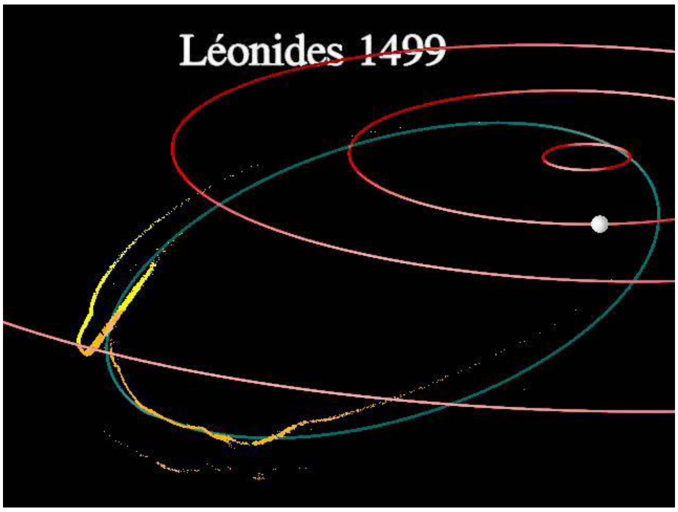

Figure 6: Simulation of the meteoroid stream ejected by comet 55P/Tempel-Tuttle (Leonids) in 1499, when the comet was in perihelion.[17]

4.1. Spread time estimation

In this chapter we shall take a look how much time would dust particles from evaporating comet need, to spread around the entire orbit. For this, we have to first take a closer look to the orbital elements.

4.1.1. Orbital elements

A total of six independent parameters are required to describe the motion of an object around the Sun. Two of these orbital elements (a and e) describe the form of the orbit, one element (M) defines the position along the orbit and the three others (Ω, i and ω) finally define the orientation of the orbit in space:

a - semi-major axis;

e - eccentricity;

M - mean anomaly;

Ω - longitude of the ascending node;

i - inclination of the orbit;

ω - argument of periapsis[4].

[4] For an object moving in an elliptical orbit about another celestial body, the point of closest approach is called the periapsis. Periapsis of an object that is orbiting the Sun is called perihelion.

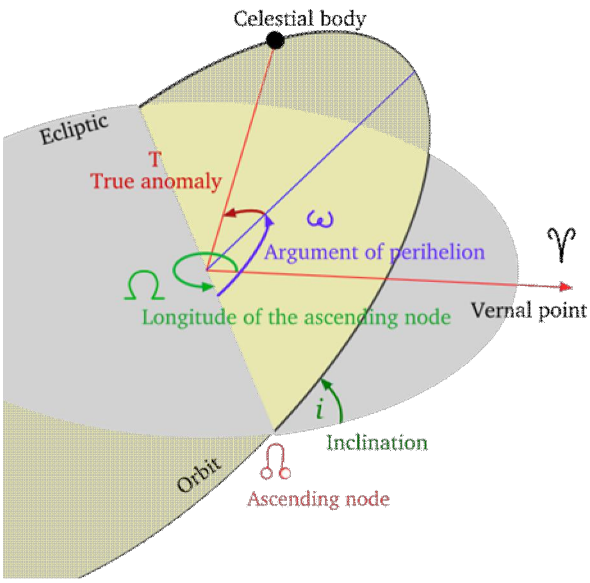

Figure 7: The orbital plane (yellow) intersects a reference plane called the plane of the ecliptic (grey). The intersection is called the line of nodes, as it connects the center of mass with the ascending and descending nodes. This plane, together with the Vernal Point, establishes a reference frame. [16]

Mean motion changes by 360° during one revolution but – in contrast to the true and eccentric anomalies (see Figure 7 and [8] for more information) – increases uniformly with time:

$$M = M_0 + n\left(t - t_0\right), \tag{4.1}$$

where the M_0 denotes the value of the mean anomaly at some reference epoch t_0 and n denotes mean motion. Mean Motion is defined as:

$$n \equiv \frac{2\pi}{P}, \tag{4.2}$$

If P denotes periodic of an object. Mean motion is a measure of how fast an object progresses around it's orbit. Unless the orbit is circular, the mean motion is only an average value of angular velocity.

