Teacher’s Manual

Chapter 5: Meteors

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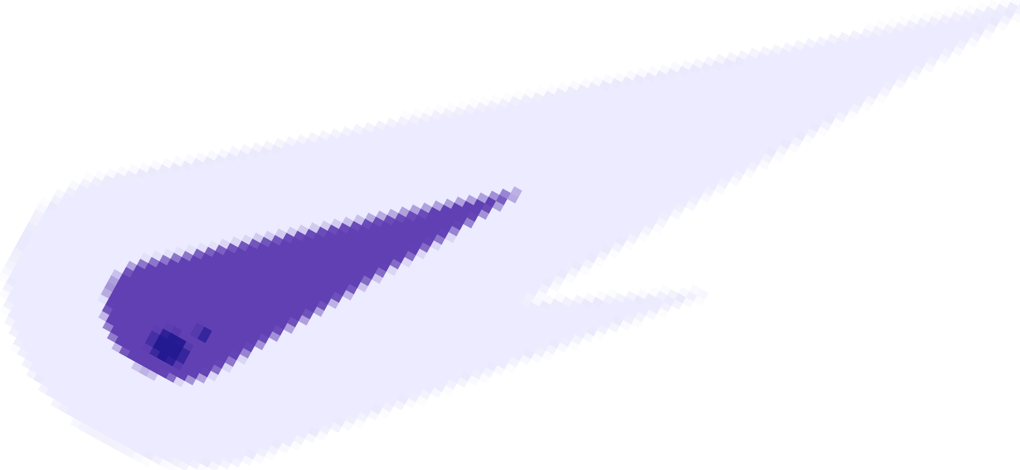
Work Package 3
StAnD Academy



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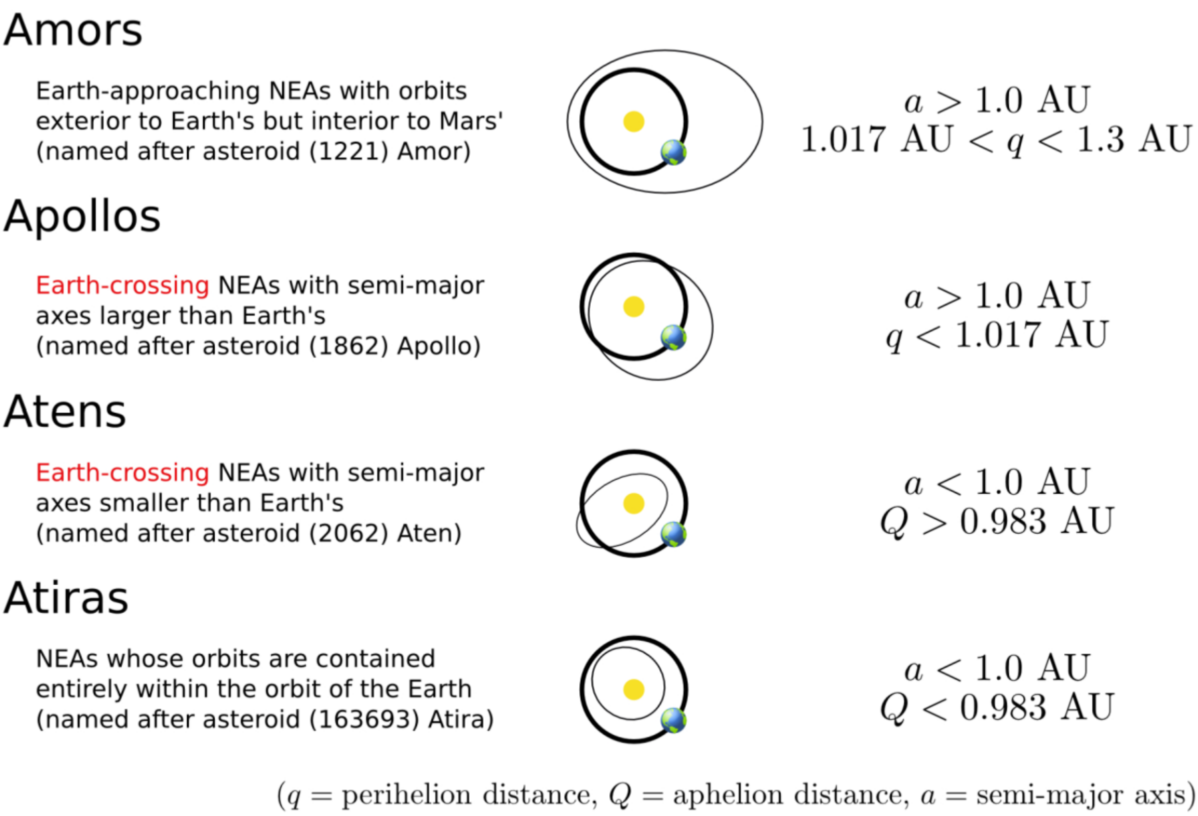
5.1 Meteoroids and Their Parent Bodies

Among the many minor bodies orbiting around the Sun, a small minority are Near-Earth Objects (NEOs).

