Teacher's Manual

Chapter 4: Asteroids and Comets

Author: Maria Panagopoulou (EA)
Contributions by: Gustavo Rojas (NUCLIO)
Lothar Kurtze (FTP-Europlanet)

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StAnD
Students as Planetary Defenders

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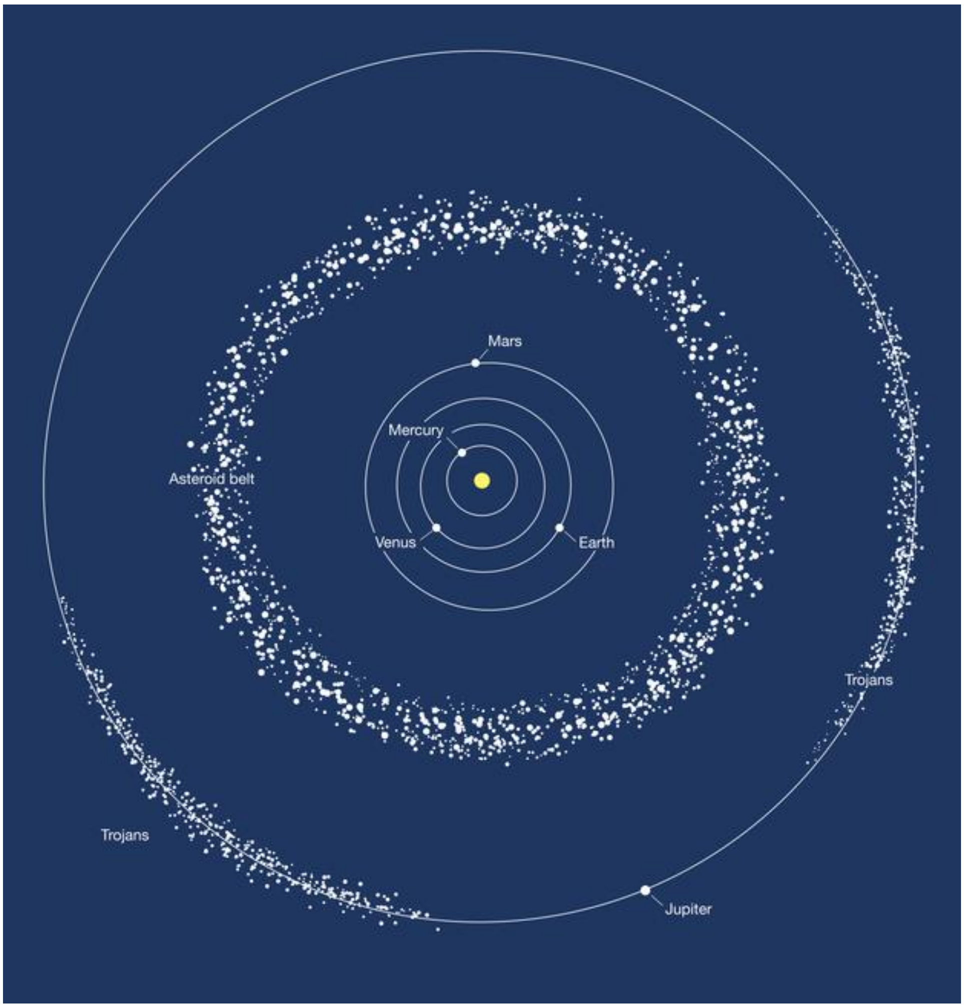
4.1.1 MAIN ASTEROID BELT

The main asteroid belt is a vast, ring-shaped region located between the orbits of Mars and Jupiter. It is home to the majority of asteroids in our solar system. While often depicted as a densely packed field of space rocks, the asteroid belt is actually quite sparsely populated. The average distance between asteroids is hundreds of thousands of kilometers.

Despite the vast area of the main asteroid belt, millions of asteroids inhabit this region. They vary significantly in size, from small rocks to objects several hundred kilometers across. The largest asteroid, Ceres, is so massive it has been reclassified as a dwarf planet.



Main asteroid belt and Trojan asteroids in the Solar System (© ESA-HUBBLE https://sci.esa.int/web/hubble/-/59582-asteroid-belt).

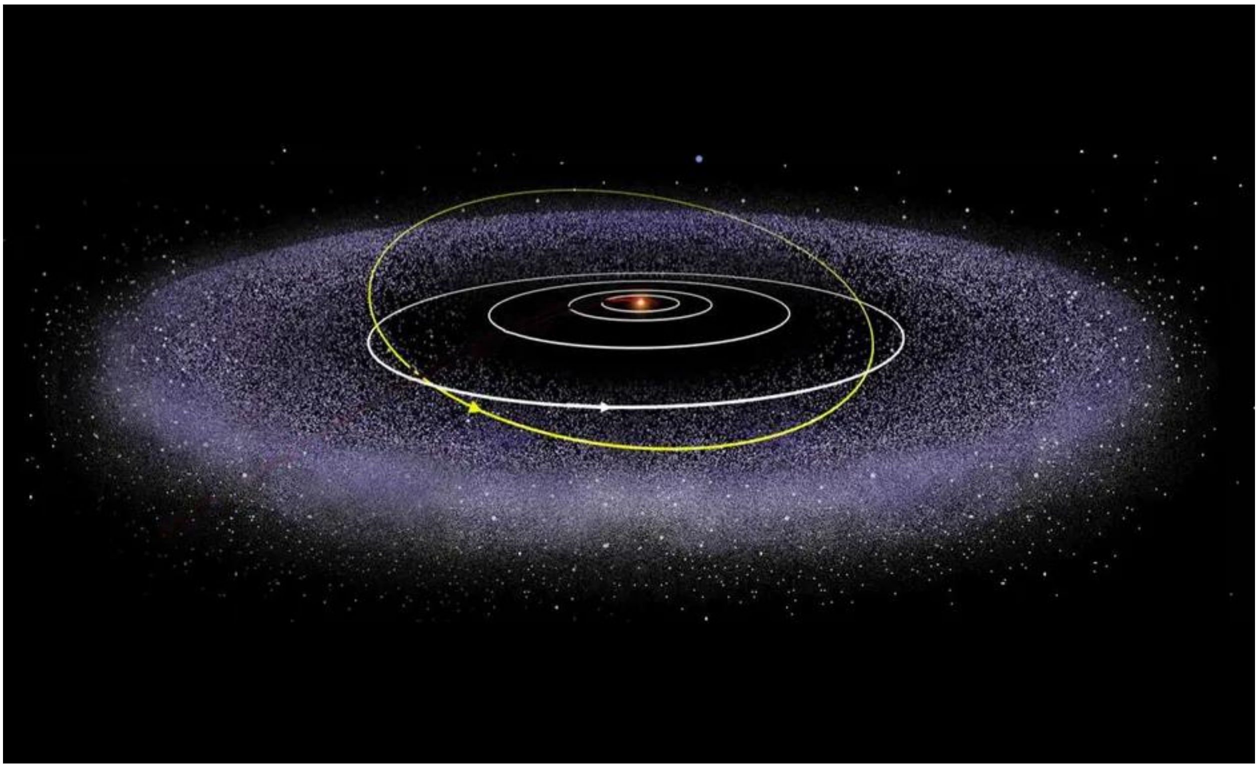
The asteroid belt is believed to be a remnant of the early solar system, where the formation of a planet was prevented by the gravitational influence of Jupiter. Instead of coalescing into a planet, the material in this region remained as countless smaller bodies.

Close to the main asteroid belt are the Trojan asteroids that share Jupiter's orbit around the Sun and they are distributed in two elongated, curved regions. They can be distinguished, based on these two regions, to the leading Trojans (they orbit ahead of Jupiter) and to the trailing Trojans (they orbit behind Jupiter).

4.1.2 KUIPER BELT

The Kuiper Belt is a vast region of icy bodies located beyond the orbit of Neptune. It is often referred to as the "third zone" of the solar system, after the inner terrestrial planets and the outer gas giants. The Kuiper Belt is home to a vast number of icy objects, including dwarf planets like Pluto. The Kuiper Belt objects (KBOs) are also called trans-Neptunian objects (TNOs).

Like the asteroid belt, the Kuiper Belt is a region of leftovers from the creation of the solar system but it's more of a thick disk (like a donut) than a thin belt. The Kuiper Belt is one of the main sources of comets.



