# LITERATURE REVIEW

## Minor planets

Asteroids found in our solar system are crucial celestial bodies due to their value and importance in astronomy and the public. Their main importance comes from clues of the origin of our solar system and the formation of rocky planets. Some of them have a material originating from the birth of our solar system. While the study of asteroids has revealed major clues about our solar system, concerns arise when a collisional event with a planet could cause life extinction and climate change. [ref]

### Origin of our solar system

Our solar system was formed 4.657 billion years ago. Scientists believe it was due to the collapse of a giant molecular cloud containing hydrogen and helium and heavy elements synthesised from a previous generation of stars. The cloud is in equilibrium, for which a local perturbation would cause a contraction on the part of the cloud. A nebula is born from the contraction that flattens from the first rotation, comprising of a star in formation and surrounded by a protoplanetary disk. Most of the collapsed mass formed our star (the Sun), while the remainder of that mass started to swirl around the Sun. As time passed, the swirling mass kept being depleted by the suns gravitational force. The leftover mass is now what made the celestial bodies, like planets, comets, and asteroids.

The planet formation occurred in the following sequence. First, coagulation takes place, forming large grains from the dust particles. These grains will grow to the size of a kilometre (from a μm size). These grains were named planetesimal and formed between 1 and 2 million years ago. As the grains kept forming, they become large enough to deflect and accrete smaller objects. But dynamic friction, eccentricity and inclination decrease as these planetesimals grow, while the reverse happened for smaller grains. Therefore, the rate of collision grew, and the largest of planetesimal started to grow rapidly. The growth rate of these bodies increased as a function of their respective masses, accreting nearby materials and forming the rocky planetary embryo. In the end, they collide and form the core of giant planets in ten million years while slowly accreting the remaining gas. Terrestrial planets formation is much slower and takes from 10~100 million years.

To better understand the planet formation, the clue lies on asteroids. Asteroids have a layer composition of the material, and the denser material is located at the centre of the asteroid or at its core. They resemble the layer structure of the Earth and proves they had a stunted evolution. Therefore, more study is done on asteroids to understand better the formation of rocky planets in our solar system. [ref]

Apart from the origins of our solar system, asteroids also can provide clues on life. Some asteroids that have been discovered have contained water, ice, and other organic matter, which are building blocks to support life. Therefore, the formation of planet earth could have undergone a similar process of many types of asteroids carrying these life building blocks colliding and bonding over time. [ref]

### Space exploration and NHATS

Asteroids possess unique characteristics in their orbits, and this could be a key feature of current and future space missions. In recent years, most space exploration has focused on the moon and the red planet neighbouring us. NEAs are now the next hot take for human space flight and can improve on new missions to Mars and beyond. The NEAs potential for space missions and round trips have been identified as the Near-Earth Object Human Space Flight Accessible Target Study (NHATS) [ref]. NHATS uses dynamic trajectory performance constraints to pinpoint potential NEAs.

Upcoming human spaceflights capabilities are ongoing, as the Orion Multi-Purpose Crew Vehicle and the Space Launch System are developing. Potential NEAs have an orbit like that of the Earth as velocity change and mission duration are critical for human spaceflight. The classification of a NHATS is that the NEA must provide at least a round trip trajectory solution that satisfies constraints, including the total that is less than 12km/s and a mission duration less than 450 days. The NHATS are being observed by radar observations that help in identifying potential NEAs. These NEAs will also be helpful for robotic missions, finding optimal trajectories for a round trip and recognising objects of interest for future ground-based observations. [ref]

Another exploration advantage is the identification of resources. Asteroids contain a variety of materials that can be extracted during space flights. These resources could boost further the mission duration and and may reduce the launch mass. Thus, the payload mass can be increased during launches. [ref]

## Asteroid Types

### Near-Earth Asteroids

These asteroids are part of the NEO group. They do survive in their orbits for a few million years before they are eliminated by planetary perturbations causing them to exit the solar system or a collisional event with a planet, Sun or another asteroid or minor planet. The primary source of NEAs is the MBA that move towards the inner part of the solar system caused by orbit resonances with Jupiter. Kirkwood gaps also have caused resonances to occur, moving these asteroids into other orbits [ref]. The NEAs are divided into groups, and Fig. 2.1 shows the orbit of some of the groups.