The name of these objects defines quite clearly their main property, i.e. being in the proximity of our Earth. However, a more precise scientific definition is needed: an object is a NEO if its perihelion distance, *q*, is lower than 1.3 AU. This means that NEOs orbits penetrate deep into the inner Solar System and are therefore close to the Earth's orbit, if not crossing it. They usually have an aphelion distance Q < 5.2 AU, internal to Jupiter. NEOs can be either asteroids (NEA) or comets (NEC), NEAs being the vast majority.



Amors

Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars' (named after asteroid (1221) Amor)

$a > 1.0$ AU
$1.017 \text{ AU} < q < 1.3 \text{ AU}$

Apollos

Earth-crossing NEAs with semi-major axes larger than Earth's (named after asteroid (1862) Apollo)

$a > 1.0$ AU
$q < 1.017$ AU

Atens

Earth-crossing NEAs with semi-major axes smaller than Earth's (named after asteroid (2062) Aten)

$a < 1.0$ AU
$Q > 0.983$ AU

Atiras

NEAs whose orbits are contained entirely within the orbit of the Earth (named after asteroid (163693) Atira)

$a < 1.0$ AU
$Q < 0.983$ AU

(q = perihelion distance, Q = aphelion distance, a = semi-major axis)

Figure 5.1.1. Classification of NEOs based on their orbital parameters (https://cneos.jpl.nasa.gov).

According to their orbital configuration, NEOs are conventionally classified into four groups, (see Fig. 5.1.1), namely:

1. **Amors**, with orbits external to the Earth’s one but internal to Mars;
2. **Apollos**, with Earth-crossing orbits and semi-major axes greater than 1 AU;
3. **Atens**, with Earth-crossing orbits and semi-major axes less than 1 AU;
4. **Atiras**, whose orbits are confined within the Earth’s one.

They are all named after a particular member of the group (the first discovered belonging to that group). The most populated group is the one of Apollos, which alone accounts for 56% of all currently known NEOs, followed by Amors (36%) and Atens (8%). Only 29 Atiras asteroids are known to date.