4.1.2. Characteristic time

For estimating the characteristic time that is needed for comet's debris to spread around the entire orbit, we only need definitions from 4.1.1, third Kepler's law, and energy or so called vis-viva law. Third Kepler's law tells us:

$$n = \sqrt{\frac{GM_\odot}{a^3}} \tag{4.3}$$

and from energy law for orbiting object we can obtain:

$$a = \left(\frac{2}{r} - \frac{v^2}{GM_\odot}\right)^{-1} \tag{4.4}$$

From here, we can easily calculate needed derivates:

$$\frac{\partial n}{\partial r} = -\frac{3}{r^2}\sqrt{\frac{GM_\odot}{a}} = -3n\frac{a}{r^2} \tag{4.5}$$

and:

$$\frac{\partial n}{\partial v} = -3v\sqrt{\frac{1}{GM_\odot}} = -3\frac{v}{a^2 n} \tag{4.6}$$

From here, we can easily see, how mean motion n will change due to changed initial position r and velocity v, witch both are caused by evaporation of parent comet:

$$\begin{aligned}\Delta n &= \frac{\partial n}{\partial r}\Delta r + \frac{\partial n}{\partial v}\Delta v \\ &= -3n\frac{a}{r^2}\Delta r - 3\frac{v}{a^2 n}\Delta v\end{aligned} \tag{4.7}$$

This change of mean motion Δn tells us directly (see (4.1)) the time τ that is needed for evaporated dust to spread around the orbit:

$$\tau = \frac{\pi}{|\Delta n|} \tag{4.8}$$

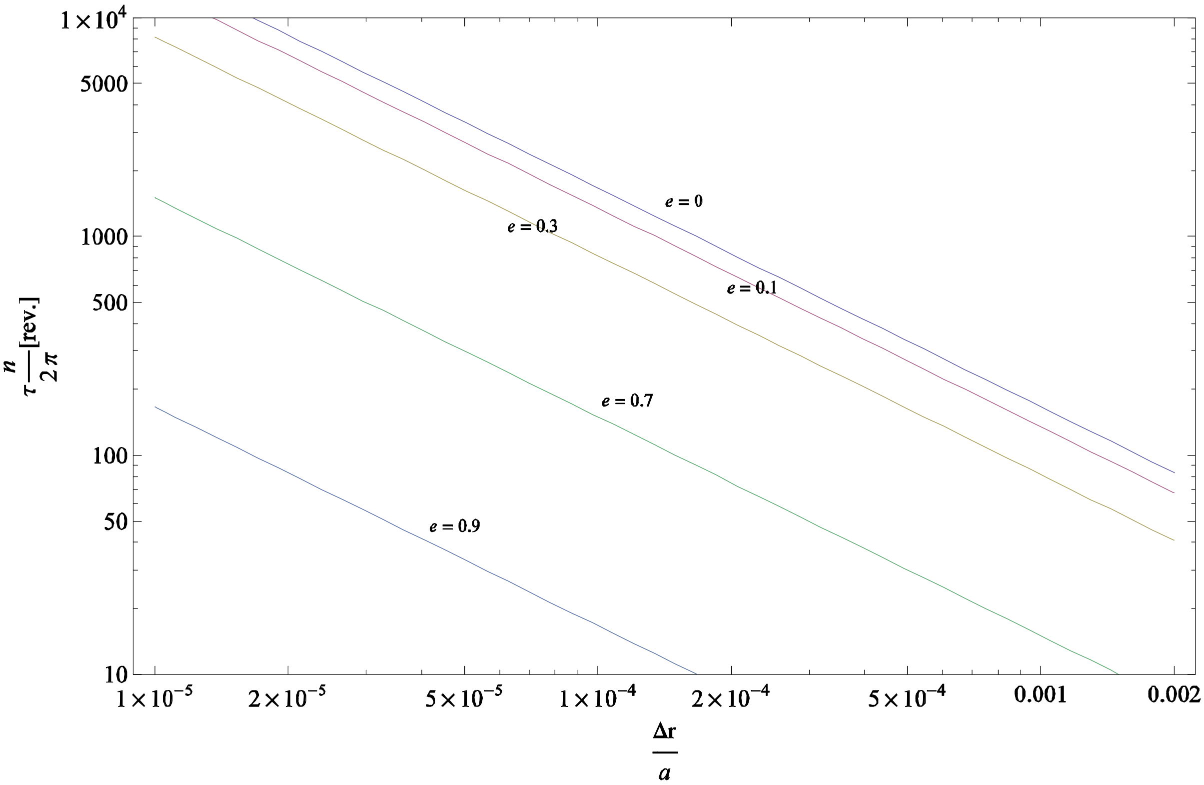

Figure 8: Logarithmic plot represents time (in comet's revolutions) that is needed to spread it's evaporated material over the entire orbit. Initial dispersion of velocity Δv is ignored[5].

[5] According to [9],p.302 total velocity change due to evaporation are in size order of few ms^{-1}.

If we set $\Delta v = 0$, we can write down:

$$\begin{aligned} \tau &= \frac{\pi r^2}{3n \cdot a \cdot \Delta r} \\ &= \frac{\pi r^2}{3\Delta r}\sqrt{\frac{a}{GM_\odot}} \end{aligned} \tag{4.9}$$

If we are interested for comets, with their perihelion close to the Earth ($r \approx 1AU$), and we assume that major of evaporation is happening when the comet is in perihelion, then the characteristic time is proportional to:

$$\tau \propto \frac{1}{\Delta r\sqrt{1-e}} \tag{4.10}$$

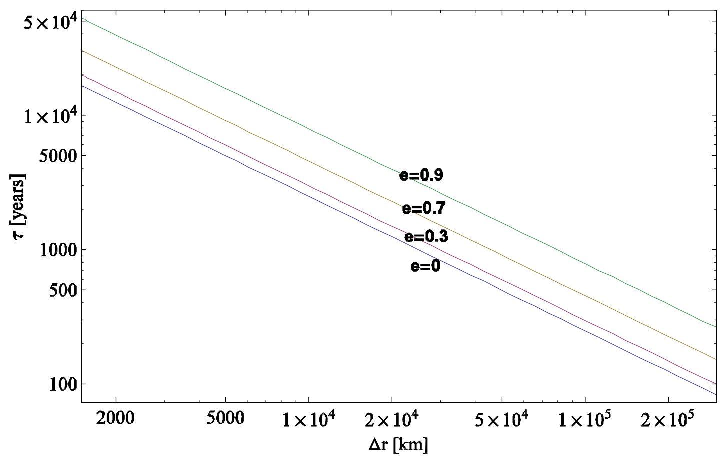

Figure 9: For us are interesting only those meteoroid streams, which can reach the Earth, meaning, their perihelion is at about 1AU from the Sun (or closer). This chart shows us such meteoroid streams (their characteristically time to be spread over the entire orbit) for different eccentricities. We can see, that the time is as long as several thousands years. This is the reason, why younger streams, such as Leonids, are not yet distributed over entire orbit and why we see meteor activity of such stream only when their parent comet is at perihelion.

Over time, initial dispersion of position[6] Δr and velocity[5] Δv and also planetary perturbations[7] displace a comet's trail from the nucleus and the trail becomes increasingly tenuous. The trail is then considered to be a meteoroid stream and produces meteor showers if the stream and a planet collide.

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[6] For initial position dispersion Δr we take size order of several thousands kilometers, witch correspond to size order of typical comet's coma.

[7] For our simple estimation of typical dust life time we ignored all the planetary perturbations. However, it is more likely to be disturbed by planetary perturbation for comets with higher eccentricity orbits, since they reach further into the Solar system and spend more time around more massive planets.