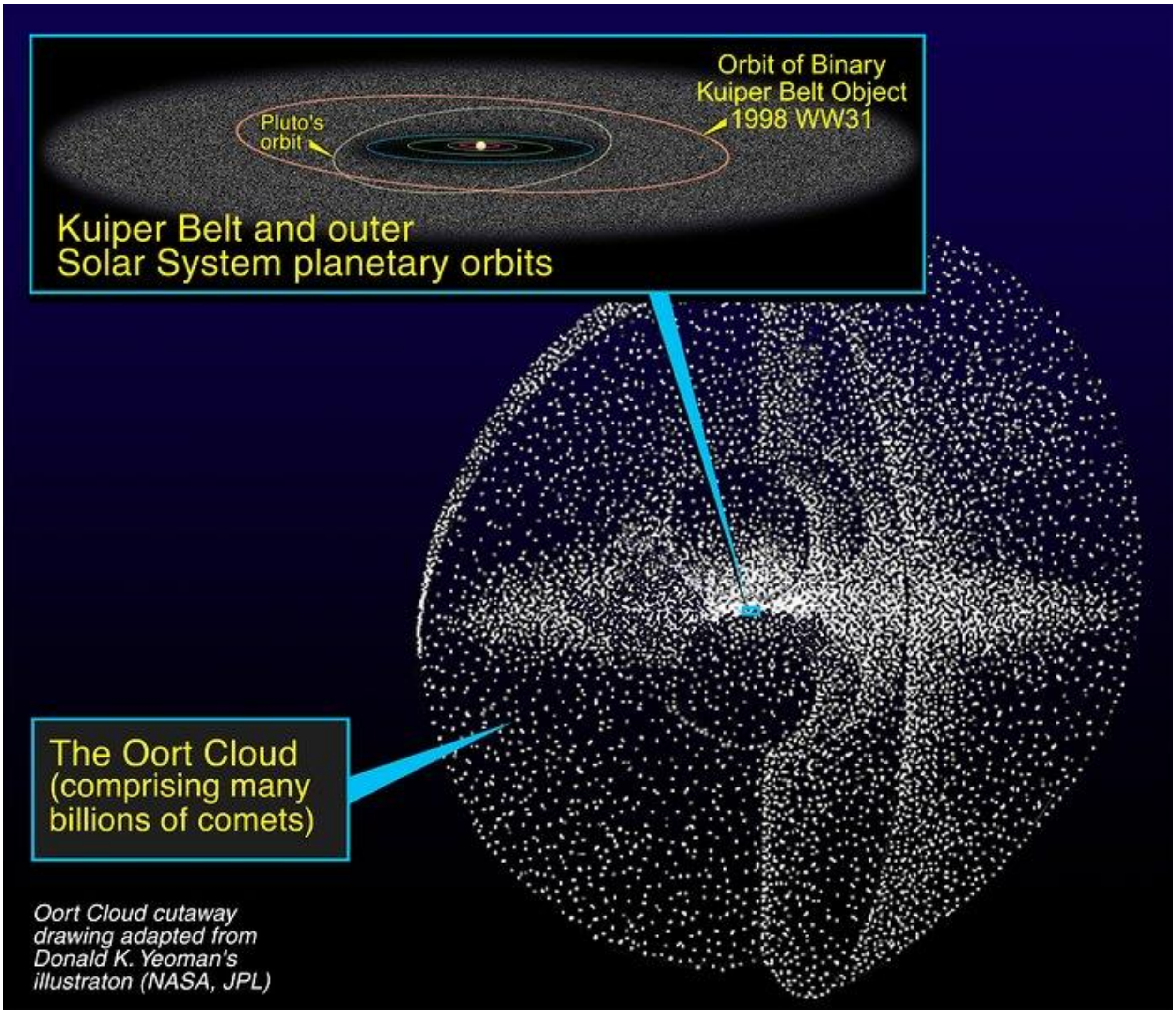
Artistic representation of the Kuiper Belt (https://www.skyatnightmagazine.com/space-science/what-is-kuiper-belt-outer-solar-system).

4.1.3 OORT CLOUD

The Oort Cloud is a vast, spherical cloud of icy bodies located far beyond the Kuiper Belt. It is thought to extend from approximately 1,000 to 100,000 astronomical units (AU) from the Sun.

The Oort Cloud is believed to be the source of long-period comets, which have highly elliptical orbits that take thousands of years to complete. These comets are thought to be ejected from the Oort Cloud by gravitational perturbations from passing stars or other celestial bodies.

The Oort Cloud is a relatively unexplored region of the solar system, and its exact size and composition are still uncertain. However, it is believed to contain billions of icy bodies, many of which may be larger than Pluto. The Oort Cloud is a valuable source of information about the formation and evolution of the solar system.



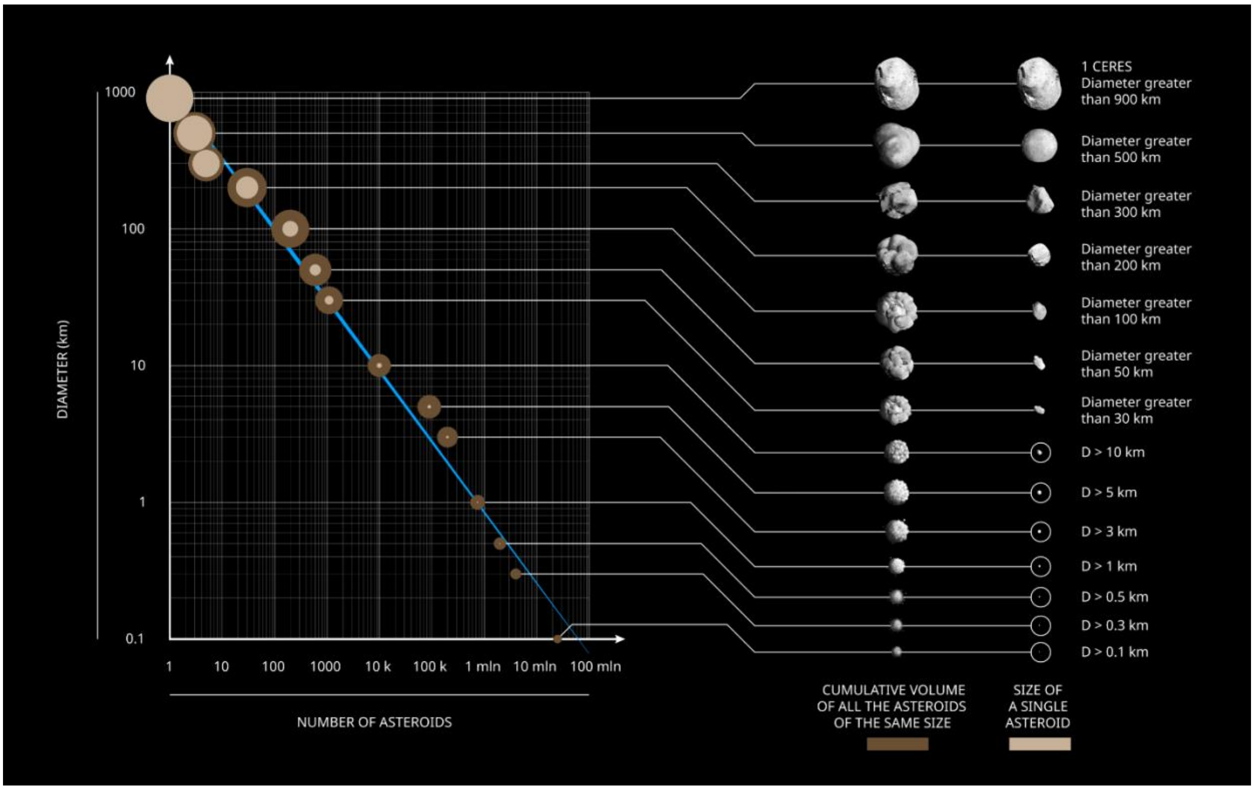
The Oort Cloud compared to the size of the Kuiper Belt (© NASA/ESA and A. Feild (Space Telescope Science Institute), https://esahubble.org/images/opo0204i/)

Sometimes objects that orbit the Sun, like asteroids and comets, come close to the Earth and could potentially pose a threat to our planet. These objects can come from any of the three areas that were already described and since they come close to the Earth's orbit they are also called **Near-Earth objects (NEOs)**.