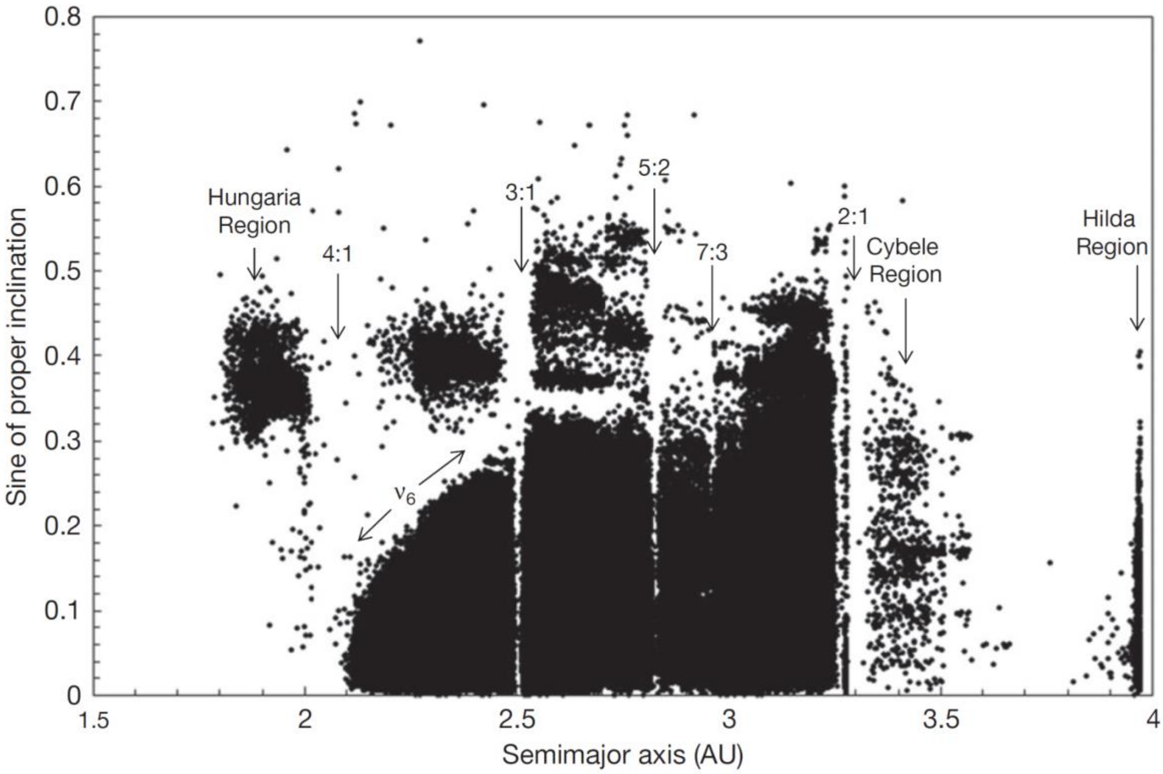


Figure 5.1.2. Inclination of orbit vs. Semimajor axis for asteroids. Arrows mark the position of the main Mean Motion Resonances with Jupiter. The Kirkwood gaps are clearly visible as white vertical stripes. The secular ν6 resonance with Saturn and some asteroid families are also shown.

As we will further discuss, small objects do not pose any concern from the point of view of our safety. However, larger asteroids do and are therefore labelled as Potentially Hazardous Asteroids (PHAs). PHAs have a magnitude brighter than H = 22, corresponding to a size greater than 140 m, and an Earth’s Minimum Orbital Intersection Distance (MOID) of less than 0.05 AU. These limits are connected to the degree of threat that PHAs pose to the Earth. They are large enough to survive atmospheric transit without significant deceleration, striking the Earth’s surface at orbital speed. In fact, the impact of a 140 m size object on the Earth can have destructive effects on a regional scale. The impact of a PHA is a very rare event, but it has occurred in the past and will for sure occur in the future, with a time span depending on the PHA size.

NEOs and other asteroid types counts are available at the website of the Minor Planet Center (https://www.minorplanetcenter.net/mpc/summary). Currently, almost 35000 NEOs and more than 2400 PHAs are listed.

But how did asteroids and comets become NEOs? Both gravitational and non-gravitational effects contribute to the refurbishment of the NEO population. One delivery mechanism of minor bodies from outer to inner orbits is related to the *Mean Motion Resonances* (MMR). Resonance effects arise when the orbital period of a Main Belt Asteroid and the period of a large and close planet (e.g. Jupiter) are related by a ratio of small integers (e.g. 2:1, 3:2, 3:1, and so on). This causes an unbalanced gravitational pull exerted by the planet onto the asteroid orbit, which is *stretched* towards larger semi-axes: the aphelion distance increases while the perihelion decreases, thus causing the asteroid to become a NEO. Resonance regions become depleted in asteroids, forming the so-called *Kirkwood gaps* shown in Figure 5.1.2.

However, gravitational effects are not enough to explain the NEO population. In fact, the MMR mechanism is very fast, in astronomical terms, and should already have come to an end, while, instead, we see that the refurbishment of NEOs is still ongoing. Recently, astronomers have discovered the importance of non-gravitational effects, such as the Yarkowsky effect. In a nutshell, the asteroid surface absorbs and re-emits the Sun radiation. If the asteroid is rotating, the process of absorption and re-emission is anisotropic, due to thermal hysteresis. As a result, the asteroid experiences a net non-zero momentum. This effect is size dependent (large asteroids are less affected). Slowly, the body drifts towards MMR regions. When the MMR region is reached, the asteroid can be injected into a NEO orbit.

5.2 Meteors and Fireballs

Even though some NEOs can be large in size (as large as to become Potentially Hazardous Asteroids), the vast majority are smaller than 1 m. Such objects are called meteoroids, and are responsible, together with cometary fragments (see Section 5.3 Meteor Showers), for the extraordinary spectacle that is a *meteor*, which happens when NEOs collide with our planet.

The root word *meteor* comes from the ancient Greek *meteōros*, meaning *high in the air*. Bright meteors, conventionally brighter than the planet Venus (visual magnitude about -4, i.e. roughly 10 times the magnitude of Sirius, the brightest star in the sky), are usually called *fireballs*, and are generated by mm/cm sized meteoroids. Very bright fireballs, reaching apparent visual magnitude −14 (100.000 times Sirius) or brighter, are sometimes called bolides. Bolides often explode in an air burst.