Diagram, schematic

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Figure ‑: Types of NEAs orbits. [ref]

Compared to the total mass of the MBA, a small mass is needed to maintain the NEA population, resulting in a mass loss of 6% from the MBA in 3.5 billion years ago. The asteroid spectral type of the MBA is also like NEAs showing a matching composition of materials.

A small number of NEAs consist of comets that lost their volatile surface material. Though having a faint tail on a comet does not 100% qualify it as a NEC. The rest of the NEA originate from the MBA due to gravitational effects from Jupiter [ref]. Many asteroids tend to have a natural satellite, and the NEAs are no exception. As of February 2019, there has been 74 NEAs that have at least a moon, with the asteroid 3122 Florence, being the largest of PHAs, has two moons [ref].

### The Main-Belt of Asteroids

The MBA are a group of asteroids found in the region between Mars and Jupiter, containing hundreds of thousands of asteroids. The MBA has a total mass of 4% of the mass of our moon and 33% of the mass of Ceres. The MBA exists because of Jupiter’s gravitational influence, which prevented the formation of a planet in that region of our solar system. Jupiter is at the origin of regions inside the Main belt where no asteroids exist, causing the Kirkwood gaps. The figure below shows the mass distribution as a function of *a.* Fig. 2.1 presents different contributions of asteroid taxonomies (section…). Fig. 2.1 shows that asteroids found in the inner edge of the MBA are the stony type and have a geometric albedo of around 20%. In comparison, those found on the outer edge are carbonaceous with a lower albedo of about 4%. These are the two main types of MBAs.

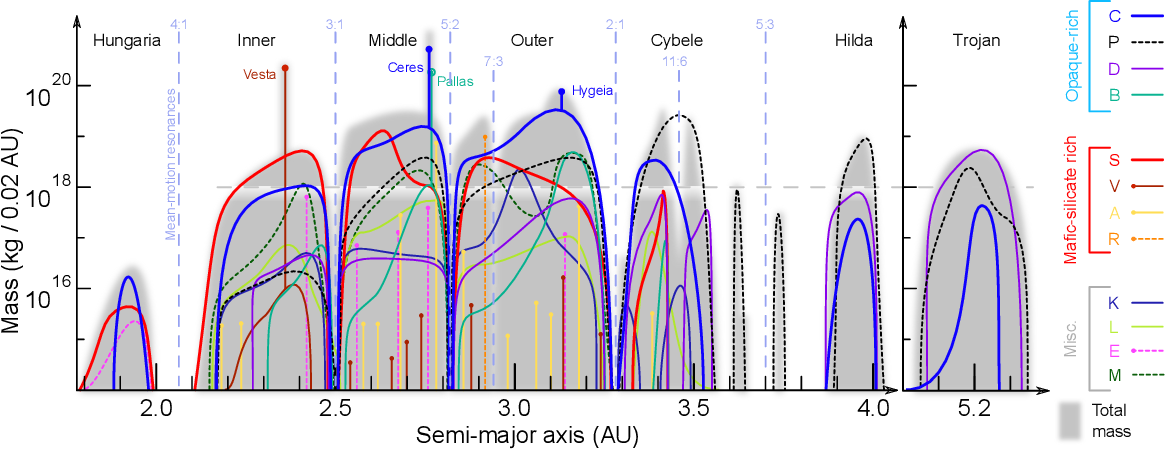


Figure ‑. Composition of the MBA as a function of the a. [ref]

Each colour is a spectral class of the MBAs, denoted by the letters in the legend on the far right. The grey area is the total mass per every 0.02 AU. The MBA’s orbital elements reveal groups that contain similar eccentricities and inclinations. Such similarity related to the orbits results in the formation of asteroid families. Their origin comes from a single parent body that had a collision forming fragments that are now existing in the same orbit as the parent body before.