5. Meteoroid impact velocity

If a meteoroid (or comet) is gravitationally bound to the Sun, the greatest velocity that it may have upon crossing the orbit of a planet is the escape velocity v_{esc} of the Sun from that point. The escape velocity is

$$v_{esc} = \sqrt{\frac{2GM_{\odot}}{R}}, \tag{5.1}$$

which is about 42 km/s at Earth's orbit. This velocity vector may be oriented in any direction. The approach direction that minimizes the encounter velocity relative to the planet is for the comet to be overtaking the planet from behind, in a prograde orbit with zero inclination. The encounter velocity is then the vector difference of v_{esc} and v_{orb} for the planet. For a planet in circular orbit:

$$v_{orb} = \frac{v_{esc}}{\sqrt{2}}. \tag{5.2}$$

The approach velocity is therefore $\left(1-1/\sqrt{2}\right)v_{esc} = 0.2929v_{esc}$. The highest possible relative velocity is achieved when the comet (or meteoroid) is in a retrograde orbit of zero inclination and strikes the planet head-on. The closing velocity is then $\left(1+1/\sqrt{2}\right)v_{esc} = 1.7071v_{esc}$. Therefore, at Earth, the closing velocity for a long-period comet can range from 12.3 to 71.7 km/s (that is the case for Leonids).

Here we neglected acceleration of the meteor by Earth gravity field. The velocity increase of an in-falling meteor is not a fixed quantity, because a fast-moving meteor spend less time accelerating. As a consequence, the total velocity increase is much smaller for fast-moving objects:

$$v_{imp}^2 = v_{app}^2 + v_{Eesc}^2, \tag{5.3}$$

Where v_{imp} is impact velocity of the meteor, v_{app} is approach velocity and v_{Eesc} denotes Earth's surface escape velocity, 11.2 km/s.

5.1. Brightness of meteor

5.1.1. Morning / evening difference

Earth is spinning in the same direction around its axis and around the Sun. Because of that fact, sporadic meteors, which we are watching in the evening sky have typically prograde orbits. On the other hand, sporadic meteors on the morning sky have typically retrograde orbits. Consider Earth's interaction with two low-inclination meteors that are both traveling at 40km/s at Earth's orbit, one of witch is in a prograde and the other, in a retrograde orbit. Earth's Keplerian velocity is about 30km/s, so the prograde object will approach Earth from behind at a closing speed of 10km/s, whereas the retrograde object will approach the down side of Earth at a relative speed of 70Km/s. The kinetic energy per gram are than 50 kJ and 2.5 MJ. Adding to each the gravitational energy per gram picked up by falling into Earth's gravitational field ($0.5v_{Eesc}^2$) , the kinetic energies of the two particles upon striking the upper atmosphere are:

$$E_{prograde} = 0.12MJ$$
$$E_{retrograde} = 2.6MJ \tag{5.4}$$

Therefore relatively faint meteors (we will notice less of them) will be expected for evening meteors.

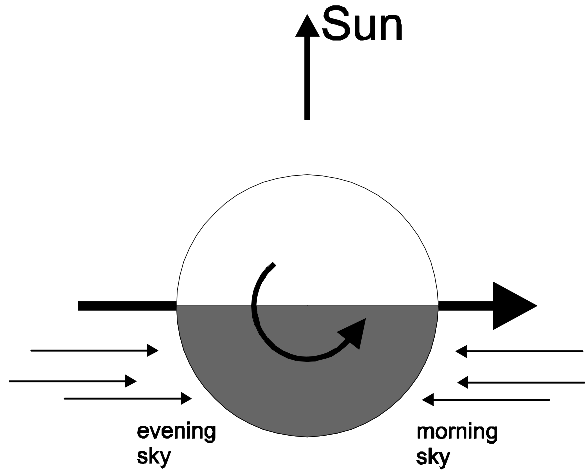


Figure 10: Prograde meteors in the evening sky, and retrograde meteors in the morning sky.