4.2 Asteroids

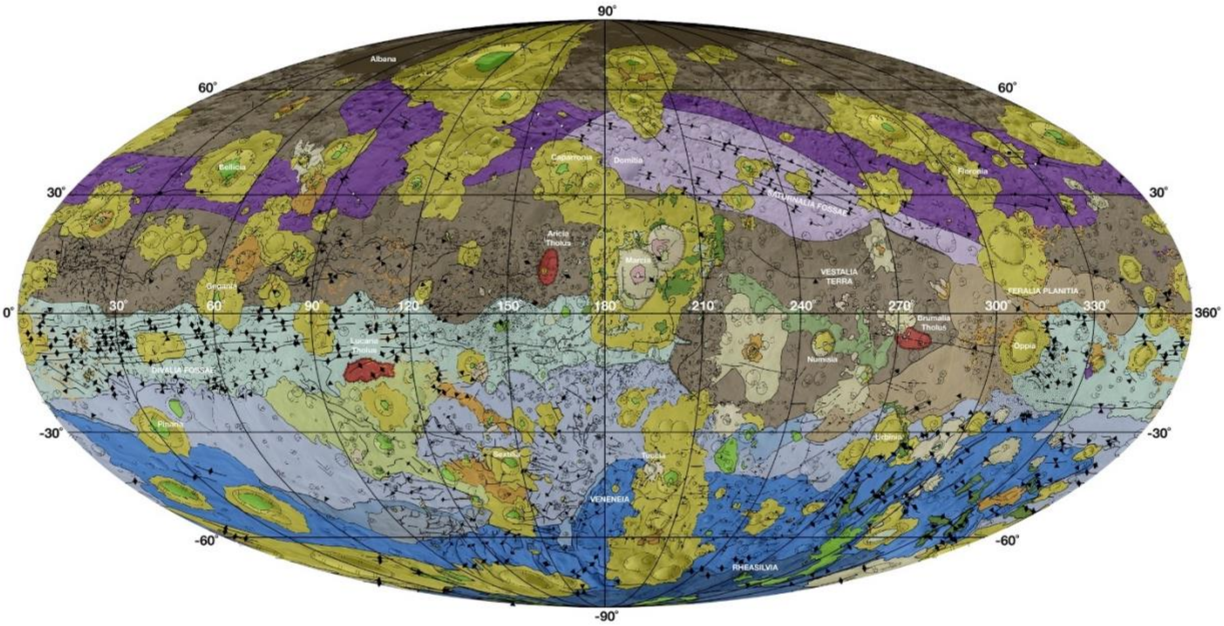
Asteroids are **rocky** remnants from the formation of our solar system that orbit the Sun. Sometimes they are called minor planets, and they can **range in size** from a few meters to hundreds of kilometers in diameter. The largest asteroid (Vesta) is about 530 kilometers in diameter while the smallest asteroids are less than 10 meters across. The total mass of all the asteroids, in our Solar System, combined is less than that of the Earth's Moon.

You can see the sizes of some known asteroids in scale in this video.



Number of asteroids by size (https://en.wikipedia.org/wiki/File:Asteroids_by_size_and_number.svg).

Asteroids are generally **irregular in shape**, often with a pitted or **cratered surface**. While some are more spherical, most are far from round. As they follow **elliptical paths** around the Sun, asteroids also **spin** on their axis, sometimes with a chaotic tumbling motion. Interestingly, over 150 asteroids have been found to have at least one smaller **moon**, and a few even possess two. Beyond this, there are also binary asteroids, where two similarly sized rocks orbit each other, and even triple asteroid systems.



Geological map of asteroid Vesta reveals history of large impacts (© NASA/JPL-Caltech/Arizona State University https://meteorites.asu.edu/news/vesta_map).

Asteroids are often grouped, based on their orbital characteristics, in groups and families. Usually, a group of asteroids is named after the first member of that group that was discovered. Compared to asteroid families, asteroids within a group are more loosely connected. Asteroid families are believed to be the result of one larger, parent asteroid breaking up to smaller piece at some point of the solar system's history.

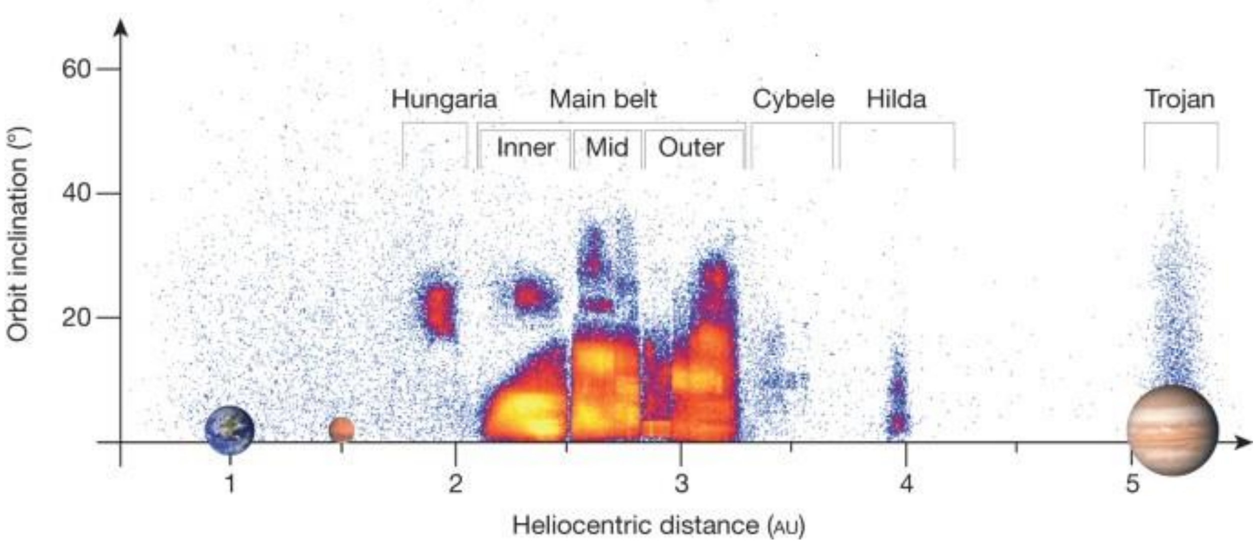
See a video about asteroid families [here](#).

Asteroids are classified into three main types based on their composition: C, S, and M. Most asteroids are C-type (chondrite), dark-colored objects likely made of clay and silicate rocks. They are among the oldest objects in our solar system. S-type ("stony") asteroids contain silicate materials and nickel-iron. M-type asteroids are primarily metallic. These compositional differences are linked to the distance of the asteroids from the Sun when they were formed.

Jupiter's enormous gravitational pull can significantly alter the orbits of asteroids, sometimes even ejecting them from the main belt. Close encounters with Mars or other celestial bodies can also disrupt asteroid trajectories, sending them careening through the solar system. These asteroids and their fragments have collided with Earth and other planets throughout history, leaving their mark on the geological landscape and potentially influencing the evolution of life.

In some cases, moons have been observed orbiting asteroids. They are relatively uncommon, since only about 2% of asteroids are believed to have moons. For an object to be considered an asteroid moon, it must be smaller than the asteroid it orbits. An example of a well-known asteroid moon is Dimorphos, that served as the target for the Double Asteroid Redirection Test (DART) mission, a significant innitiative in planetary defense.

See the ground of Dimorphos from [this video](#) showing the DART spacecraft hitting its surface.