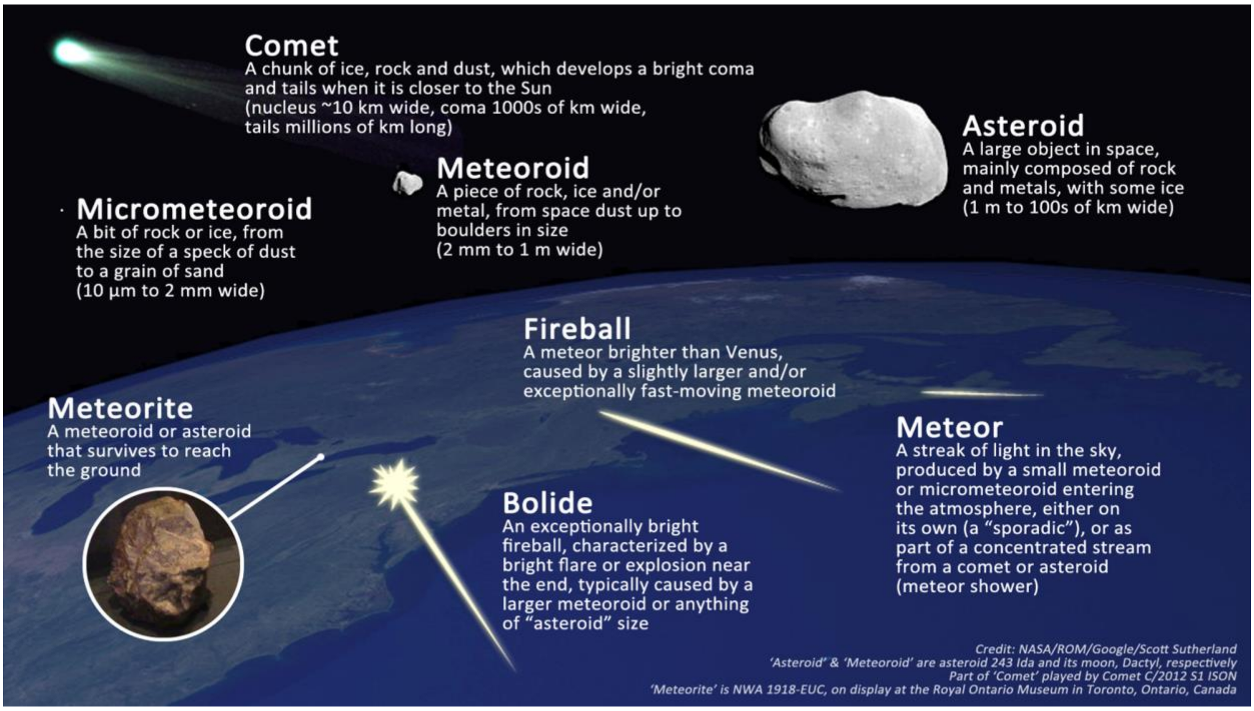
Meteors come in many different colours. The colour of the light produced by a meteor depends upon the chemical composition of the meteoroid and of the atmosphere. As layers of the meteoroid ablate and ionise, the colour of the light it emits may change according to the layering of minerals. For instance, an orange-yellow colour is related to Sodium (Na), green to Magnesium (Mg), yellow-green or blue to Iron (Fe), violet to Calcium (Ca), red to atmospheric Nitrogen (N) and Oxygen (O).

The energy carried by the meteoroid is mainly kinetic:

$$E_c = \frac{m.v^2}{2}$$

Therefore, both the *mass* and the *speed* of the meteoroid concur to the total meteoroid kinetic energy. However, while the energy scales linearly with the meteoroid *mass*, the *speed* contributes in proportion to the square. This is why even small fragments, colliding at high speed, generate very bright meteors. In fact, due to the combination of the meteoroid and the Earth's cosmic velocities, the impact speed is in the range between 11 km/s and 72 km/s. The lower end of the speed range refers to NEOs motion in the same direction of the Earth (i.e. prograde orbits), whereas the higher end of the speed range is typical of cometary fragments and it is due to meteoroids in retrograde orbits, thus causing head-on collisions with the Earth. This is the case of the *Perseids* meteor shower (see Section 5.3), produced by fragments of the comet *109P/Swift-Tuttle*, which was discovered in 1862. The link between the recently discovered comet and the *Perseids* meteor shower was demonstrated for the first time by the Italian astronomer Giovanni Virginio Schiaparelli a few years later.