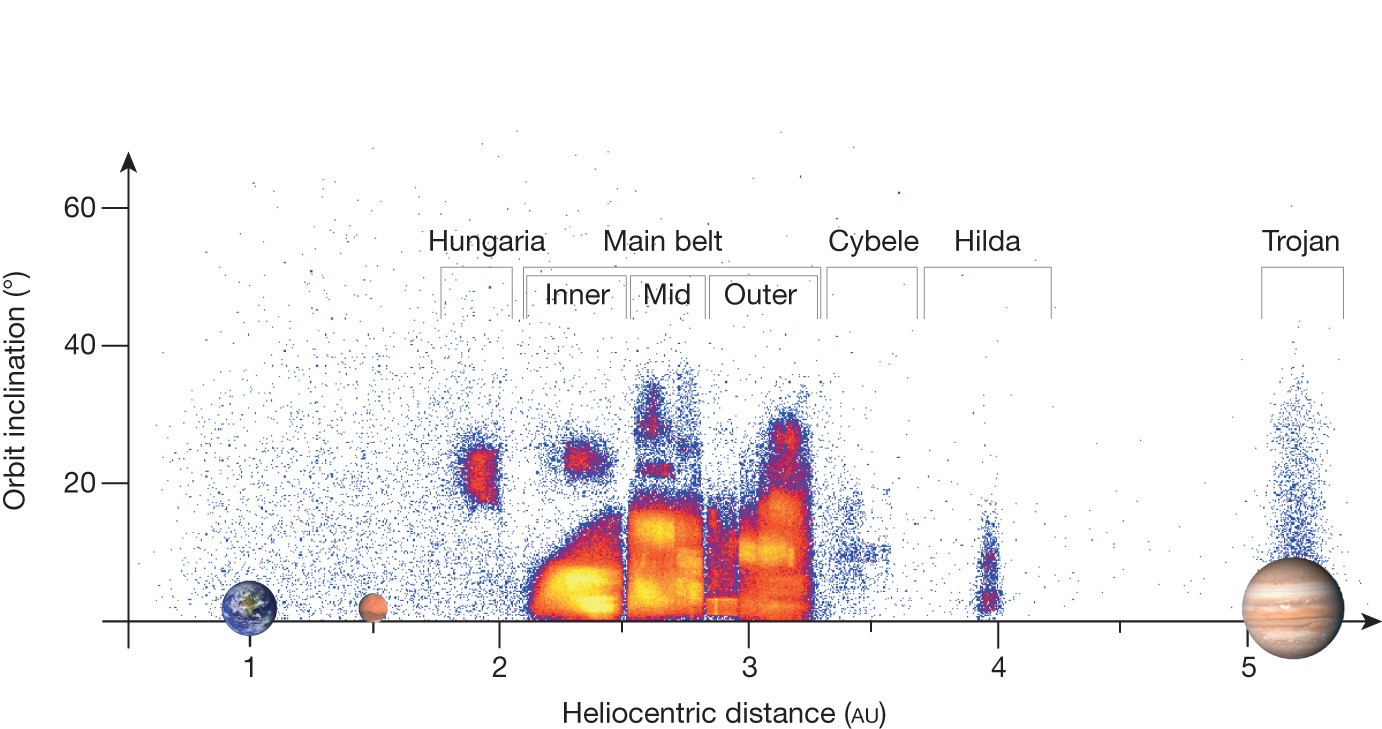


Figure ‑ The asteroid belt with neighbouring planets [ref]

Fig. 2.2 shows the location MBA to the neighbouring planets and the heliocentric distance from the Sun. The density of the MBA is represented by the colour where yellow shows the highest density of the asteroids while blue is the lowest. The MBA asteroids have higher eccentricities and inclinations than the planets.

The Main belt is divided into unstable regions that occurs between 2.5 and 2.8 au. This location is where the asteroids are in resonance with Jupiter’s orbit. This effect separates the inner, middle, and outer sectors of the main belt. The Hungarian asteroids (the name comes from the largest member asteroid, 434 Hungaria) are closest to the Sun and in front of the main belt. They can be found between 1.78 and 2.00 au. Their orbits have an inclination centred around 20° [ref]. The Cybele asteroids appear after the main belt and are considered the last outpost of the extended asteroid belt. It comprises two thousand asteroids and few collisional families[ref]. They have an orbit resonance of 7:4 with Jupiter [ref]. Their orbit has an *a* of 3.28 to 3.70 au with an eccentricity less than 0.3 and an inclination less than 25°. [ref] The Hildas asteroids are more than four thousand located beyond the main belt and have a 3:2 orbit resonance with Jupiter [ref]. The name originates from the asteroid 153 Hilda. They can be found between 3.7 to 4.2 au, have an eccentricity less than 0.3 and an inclination less than 20° [ref]. Only two collisional families exist, and they include the Hilda family and the Schubart family (the name from the asteroid 1911 Schubart [ref]). The trojans are in the L4 and L5 (Lagrange point) of Jupiter’s orbit with an average *a* of 5.2 au. [ref]