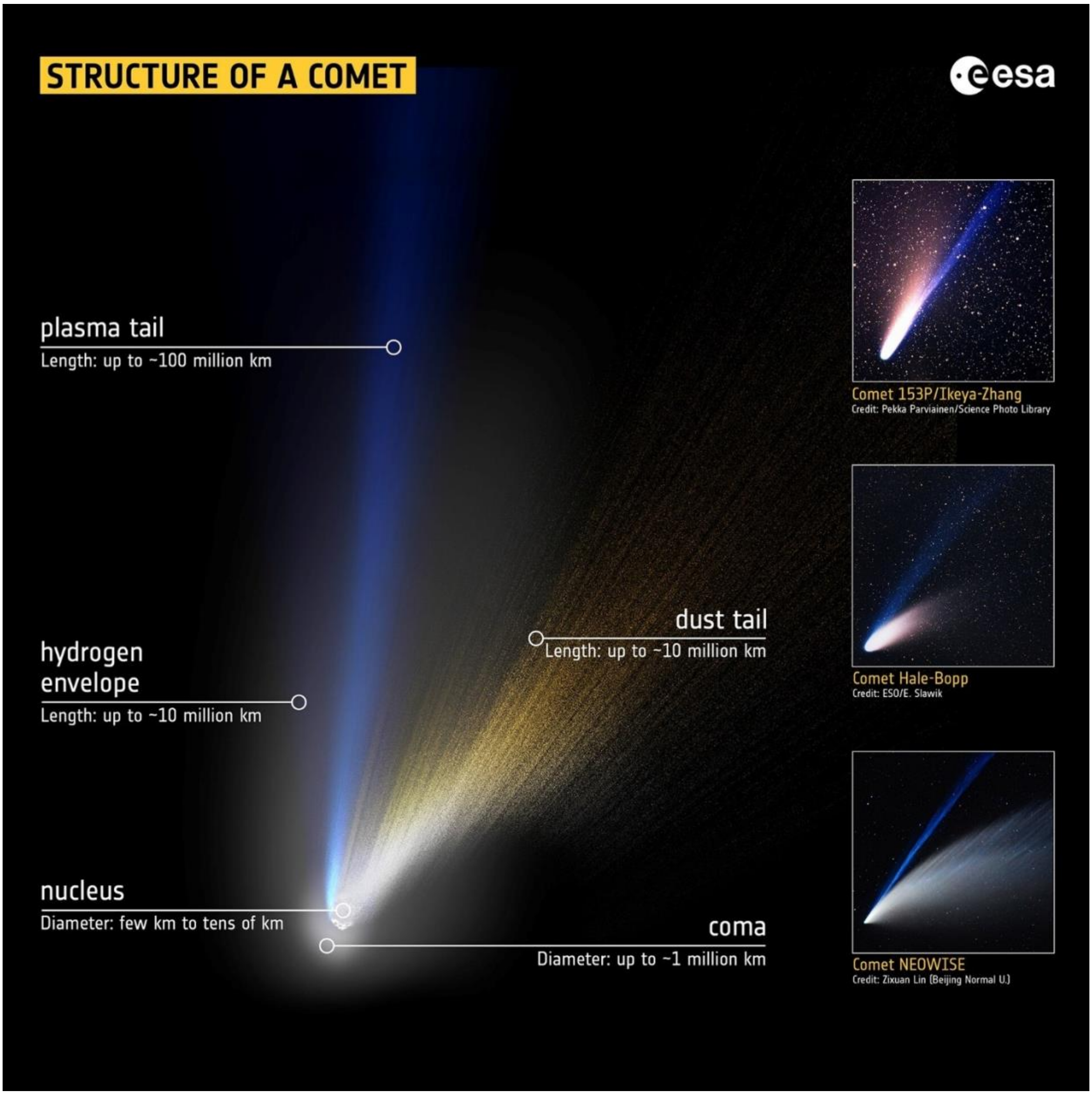
Mapping the asteroids of our solar system (DeMeo, F., Carry, B. Solar System evolution from compositional mapping of the asteroid belt. Nature 505, 629–634 (2014). https://doi.org/10.1038/nature12908).

4.3 Comets

In ancient times, comets were both inspiring and frightening, as they appeared to the sky unpredictably and looked like long-haired stars. Today, we understand that these celestial objects are remnants from the solar system's birth, roughly 4.6 billion years ago. They are composed mostly of ice covered in dark organic material. Due to that they are often called "dirty snowballs." Comets hold the potential to reveal secrets about our solar system's formation. They might have delivered water and organic compounds to our planet and other parts of our cosmic neighborhood.

Comets are celestial bodies composed of **ice, dust, and rocks**. They originate in the outer reaches of the solar system, in the Kuiper Belt or the Oort Cloud. As a comet approaches the Sun, its icy core begins to vaporize, releasing a cloud of gas and dust known as a **coma**. The pressure of the solar wind creates the known long **tail**, giving comets their characteristic appearance. Comets are categorized in **short-period comets** (with a period that is less than 200 years and usually originate from the Kuiper Belt) and in **long-period comets** (that have a orbit that lasts more than 200 years and are usually from the Oort Cloud).

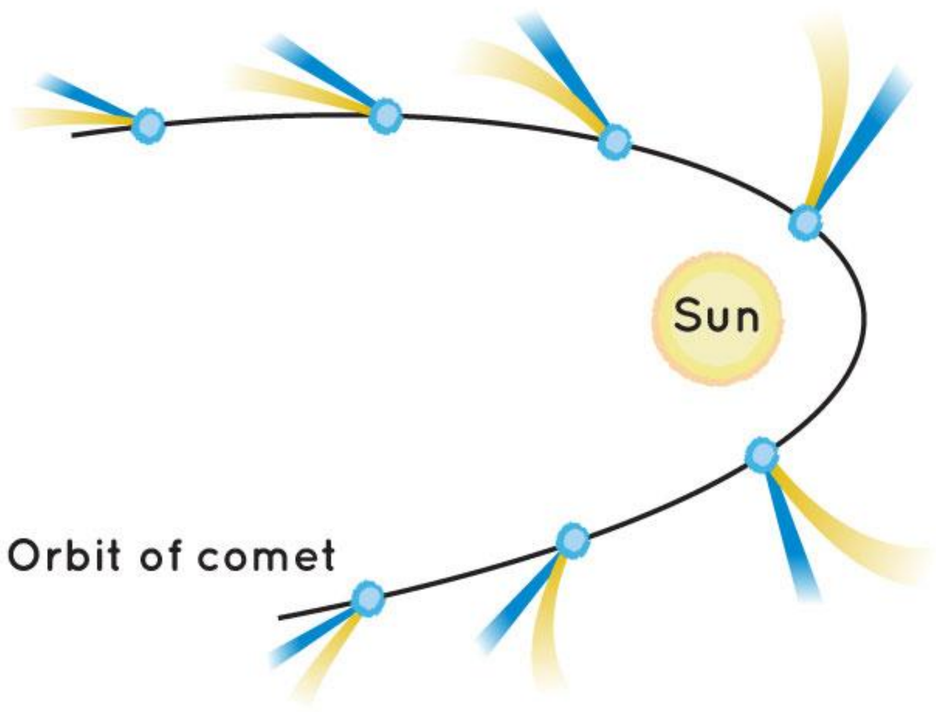
See a video about short-period and long-period comets here.



Structure elements of comets with examples from images of well-known comets (© ESA https://www.esa.int/ESA_Multimedia/Images/2023/11/Structure_of_a_comet).

There are typically two distinct tails associated with comets: the dust tail and the ion tail. The ion tail is composed of ionized gas, which is created when the comet’s gas is exposed to the solar wind. The ion tail of a comet is straight because it is primarily influenced by the magnetic field of the Sun. When the gas of a comet's coma is ionized by the solar wind, it becomes highly charged. These charged particles are then strongly influenced by the magnetic field of the Sun, which is a complex system of magnetic field lines that extend outward from the Sun. The charged particles in the comet's ion tail align themselves with the magnetic field lines, causing the tail to point directly away from the Sun. This is why the ion tail appears straight, even when the comet's orbit is not perfectly aligned with the Sun.

In contrast, the dust tail of a comet, that is composed of dust particles that are pushed away from the comet by the solar wind, is curved because it is primarily influenced by the comet's orbital motion and the solar wind. The dust particles in the tail are not as strongly influenced by the Sun's magnetic field. This tail reflects the sunlight, appearing golden or white.



The two tails of a comet. A comet has two tails that get longer the closer it gets to the Sun. Both tails are always directed away from the Sun. The ion tail (blue) always points directly away from the Sun, while the dust tail (yellow) points away from the Sun in a slightly different direction than the ion tail. (© NASA/JPL-Caltech https://spaceplace.nasa.gov/comets/en/)

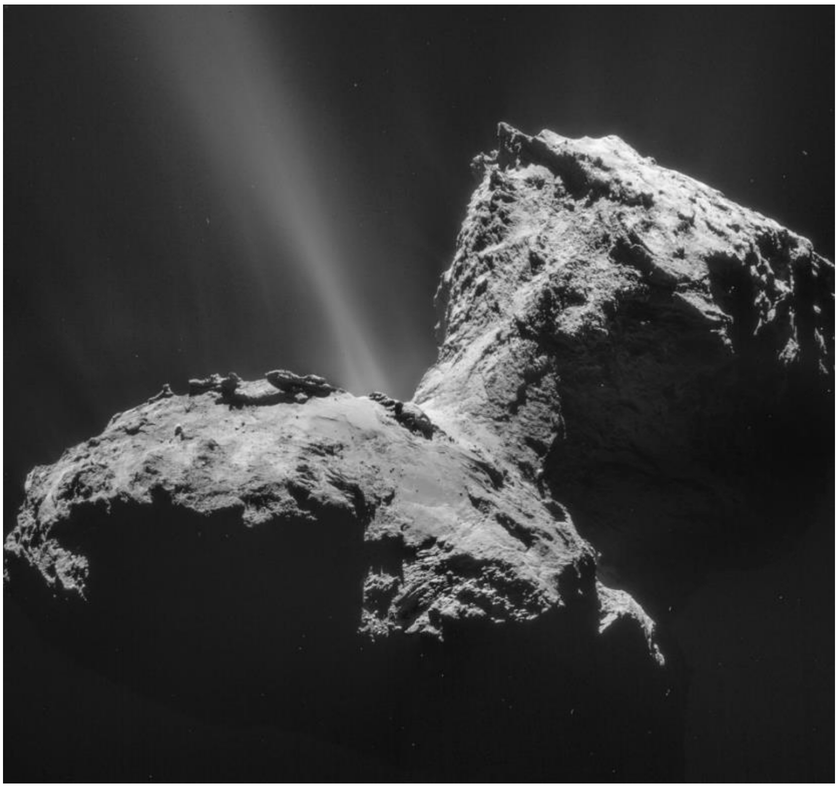
The color of a comet's tail can vary depending on its composition and the wavelength of light it reflects. The dust tail is typically golden or white due to the reflection of sunlight by dust particles. The specific color can vary depending on the composition of the dust. The ion tail is primarily blue due to the emission of ionized gases, such as carbon monoxide and nitrogen. Other gases present in the comet's coma, such as carbon dioxide and water vapor, can also contribute to the overall color of the comet. The way sunlight is scattered by the comet's particles can also affect its color.