5.1.2. Magnitude estimation

Milligram meteors meteor are visible under good seeing conditions. Truly bright meteors, with masses of kilograms and many tons, are sometimes observed in conjunction with meteor showers. But even the brightest cometary meteors seem to be so fragile that they are utterly consumed by their explosive interaction with the upper atmosphere. Considering that roughly 0.1 KJ will crush a gram of strong rock and 10 MJ will vaporize it, the entry of weak rocks with kinetic energy densities of up to about 2.7 MJ per gram should not often permit solid material to survive and land intact on Earth as a meteorite. [9]

Let's estimate upper limit for a meteor magnitude, which is caused by in-falling object with known mass. If we suppose that majority of kinetic energy transforms into visible light we can estimate, how massive the impact object should be to be visible with naked eye:

$$M = M_{\odot} - 2.5 \log\left(\frac{j}{j_{\odot}}\right) \tag{5.5}$$

We can choose Sun's magnitude and flux for reference:

$$j_{\odot} = 1380 W/m^2$$
$$M_{\odot} = -26.7$$

For flux density of a meteor, we can simply take:

$$j = \frac{W_k / t}{4\pi \cdot r^2} = \frac{m \cdot v_{imp}^2}{8\pi \cdot t \cdot r^2} \tag{5.6}$$

Where t defines how much time meteor is visible (typical $t \sim 1s$), and r defines distance between an observer and meteor (typical $r \approx 100km$).

From here we can see, that object with mass $m = 1g$ and impact velocity $v_{imp} = 70km/s$ would cause -5 magnitude bright meteor. But as mentioned, these are only upper limit estimates. The problem is that only a small part of energy is transformed into visible light and the brightness itself is also dependent by the material that is meteoroid composed from. According to [18] an object with mass of one gram would cause 0 magnitude bright meteor, so only about 1 percent of the kinetic energy transforms into visible light:

magnitude	6	0	-7	-15
mass	$10^{-3}g$	$1g$	$10^{3}g$	$10^{6}g$

Table 1: Table is calculated for impact velocity $v_{imp} \approx 70km/s$. We can see, that a particle as light as a part of a gram can cause quite a bright meteor. [18]

6. Visual observation

Visual observation of meteor showers is one of the most popular activities for amateur astronomers. An easy way to observe meteors visually is what we call the 'counting method.' The observer notes the meteors seen on a tape recorder or just a piece of paper. He gives the estimated magnitude of the meteor and whether or not it belonged to the observed shower (e.g. Leonid or non-Leonid). This method is applicable for major shower maxima like the Quadrantids, Perseids, and Geminids.

Notes of these observations are widely sent to the International Meteor Organization (IMO). IMO was created in response to an ever growing need for international cooperation of meteor amateur work. The collection of meteor observations by several methods from all around the world ensures the comprehensive study of meteor showers and their relation to comets and interplanetary dust.

6.1. Radiant

The radiant of a meteor shower is the point in the sky that meteors appear to originate from to an observer. The Perseids, for example, are meteors which appear to come from a point within the constellation of Perseus. An observer might see such a meteor anywhere in the sky but the direction of motion, when traced back, will point to the radiant. A meteor that does not point back to the known radiant for a given shower is known as a sporadic and is not considered part of that shower. Position of the radiant tells us from which direction the meteoroids are coming.