### Trojan Asteroids

The trojan asteroids, also known as the Jupiter trojans, are located after the MBA. The first Trojan asteroid was discovered by a German astronomer named Maximilian Wolf, who spotted the 588 Achilles in 1906 [ref]. They are believed to be the second group of asteroids after the MBA and form the most populous trojan asteroids [ref]. They have a leading and trailing of 60° along Jupiter’s orbit in the Lagrange points L4 and L5. These two Lagrange points pull from the Sun and Jupiter, maintaining a balance that tends to make the trojans asteroid fly off their orbit. The total count of discovered Trojan’s asteroids exceeds 9800 as of May 2021 [ref]

The Trojans are divided into two groups. The Greek camp is found in an elongated, curved region on the leafing Lagrange point L4 ahead of Jupiter in its orbit. The Trojan camp is found on the trailing Lagrange point L5 behind Jupiter.

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Figure ‑ Jupiter’s Trojan Asteroids. [ref]

### Centaurs

Centaurs are found between 5.5 and 29 au, with their *a* of their elliptical orbits located within the orbits of Jupiter and Neptune. Their position in the solar system causes them to have a high probability of being perturbed by giant planets such as Jupiter, thus, having unstable orbits. Their orbits have dynamic lifetimes of a few million years [ref]. One known centaur, the 51410, is believed to have a stable retrograde orbit [ref]. Centaurs physically exhibit features from comets and asteroids. Thus, the name *“centaur”* from Greek is a mix of a human and a horse. Centaur population is an estimate as observation bias on large objects makes the determination difficult. Therefore, the estimated number ranges from 44000 to more than ten million centaurs of more than 1 km [ref]. The largest centaur, discovered in 1997, is the Chariklo 10199, with a radius of 260 km and has a system of rings.

### Trans-Neptunian Objects

Any minor or dwarf planet in the solar system orbiting the Sun with a semi-major axis greater than 30.1 au is referred to as a trans-Neptunian object (TNO). TNOs are classified into classical and resonant objects of the Kuiper belt, the scattered sick and detached objects. The distant ones are the sednoids [ref]. The catalogue of MPC contains 678 TNOs as of October 2020, while more than two thousand are yet to be catalogued [ref].

The first TNO object is Pluto, discovered in 1930. The discovery was motivated by the discrepancies in the 1900s, where the observed objects of Uranus and Neptune hinted at the possibility of one or more planets beyond Pluto. The largest of known TNOs is Eris, followed by Pluto, Haumea, Makemake and finally Gonggong. These TNOs have over eighty satellites orbiting them. TNOs have varying colours and can be seen as grew blue or red, with a mixture of rocks, amorphous carbon, and volatile ice (methane and water), coated with organic compounds such as tholins.

The extreme trans-Neptunian objects (ETNOs) are twelve in number. They have a semi-major axis above 150 au and a perihelion above 30 au [ref]. Fig. 2.4 illustrates the distribution of TNOs known to date with planetary orbits and centaurs. The TNOs are classified into two groups: the Kuiper belt objects (KBOs) and the scatted disc objects (SDOs)[ref].

Schematic

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Figure ‑: Distribution of TNOs [ref]

The KBO is located on an average distance between 30 to 55 au, close to circular orbit and small inclination. The Edgeworth KBOs are further classified as resonant TNO locked in an orbital resonance with Neptune, and the classical KBOs (cubewanos) are free from any resonance (unperturbed by Neptune) and have almost circular orbits. There are many resonant subgroups, the largest being twotinos with a 1:2 resonance and the plutinos with a 2:3 resonance (named after Pluto). Objects found in the classical Edgeworth-Kuiper belt include Makemake, 1560 Albion and 50000 Quaoar.

The SDOs are further away from the Sun with very inclined and eccentric orbits. They are non-resonant, non-planetary and non-orbit crossing. Tisserand’s parameter (or Tisserand’s invariant) is a value calculated from several orbital elements (semi-major axis, orbital eccentricity, and inclination) of a small object and a larger *“perturbing body.”* [ref]

Where is the orbital inclination relative to the orbit of a perturbing larger body with a semi-major axis [ref]. Using the Tisserand Parameter, the SDOs can be divided into typical SDO (Scattered near) with a TN < 3 and the detached SDOs (Scattered extended) with a TN > 3. Detached SDOs have a time average eccentricity > 0.2 [ref]. The Sednoids are sub-grouped from the detached objects with perihelia, so their orbits can be explained by neither perturbation from the giant planets [ref] nor interaction with the galactic tides. [ref]

### Comets

Comets are believed to be leftovers at the birth of our solar system and consist of ice coated with the dark material composition. Comets yield clues about the formation of our solar system. They are believed to have brought water and other organic matter, becoming the building blocks to life, Earth, and other parts of the solar system.