While meteor showers are generally linked to a periodic comet, and can therefore be seen every year in the same period, *fireballs* are usually generated by fragments of asteroidal origin, and can be considered *sporadic*. For this reason, it is very difficult and unlikely to be able to foresee them.



Comet
A chunk of ice, rock and dust, which develops a bright coma and tails when it is closer to the Sun (nucleus ~10 km wide, coma 1000s of km wide, tails millions of km long)

Asteroid
A large object in space, mainly composed of rock and metals, with some ice (1 m to 100s of km wide)

Meteoroid
A piece of rock, ice and/or metal, from space dust up to boulders in size (2 mm to 1 m wide)

Micrometeoroid
A bit of rock or ice, from the size of a speck of dust to a grain of sand (10 µm to 2 mm wide)

Fireball
A meteor brighter than Venus, caused by a slightly larger and/or exceptionally fast-moving meteoroid

Meteorite
A meteoroid or asteroid that survives to reach the ground

Meteor
A streak of light in the sky, produced by a small meteoroid or micrometeoroid entering the atmosphere, either on its own (a "sporadic"), or as part of a concentrated stream from a comet or asteroid (meteor shower)

Bolide
An exceptionally bright fireball, characterized by a bright flare or explosion near the end, typically caused by a larger meteoroid or anything of "asteroid" size

Credit: NASA/ROM/Google/Scott Sutherland
'Asteroid' & 'Meteoroid' are asteroid 243 Ida and its moon, Dactyl, respectively
Part of 'Comet' played by Comet C/2012 S1 ISON
'Meteorite' is NWA 1918-EUC, on display at the Royal Ontario Museum in Toronto, Ontario, Canada

Figure 5.2.1. Infographic about the terminology of Minor Bodies of the Solar System and their interaction with the Earth's atmosphere

5.3 Meteor Showers

A meteor shower is an astronomical event where a number of meteors, also known as "shooting stars," appear to originate from a single point in the night sky. These meteors are actually small space particles called meteoroids that enter the Earth's atmosphere and burn up, creating a streak of light. Meteoroids are essentially celestial debris. If a meteoroid survives its fiery passage through the atmosphere and reaches the ground, it is called a meteorite.

Meteor showers occur when the Earth passes through a stream of debris left behind by a comet or asteroid. The meteoroids within a meteor stream travel along parallel paths and at similar speeds. Therefore, to an observer on Earth, they seem to radiate from a single point in the sky. This point is known as the radiant. Meteor showers are typically named after the constellation in which their radiant is located.

5.3.1 Main Meteor Showers and Their Parental Bodies

Several meteor showers occur throughout the year, some of which are regular events. Here are some of the main meteor showers and their associated parent objects:

- **Quadrantids:** This is the first meteor shower of the year, occurring between late December and January, with a peak around January 3-4. The radiant is located in the constellation Boötes, near the Big Dipper.

- **Lyrids:** The Lyrids meteor shower is active between April 16 and 26, with its radiant in the constellation Lyra. It can be observed from both the Northern and Southern Hemispheres.

- **Eta Aquarids:** This shower occurs from late April to mid-May, peaking around May 5-6. The radiant lies in the constellation Aquarius4. The meteoroids in this shower are remnants from Halley's Comet.

- **Perseids:** Active in mid-August, the Perseids peak around August 11-13 and have a radiant in the constellation Perseus. This shower is associated with the comet Swift-Tuttle.

- **Draconids:** This meteor shower occurs every October, peaking around October 7-8. The radiant is in the constellation Draco.

- **Orionids**: The Orionids, which are also associated with Halley's Comet, peak around October 21-22, with the radiant located in the constellation Orion.

- **Leonids:** The Leonids meteor shower occurs in November, typically peaking around mid-November. Its radiant is in the constellation Leo. The parent comet of this shower is Tempel-Tuttle.