In some cases, comets may exhibit multiple colors due to the presence of different gases and dust particles. For example, a comet with a significant amount of water vapor may appear green, while a comet with a high concentration of carbon monoxide may appear blue. Overall, the color of a comet's tail is a complex interplay of factors, and it can change as the comet's composition and distance from the Sun vary. In the following images you can see three comets and notice the differences in their tails and colors.

Comet C/1995 O1 (Hale-Bopp) (Credit: Kosmas Gazeas http://users.uoa.gr/~kgaze/menu_photography_gr.html)

Comet C/1996 B2 (Hyakutake) (Credit:Jerry Lodriguss https://www.astropix.com/html/comets/comet_hyakutake_04.html)

Comet C/2012 S1 (ISON) (Credit: Kosmas Gazeas, University of Athens Observatory http://observatory.phys.uoa.gr/images/solar_system/UOAO_photography_Comet_ISON_131118.jpg)



Comet 67P (Churyumov-Gerasimenko) (Credit: ESA/Rosetta/NAVCAM https://science.nasa.gov/solar-system/comets/67p-churyumov-gerasimenko/)

4.4 Asteroids VS Comets - Their discovery and some historical observations from earth

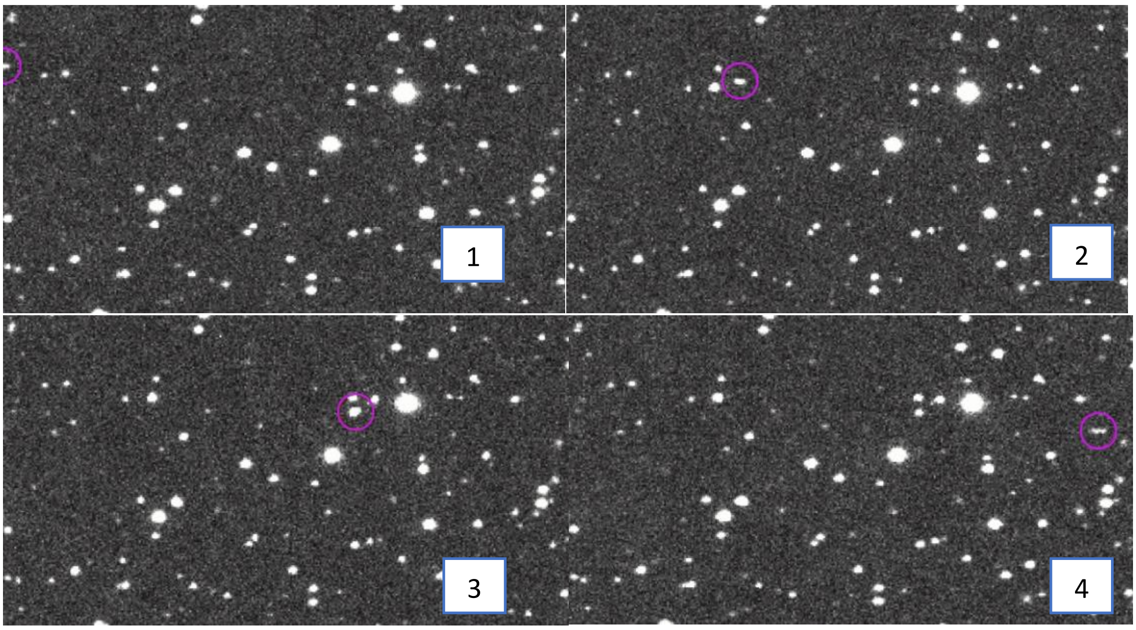
Similarities and differences between comets and asteroids. (© NASA file:///C:/Users/mariapanago/Downloads/comets-vs-asteroids%20(1).pdf) (Comet image: APOD-Blake Estes https://apod.nasa.gov/apod/ap220112.html , Asteroid image: NASA/Goddard/University of Arizona https://science.nasa.gov/resource/bennu-mosaic/)

4.4.1 DISCOVERY OF ASTEROIDS

In the 18th century, astronomers were intrigued by Bode's law, a mathematical formula that seemed to predict the locations of known planets. However, there was a discrepancy as Bode's law suggested a planet should exist between Mars and Jupiter. The discovery of Uranus in 1781, at a distance predicted by Bode's law, fueled excitement about the formula's accuracy.

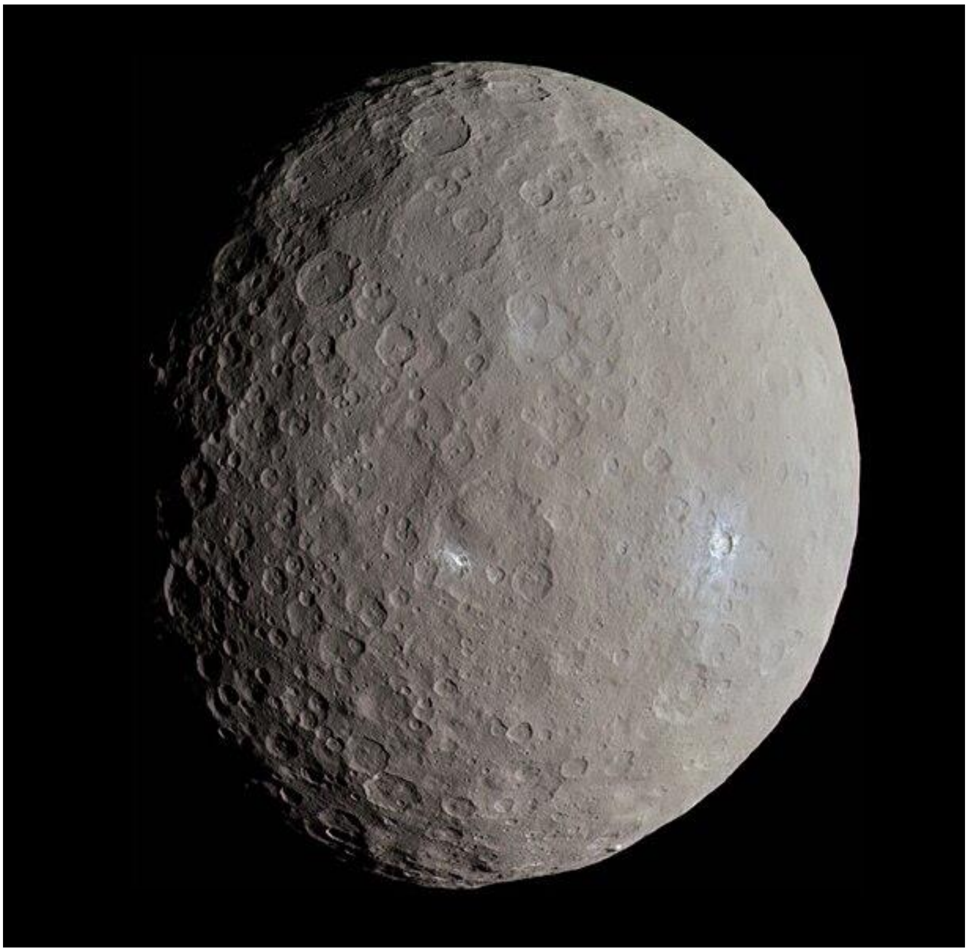
A group of astronomers, known as the "Celestial Police," formed to search for the missing planet using the Lilienthal Observatory in Germany, owned by Johann Hieronymous Schröter. Giuseppe Piazzi discovered Ceres in 1801 from the Palermo Obseratory, beating the “Celestial Police” in this race. Initially, Giuseppe Piazzi believed the small object he observed was a faint star not listed on his star chart. However, upon revisiting it the next day, he realized its movement indicated it was not a star. Due to illness and unfavorable weather, Piazzi couldn't continue his observations for a few nights. By January 24, 1801, through careful tracking of its movement against the star background and calculating its distance, he confirmed that the object belonged to our solar system.