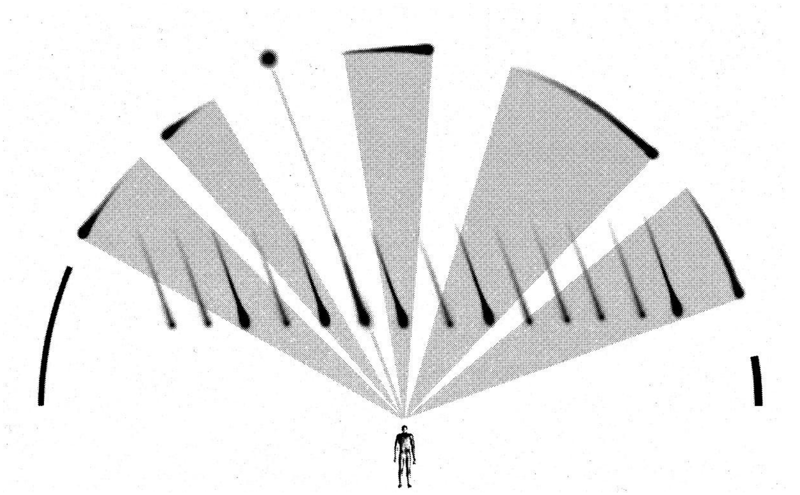


Figure 11: Meteors witch belongs to the same shower are parallel, so an observer sees them as they would originate from one point – radiant. [12]

6.2. Zenith hourly rate (ZHR)

Zenith hourly rate (ZHR) is one of the main results from amateur observations. Zenithal Hourly Rate (ZHR) of a meteor shower is the number of meteors an observer would see in one hour in ideal conditions[8] and if the radiant of the shower were in the zenith. Conditions are very rarely (never) ideal and the rate is nearly always lower and decreases as the radiant is closer to the horizon. So when we calculate ZHR for ideal conditions, we have to make a few corrections:

$$ZHR = \frac{N}{t_e} F \cdot C \cdot K\,, \qquad (6.1)$$

Where N/t_e represents frequency of actual seen meteors, and the correction due to no ideal conditions are as follows:

F is cloudiness correction. We estimate this correction factor by cloudiness in the part of the sky that we are observing[9]. Meaning: if we estimate, that 10 percent of the sky is covered with clouds, the cloudiness correction factor would be $F = 1/(1-0.1) = 1.11$

C is limiting magnitude correction. In ideal night, our limiting magnitude would be around $L_M = 6.5$. Correction factor C is ratio between number of meteors that would be seen with $L_M = 6.5$ and number of meteors that are seen with limiting magnitude L_M. This factor is also closely connected with population index r[10]. In [10] we find the equation: $C = r^{(6.5-L_M)}$.

[8] Ideal conditions are: clear, dark sky (limiting apparent magnitude of 6.5) and radiant of the shower in the zenith

[9] Our viewing angle is around 100 degrees.

[10] Population index for certain meteor shower tells us something about meteor distribution versus their magnitude, and it is also closely connected with mass distribution of the meteoroids in the stream. For more information about population index see [18].

K is correction for the radiant's elevation . Because the radiant of the shower is not in the zenith, we will see less meteors. The correction $K = 1/\cos Z$, where Z represents zenithal distance.

For more detail information about Zenith Hourly Rate and it's correction factors, please see [10] or [18].

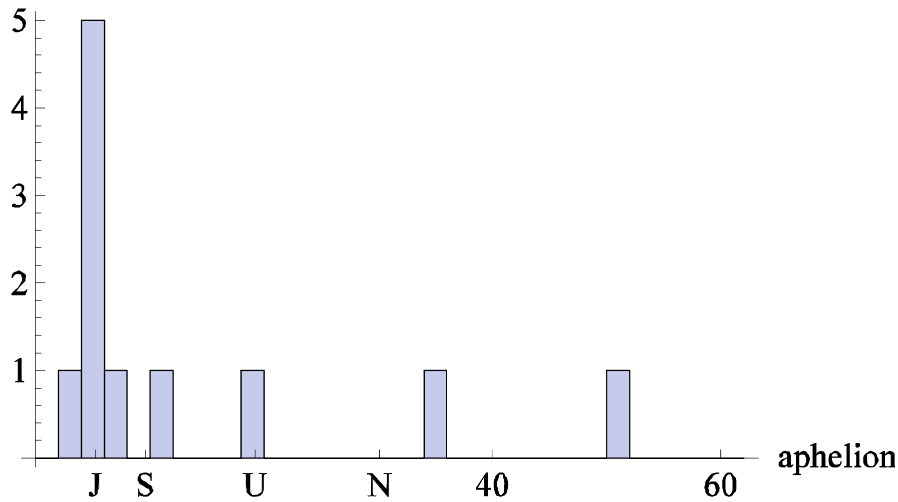
7. Parent objects

Every meteor shower, has its own parent body. For many of them, parent comets already evaporated, but for some of them are still present:

Shower	Time	Parent Object	Perihelion	Aphelion
Quadrantids	Jan 1 - Jan 5	Minor planet 2003 EH1[11]	1.19 AU	5.06 AU
Lyrids	Apr 15 - 28	Comet Thatcher	0.92 AU	110 AU
Pi Puppids	Apr 15 - Apr 28	Comet 26P/Grigg-Skjellerup	0.99 AU	4.93 AU
Eta Aquarids	Apr 21 - May 12	Comet 1P/Halley	0.59 AU	35.1 AU
Arietids	May 22 - July 2	Marsden Sungrazer Group		
June Bootids	June 26 - July 2	Comet 7P/Pons-Winnecke	1.26 AU	5.61 AU
Southern Delta Aquarids	Jul 12 - Aug 19	Kracht or Machholz Sungrazer Groups		
Perseids	Aug 8 - Aug 14	Comet 109P/Swift-Tuttle	0.56 AU	51.2 AU
Draconids	Oct 6 - Oct 10	Comet 21P/Giacobini-Zinner	1.04 AU	6.01 AU
Orionids	Oct 2 - Nov 7	Comet 1P/Halley	0.59 AU	35.1 AU
Southern Taurids	Nov 1 - Nov 25	Comet 2P/Encke and others	0.34 AU	4.10 AU
Northern Taurids	Nov 1 - Nov 25	Minor planet 2004 TG10 and others	0.32 AU	4.17 AU
Leonids	Nov 14 - Nov 21	Comet 55P/Tempel-Tuttle	0.98 AU	19.7 AU
Geminids	Dec 7 - Dec 17	Minor planet 3200 Phaethon	0.14 AU	2.40 AU
Ursids	Dec 17 - Dec 26	Comet 8P/Tuttle	1.03 AU	10.4 AU

Table 2: Some meteor shower with their parent comets, perihelion and aphelion of their orbits.[4]

It is obvious that all the parent comets have their perihelion within 1 AU. We can also notice, that majority of the comets have aphelion around 5 AU, witch correspond with Jupiter's semi-major axis.



[11] Minor planet 2003 EH1 suffered a catastrophic breakup in 1490.

Figure 12: Histogram of the aphelion of the comet listed in Table 2. The abscissa presents aphelion of the comets in AU. Labels 'J', 'S', 'U' and 'N' apply to aphelion of the Jupiter, Saturn, Uranus and Neptune.[4]

Since comet's elliptical orbits frequently take them close to the giant planets, their orbits are often perturbed. Short period comets display a tendency for their aphelia to match with a giant planet's orbital radius, with the Jupiter family of comets being the largest, as Figure 12 shows. Jupiter is the source of the greatest perturbations, being more than twice as massive as all the other planets combined.

8. Conclusion

Some meteors showers, such as Leonids or Perseids are known to be observed since thousands year ago. So, as shown in 4.1.2, the meteoroid stream has enough time to spread all over comet's initial orbit. Such meteor shower is observable each year when the Earth crosses its orbit. But some meteor showers are still too young to be visible each year. That is the case with Pi Puppids or Leonids. The Leonids meteor shower is viewable around November 17th but only in years around the parent comet's perihelion date. The evaporation of the comet is still going on so the stream is very young and it is spread only around the comet (55P/Tempel-Tuttle).

As already mentioned in 4.1.2 also planetary perturbations are very important for stream to spread around. So we can expect that streams from Table 2 with low orbital inclination and aphelion close to Jupiter's semi-major axis will be more radically perturbed and meteoroid material will be spread around the orbit in shorter time.

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