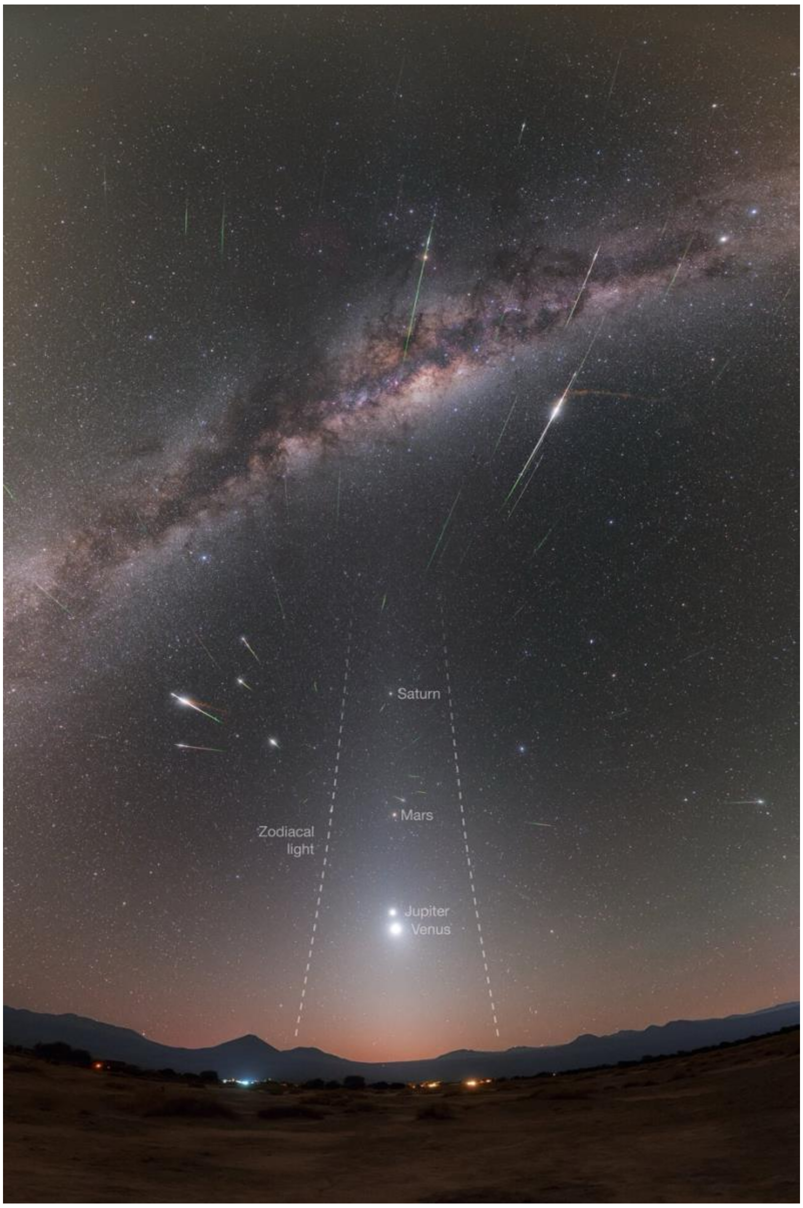
- **Geminids:** Active in early December, the Geminids peak around December 13-14. The radiant is in the constellation Gemini. Unlike most other major meteor showers, the Geminids are associated with an asteroid, not a comet.

- **Ursids:** The Ursids peak around December 22-23, with their radiant in the constellation Ursa Minor.

Observing Meteor Showers

Meteors are best viewed at night, away from city lights and on nights with minimal moonlight. The best time to observe meteor showers is during a New Moon phase.

To observe a meteor shower, look towards the direction of the constellation from which the meteors appear to originate. July and August are good months for observing meteor showers, in addition to December.



Composite image taken during the Eta Aquariids meteor shower featuring the radiant (ESO/P. Horalek)