Asteroids were (and are) discovered in the same planets were discovered. The astronomer(s) discover an object that overtime has a different position compared to the starry background. Then, through precise measurements they are able to determine the object’s orbit/distance and identify it as 'planet-like' body. The difference is that asteroids are much smaller than planets.



Asteroid 2014 AA, discovered by NASA-sponsored Catalina Sky Survey on Jan. 1 2014 as it moved across the sky (© CSS/LPL/UA https://www.jpl.nasa.gov/news/first-2014-asteroid-discovered-update)

Though initially thought to be a planet, Ceres was later classified as a minor planet due to its small size. Over the next few years, astronomers identified three more minor planets in the same region: Pallas, Juno, and Vesta. The realization of a "belt" of asteroids between Mars and Jupiter emerged, dispelling the notion of a single large planet. Since then, asteroid discoveries have been ongoing, with new ones found almost annually. Telescopes and campaigns specifically designed to identify near-Earth asteroids, which could potentially pose a threat to Earth, have become crucial tools in astronomical research.



Dwarf planet Ceres (© NASA / JPL-Caltech / UCLA / MPS / DLR / IDA / Justin Cowart)

4.4.2 DISCOVERY OF COMETS

Humans have observed comets for millennia but in the ancient time they were not studied as astronomical phenomena but treated with fear. Ancient civilizations often saw them as harbingers of misfortune, as exemplified by Halley's Comet's appearance in 1066, believed to foreshadow the Norman conquest of England. As astronomy progressed, understanding comets became a scientific pursuit. While ancient and medieval Chinese records provide the most detailed and consistent comet observations spanning over three millennia, other civilizations likely also documented them. These historical records continue to be valuable for modern scientific research, aiding in the calculation of comet orbits.

Part of astrology manuscript, 2nd century BC, Han dynasty. The page gives descriptions and illustrations of seven comets, from a total of 29 found in the document. (© China Arts, Volume 1st, Wen Wu Publishing, Beijing, China, 1979-10 https://commons.wikimedia.org/wiki/File:Mawangdui_Astrology_Comets_Ms.JPG)

In ancient times, philosophers held varying beliefs about comets. Aristotle thought they were terrestrial exhalations, while Seneca believed they were celestial bodies like planets. Aristotle's view prevailed until the 16th century, when Tycho Brahe attempted to measure a comet's distance using parallax. Unable to detect parallax, he concluded comets were far beyond the Moon.

Brahe's student, Johannes Kepler, developed his laws of planetary motion using Brahe's Mars observations but struggled to apply them to comets' eccentric orbits. Kepler believed comets followed straight paths but Isaac Newton, using his law of gravity, calculated a parabolic orbit for a 1680 comet. A parabolic orbit is open, with an eccentricity of exactly 1, meaning the comet would never return. Any less-eccentric orbits are closed ellipses, which means a comet would return.

Edmond Halley, used Newton’s methods and analyzed 24 comets, identifying their orbits and predicting a comet's return in 1758. This was the first recognized periodic comet that was named Halley's Comet and is until today the most famous comet in history. Later, Johann Encke, another astronomer, identified another periodic comet with a 3.3-year orbit. However, Encke noticed a peculiar problem: the comet was arriving earlier than predicted. This discrepancy was also observed in other comets. Various theories were proposed to explain the observed changes in comet orbits. One idea suggested that an interplanetary medium was slowing down comets, causing their orbits to shrink. However, this couldn't account for comets with expanding orbits. German mathematician Friedrich Bessel suggested that comets might be losing mass near the Sun, similar to a rocket expelling fuel. This would slightly alter their orbit with each pass, either shortening or lengthening it. Later on observations confirmed Bessel's theory.

A panel from the Bayeux tapestry showing people looking at what would later be known as Halley's comet. (By Myrabella - Own work, Public Domain https://science.nasa.gov/solar-system/comets/1p-halley/)

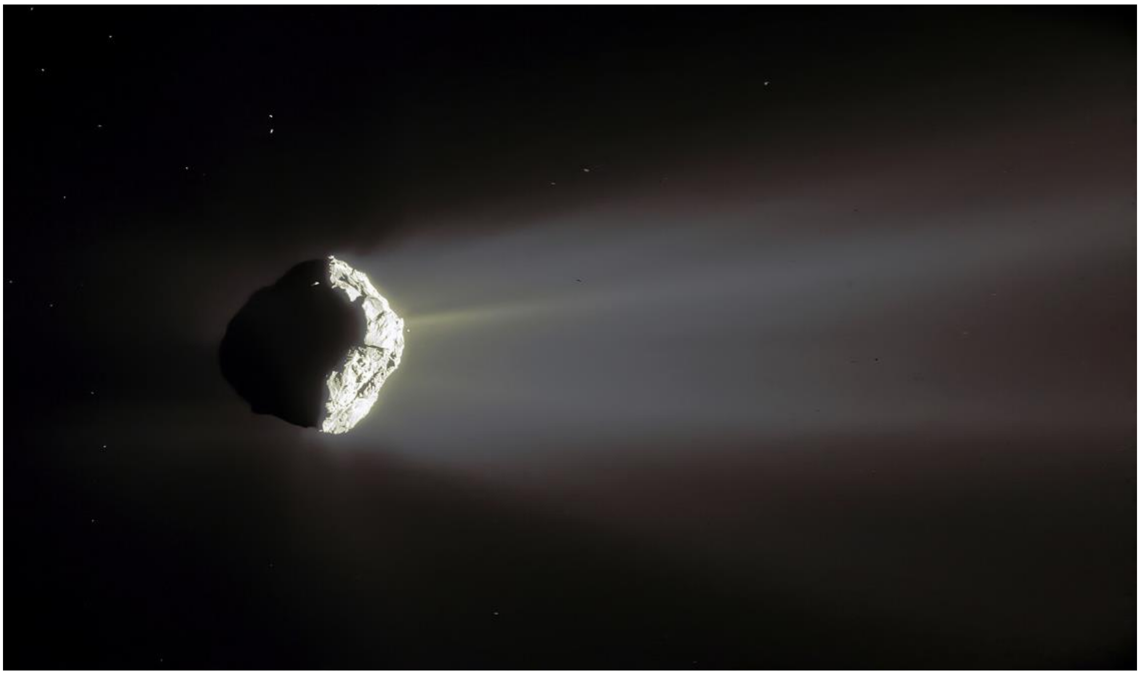
Photograph of Halley's comet nucleus from the European spacecraft Giotto in 1986 (© ESA https://science.nasa.gov/solar-system/comets/1p-halley/)

Advances in technology, such as larger telescopes and spectroscopy, significantly improved comet research. In the 19th century, the first photographs of comets were taken, and spectral analysis revealed the composition of their tails.

4.5 Results from recent space missions

4.5.1 Rosetta

The Rosetta mission was designed by the European Space Agency to study a comet in detail. Lauched in 2004, the spacecraft spent 10 years traveling to its target, comet 67P/Churyumov–Gerasimenko, and then following it as it approached and moved away from the sun. One of the key objectives of the mission was the deployment of the Philae lander to the surface of the comet, which was the first controlled touchdown on a comet nucleus. The data collected from Rosetta revealed that comets are different than previously thought.



Comet 67P with a tail of gas and dust, seen from Rosetta from a distance of 160 km. (© ESA)

Rosetta first mapped the comet to identify an ideal landing site for Philae. Philae detached from Rosetta and approached the comet, initially landing on the surface. However, the lander bounced twice before finally coming to rest. Despite the unexpected landing, Philae was able to send back the first images from a comet's surface and make the first *in situ* analysis of its composition. Unfortunately, Philae settled in the shadow of a cliff, preventing it from adequately collecting solar power, and it lost contact with Rosetta after three days. Contact was briefly reestablished several months later, but ultimately the transmitter was switched off. The precise location of the lander was later discovered when Rosetta took high-resolution pictures of the comet's surface, which allowed scientists to contextualize Philae's findings.

Rosetta's findings include the discovery of organic molecules and a type of amino acid called glycine, which are important for the building blocks of life. Rosetta also discovered that comets have seasons that greatly influence their activity. The mission observed several outbursts on the comet, which are difficult to plan for and observe. Rosetta's analysis of the comet's nucleus revealed that it is about 10 billion tons, and the mission measured that about 0.1 percent of its mass was lost during its approach to the sun.

The Rosetta mission has provided a wealth of information, and scientists are still working on analyzing the data. The information from Rosetta and Philae have provided scientists with information about what the solar system was like during its formation. The composition of the dust particles collected by Rosetta, which included organic material, sodium, magnesium, aluminum, silicon, calcium, and iron, remained consistent throughout the mission, suggesting that the entire nucleus has a consistent composition.

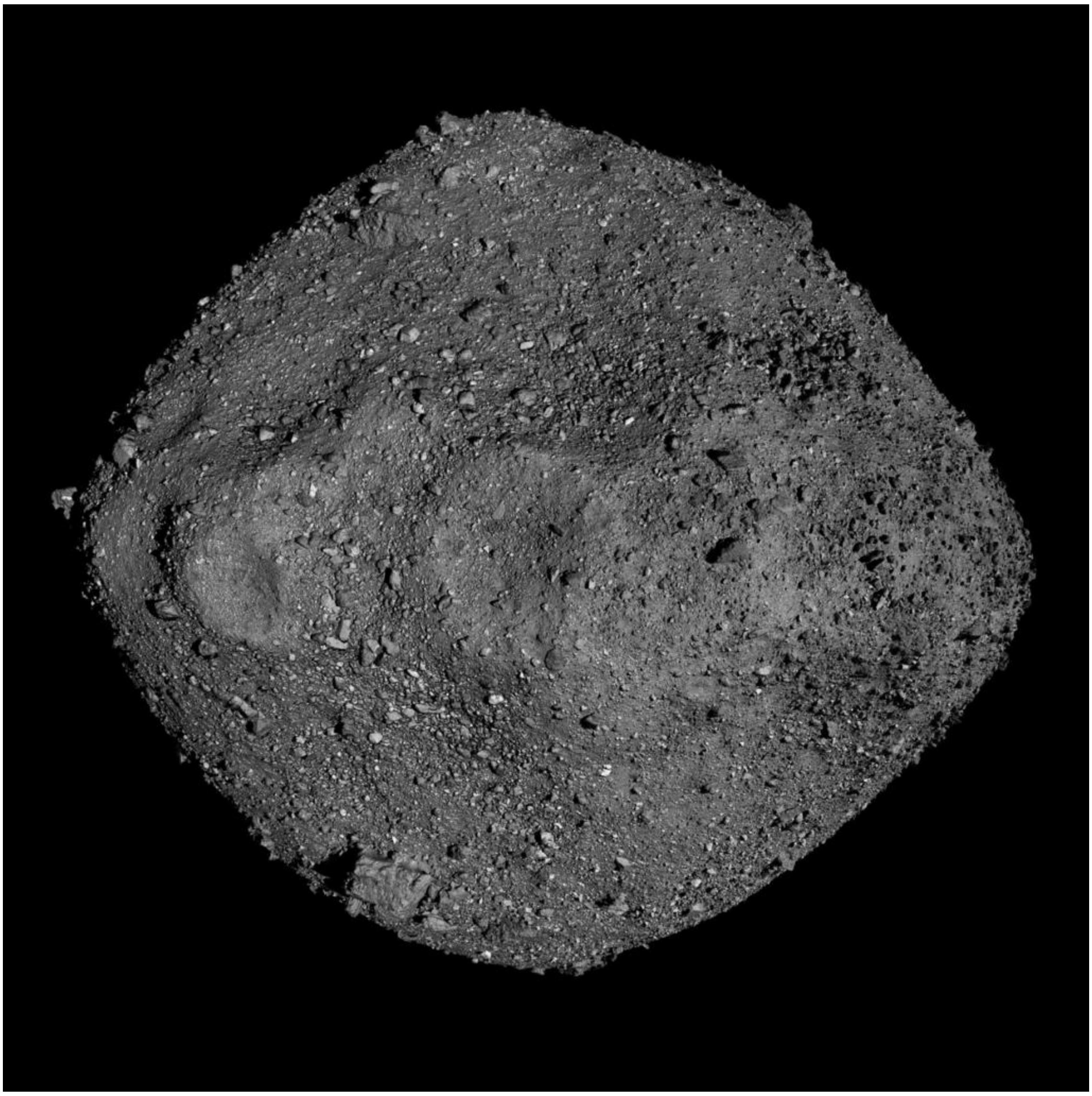
4.5.2 OSIRIS-REx

The OSIRIS-REx mission was designed to rendezvous with the near-Earth asteroid Bennu, survey it, and collect a sample to bring back to Earth. Launched in 2016, the spacecraft traveled for two years to reach Bennu. The spacecraft's journey included a flyby of Earth in September 2017 for a gravity assist, which helped to adjust its trajectory to match Bennu's orbit.

Upon arrival at Bennu in December 2018, OSIRIS-REx began an extensive survey of the asteroid, mapping it in great detail and analyzing its composition. OSIRIS-REx was able to explore the asteroid's environment with great precision due to its microgravity, which allowed it to perform ultra-precise maneuvers. Bennu is a relatively small asteroid, about half a kilometer across. The detailed mapping and analysis of Bennu helped the mission team select a suitable site for sample collection.

The mission selected a sampling site called Nightingale, which was determined to be darker, redder and fresher, and thus more scientifically valuable. The spacecraft’s Touch-And-Go Sample Acquisition Mechanism (TAGSAM) was used to collect the sample. The spacecraft touched down within 92 cm of the target location. During the brief contact with the surface, the TAGSAM deployed a burst of nitrogen gas to stir up the regolith, which was then captured by the sample collection head.

After the sample was collected, the spacecraft stowed the sample head into the return capsule and began its journey back to Earth. The sample return capsule was released by the OSIRIS-REx spacecraft and landed in the Utah desert on September 24, 2023. The sample, weighting 121 grams, was transported for processing. This pristine material will be studied for decades to come, and the first results from the analysis of the samples have shown rocks unlike any meteorite ever found, and organic molecules. The mission is NASA's first sample return from an asteroid.