5.4 Atmospheric Entry

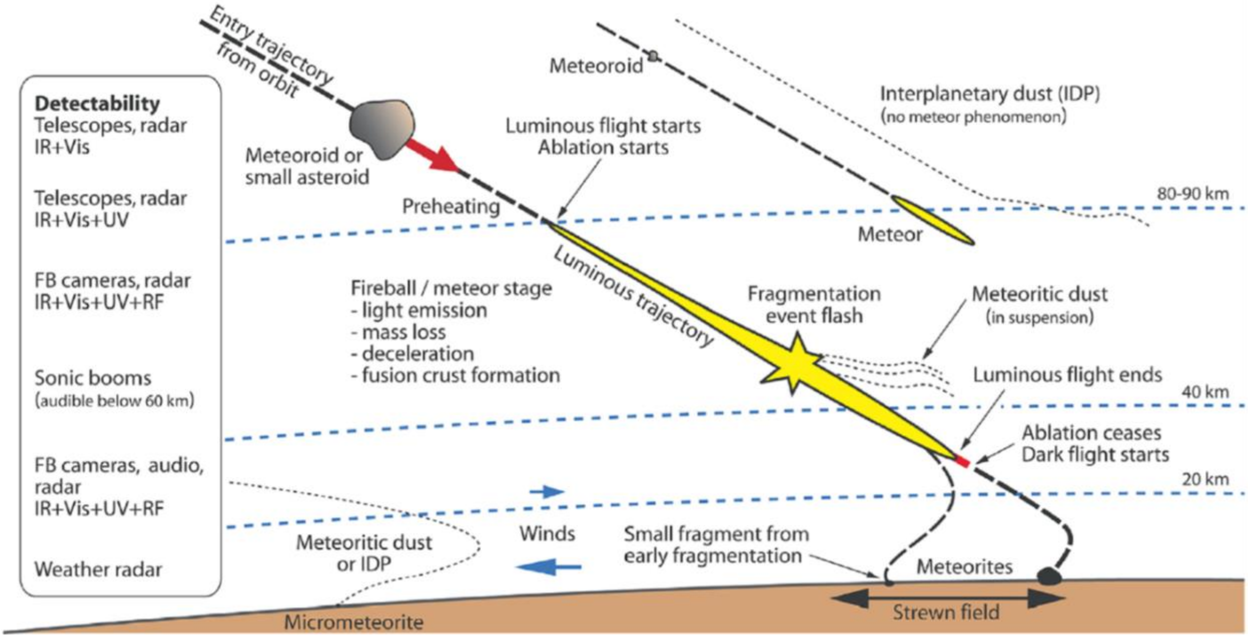


Figure 5.3.1. Comprehensive physics of a meteoroid entry into the Earth's atmosphere

While penetrating the atmosphere, the meteoroid goes through three main stages that can be summarised as follows:

1. Preheating: at altitudes between 300 and 100 km from the ground, the atmosphere is still very rarefied and air molecule impacts cause the heating of the meteoroid surface. While the surface temperature rises quite rapidly, the inside of the meteoroid remains practically unheated. At these altitudes, very small bodies (of the order of 10 µm or less, also called IDP or Interplanetary Dust Particles) can be significantly decelerated by the atmospheric friction and may not enter the next phase.

2. Ablation: this is the real meteor stage and is the most important phase of the atmospheric flight of a meteoroid. During the preheating, the temperature can rise as high as a few thousand degrees, and the meteoroid material starts to melt and evaporate. When reaching ~2500 K, the light emission starts, due both to the ionisation and electronic transitions of elements from the surrounding air molecules and the meteoroid material itself, and to thermal (black-body) radiation. In this stage, the energy loss due to ablation (mass loss) competes with the one due to deceleration (speed loss), and the fate of the meteoroid depends on the balance between these two processes. The amount of total light emitted, L, is a fraction of the original kinetic energy of the meteoroid (usually a few percentage points): $L = \tau * E$

where τ is the *luminous efficiency*. Only meteoroids larger than 10-20 cm in size are usually able to survive the ablation phase. It is not unusual for them to experience one or more fragmentation events, thus causing sudden flares.

The light emission usually ceases at heights of 25-20 km above sea level, when the meteoroid has lost most of its original cosmic speed, decelerating down to ~4 km/s in the lower atmosphere.

3. Dark Flight: if the meteoroid survives the ablation phase preserving a significant mass, its residue(s) will continue travelling towards the ground without emitting light. This is because there is no longer enough kinetic energy to either evaporate or melt the meteoroid material. The body decelerates until it completely loses its cosmic speed and consequently starts to freefall due to the Earth's gravity. In these conditions, the meteoroid motion is quite sensitive to the state of the atmosphere, in particular to the wind intensity and direction in the troposphere that modify the free fall trajectory of the residue. Impact velocities on the ground can vary in the order of 10–100 m/s, depending on the size of the fragments that once fallen on the Earth become meteorites. The area of probable fall is called *strewn-field*.

5.5 Meteor Detection and Triangulation

Why is it of major scientific relevance to observe meteors? To answer this question let's start with an example. The smallest NEA ever observed by a ground-based telescope is 2015 TC25, estimated to be about 2 m in size. Its observation was only possible thanks to its very high albedo (~60%). In general, the asteroid population below 100 m in size is poorly known via telescopic observations; nevertheless, it is a source of potential Earth's impactors in the medium term. Therefore, the observation of meteors allows to probe, with significant statistics, the sub-metre population of bodies. Remember that even small objects can be dangerous, suffice to think, for instance, about human space operations and satellites.