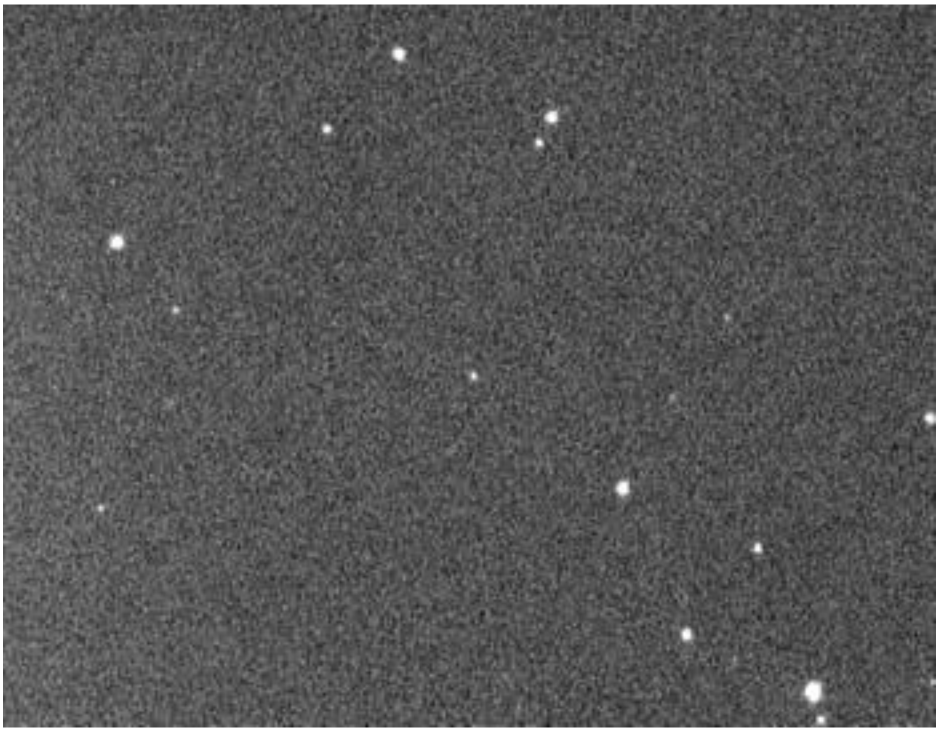


4.6 Observing asteroids and comets with Robotic Telescopes

4.6.1 How to observe an Asteroid?

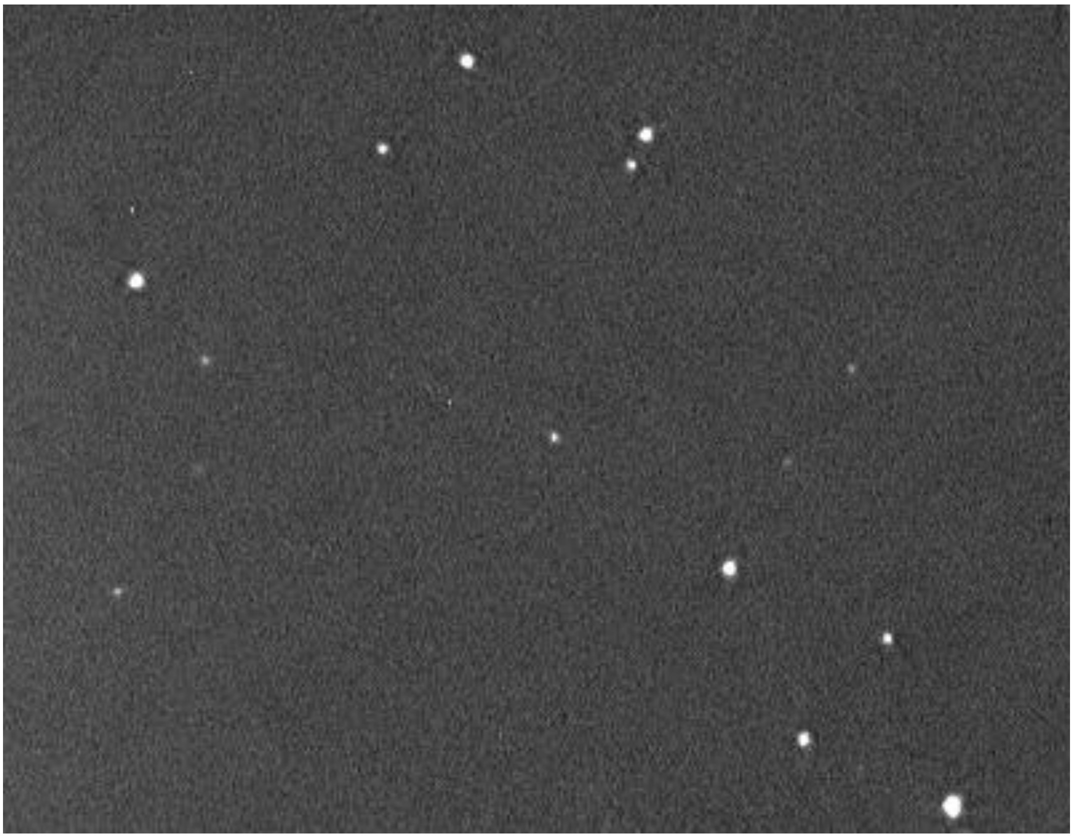
Like Planets, Asteroids reflect sunlight. This means that with a suitable telescope we can see asteroids from the Earth.

When we take a single picture of an asteroid from the Earth with a telescope, we typically get images that look like this one [1]:



One of the white dots in this image is an asteroid, while the others are stars. This distinction is crucial because although the asteroid appears like a star, it is only a few million kilometres from Earth, whereas stars are many times farther away, beyond our Solar System. The difference in these distances is almost unimaginable, and yet they appear very similar in this image. **How can we identify the asteroid in the image?**

As the asteroid is within our Solar System, it moves against the background stars. If you make multiple images, one after the other, the asteroid appears to move constantly against the starry background. This is particularly useful because asteroids, and in particular Near-Earth Objects (NEOs) can change position noticeably in just a few minutes, as shown animation below [1]:

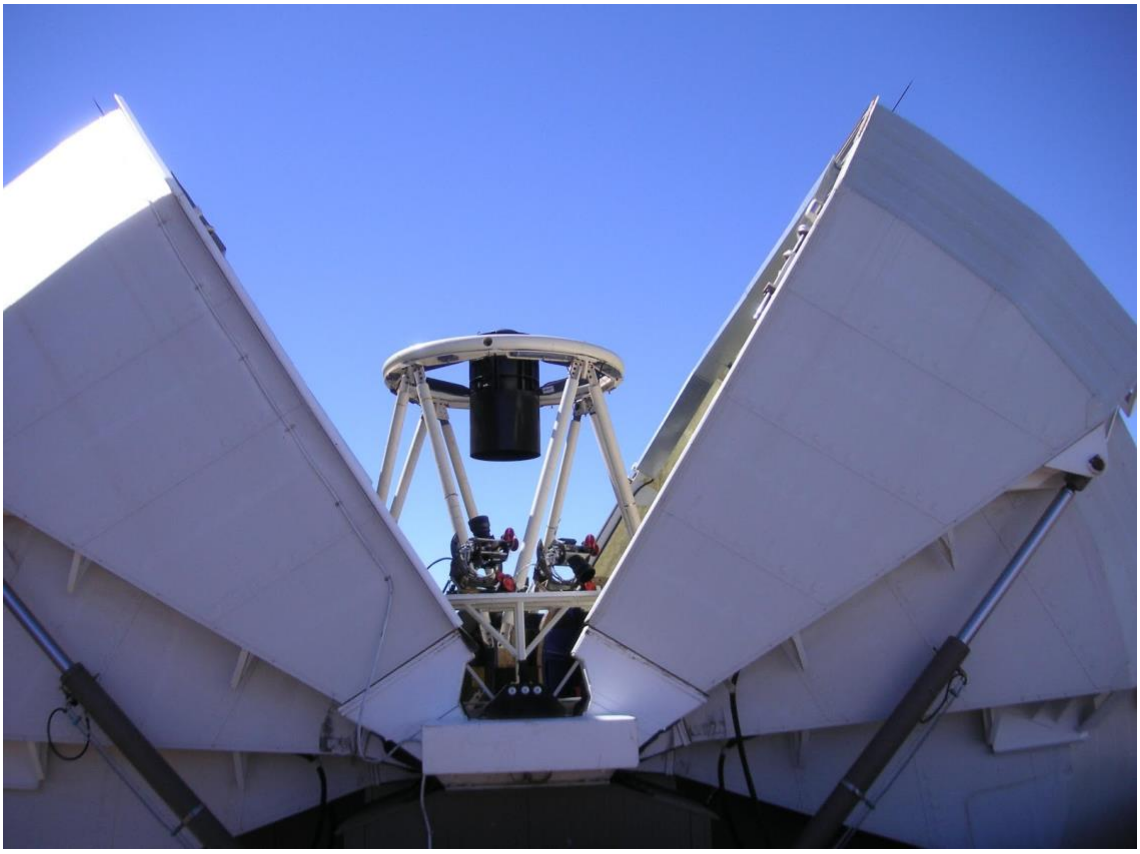


This animation shows three images taken consecutively on the same day, with only a few minutes time difference. “Playing” these images back in sequence, one after the other, we can easily compare the position of the asteroid in each frame. Astronomers call this “blinking”. If you look very carefully at the animation, you will see one of the white dots moving. In this case, it is the asteroid (1078) Mentha. [1]

Although this is an easy example with a bright, arger asteroid, sometimes spotting the asteroids can be quite difficult. This is why, within the project StAnD, we have access to large robotic telescopes with up to 2m diameter.

4.6.2 What are robotic telescopes?

A robotic telescope is an astronomical telescope and detector system that makes observations without the human intervention. In astronomical disciplines, a telescope qualifies as robotic if it makes those observations without being operated by a human, even if a human has to initiate the observations at the beginning of the night or to download the data afterwards. It may have software agents that assist in various ways such as automatic scheduling. [2]
Among the largest robotic telescopes in the world are the Faulkes Telescope North in Maui, Hawaii (see image below) and the Faulkes Telescope South in Siding Spring, Australia.



The Faulkes Telescope Project is supported by the Dill Faulkes Educational Trust in the UK and the FTP-Europlanet gUG in Germany. It provides access to 1,500 hours of observing time on the telescope which are available for school projects. This time is dedicated to education and public outreach, mainly in the UK, but also for projects in Europe and the US. [3]

To use the telescopes, you need to register for an account as it is described in the toolkit (XXX). How to program the interface is described in detail in the toolkit as well.

4.6.3 How to measure the position of an Asteroid?

Astrometry is a branch of astronomy that involves precise measurements of the positions and movements of stars and other celestial bodies. It provides the kinematics and physical origin of the Solar System and this galaxy, the Milky Way.
Astronomers use astrometric techniques to track near-Earth objects. By measuring the images with the asteroids as shown above, their movements relative to the background stars, which remain fixed, can be detected with an accuracy of 0,5 arc seconds. This is equivalent to the size of your thumb in 4 km distance! Once a movement per time unit is observed, astronomers compensate for the parallax caused by Earth's motion during this time and the heliocentric distance to this object is calculated. Using this distance and other photographs, more information about the object, including its orbital elements, can be obtained. Asteroid impact avoidance is among the purposes. [4]

To understand how the astrometry is done with the images from the Faulkes Telescopes Project, using the Software “Astrometrica”, please have a look at the Toolkit “Measuring Asteroids with Astrometrica”, where the procedure is described in detail.