Meteor detection can be performed by several methods: capturing radio waves reflected by the ionised meteor trail with a radio receiver, carefully looking for infrasound emissions and seismic waves generated by the passage of the meteoroid in the atmosphere or trying to collect meteor spectra. However, the most important and fruitful method is to observe the light emission in the visible domain with a video camera. Fireball networks around the world deploy a large variety of cameras for meteor detection, with very different characteristics such as type of detector, operational mode, spatial and temporal resolution, and so on. Regardless of the type of camera the principle of detection is the same. The device records the passage of a meteor on a (digital) support with some kind of time tag (e.g. a video at a given frame rate). An algorithm (e.g. a dedicated software program) computes the positions of the meteor, that change with time, onto the sensor, and then compares them with the position of known stars visible in the same field of view (this latter process is called astrometric calibration). In this way, it is possible to eventually derive the meteor position in horizontal coordinates (i.e. azimuth and elevation/zenith angle). Horizontal coordinates can be converted into celestial coordinates (i.e. right ascension and declination) considering the epoch (i.e. time and date) of observation. Similarly, it is possible to compute the meteor brightness evolution with time (i.e. the *light-curve*) by comparing the light emitted by the meteor with the one emitted by known stars.

To be able to derive the actual trajectory of the meteor, a single camera observation is not enough. Indeed, to be able to *triangulate* the observations, it is necessary to have good data from two or more cameras separated by several tens of kilometres.

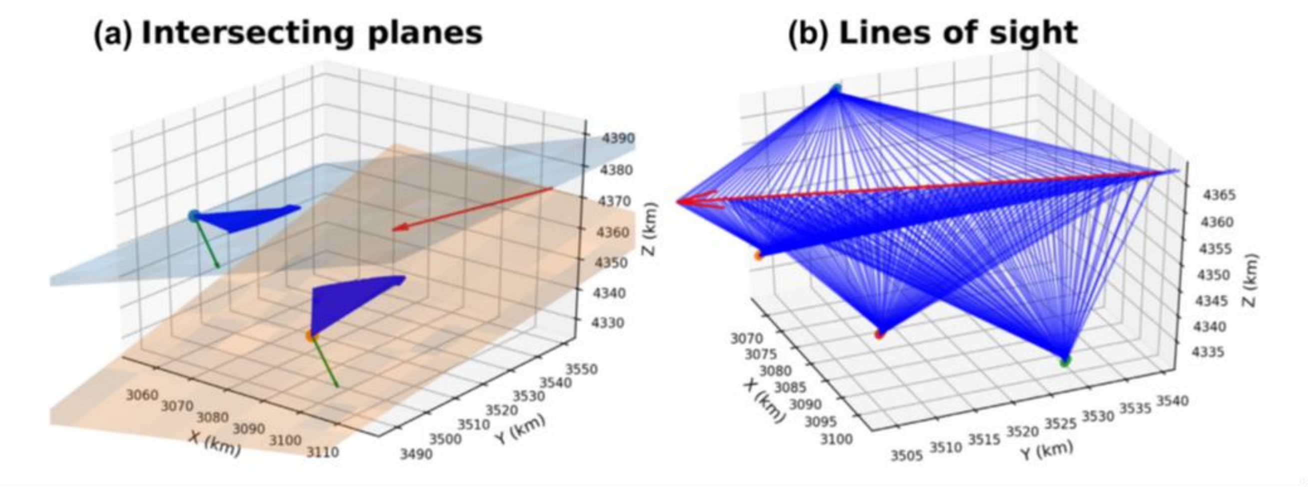


Figure 5.5.1. Comprehensive physics of a meteoroid entry into the Earth's atmosphere

The mathematical description of the triangulation process is not easy, but it can nevertheless be easily described if one thinks that each single observation of the meteor from one camera can be described by a straight line connecting the camera itself with the meteor position, called the *line-of-sight*. Therefore, the passage of the meteor generates a bundle of lines passing through the same point (i.e. the position of the camera) and the unknown meteor trajectory, thus defining a plane in 3D space (see Figure 5.4.2 (a)). The observations of a second camera, located far away from the first one, will define a plane as well, different from the first one. The trajectory of the meteor can therefore be obtained as a segment lying on the line corresponding to the geometrical intersection of these two planes.

A more precise computation can combine all the lines-of-sight generated by two or more cameras using a least square minimisation process. In this case, the trajectory is defined and computed as the straight line that minimises the distances to all the lines-of-sight.

A practical example of meteor detection, astrometric/photometric calibration, and triangulation with the StAnD Meteor Camera Kit is given in section 8.3.