In 1951, astronomer Gerard Kuiper theorised that a comet is a disk-like icy object found beyond Neptune, where a population of comets orbit the Sun exist. These comets are constantly pushed by gravity into orbits and bring them closer to the Sun. Some comets take less than two hundred years to orbit the Sun. However, it is hard to predict the orbit period for comets with a longer period to orbit the Sun. These comets with longer periods come from the Oort cloud, 100000 au, and would take thirty million years to complete their orbit around the Sun.

Each comet comprises a nucleus that is frozen and not larger than few kilometres. The nucleus has icy chunks, frozen gas, and dust. As the comet approaches the Sun, the sun heat tends to evaporate the ice into gas, causing the coma to enlarge. A coma mat extends hundreds to thousands of kilometres as it nears the Sun. The solar wind tends to blow away the coma dust forming a long and luminous tail. The tails could be either dust or an ion tail.

Some comets come as close as eighty-nine kilometres and did the Halley comet. Such comets are categorised as NEOs. Others do crash straight into the Sun, causing them to break up and evaporate. These comets are known as sungrazers. [ref]

A picture containing nature, outdoor, comet, night sky

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Figure ‑. Halley’s comet approach Earth in May 1910. [ref]

### Meteorites

Fragments coming from asteroids or comets that reach the surface of the Earth are known as meteorites. Studies are conducted on meteorites to know the formation and composition of solar system materials and other minor planets. These meteorites are classified based on their material composition. The main group involves the stony, iron, or stony-iron meteorites.

The stony group is further split into two types of meteorites, the achondrites and the chondrites. Achondrites consist of 8% of the meteorites, and the iron meteorites underwent planetary and asteroid differentiation[ref]. The iron-type consists of 6% of the meteorite [ref]. The differentiation comes from the melting of the iron and signals metamorphosis because of processes like crust-mantle formation and core-mantle differentiation, separating the metals from silicates that are abundantly found on the surface.

The chondrites are about 86% of the meteorites, homogeneous, and have remained unchanged since the parent body formation. One of the large family of achondrites, the HED (howardite–eucrite–diogenite) meteorites, may have its origin from the parent body of the Vesta family [ref]. The three types of HED include the eucrite, the diogenite and the howardite. The eucrite formed from lava flows and is believed to originate from the outer crust of the Vesta. The diogenite originates from the deeper crust layer that was extracted from the bottom of the Rhea Silvia basin. The howardite is breccias of both the diogenite and eucrite type due to material mixing from impacts on the surface layer. They consist of chondrules that are embedded in a matrix. These chondrules are small, spherical grains formed from elevated temperatures mixing all the minerals. Scientists and physicists believe them to be the oldest material in our solar system. The carbonaceous type of chondrites are meteorites whose material composition match the solar and proto-stellar nebular.

Meteorite spectra are measured in laboratories and compared to the existing observed asteroid to provide information on their composition and structure. Suppose an asteroid can be linked to meteorite analogues using estimations of bulk densities obtained from observations. In that case, the asteroid’s porosity is provided by comparing the densities with the respective meteorite.

## Asteroid orbital elements

Orbital elements are unique parameters that identify the orbit of an object. They are used on planets, asteroids, and comets. In orbital mechanics, these elements are known as a 2-body system using Keplerian orbit. Asteroid orbits have their elements change over time from the effects of gravitational perturbations. Therefore, a Kepler orbit is the idealised approximation of the orbit based on a certain time.

In Fig. 2.7, the yellow plane is the orbital plane while the purple plane is the reference plane. The intersection of these two planes creates the line of nodes, which connect the centre of mass with the ascending and descending nodes.

There are six Keplerian elements. Two orbiting bodies do trace out their trajectories when viewed from an inertial frame. A body would have two sets of Keplerian elements, depending on the reference body. Mostly the reference body is the Sun, or a massive body and referred to as the primary body. In contrast, the other body becomes the secondary body. The primary object does not have more mass than the secondary object; the elements depend on the primary object.

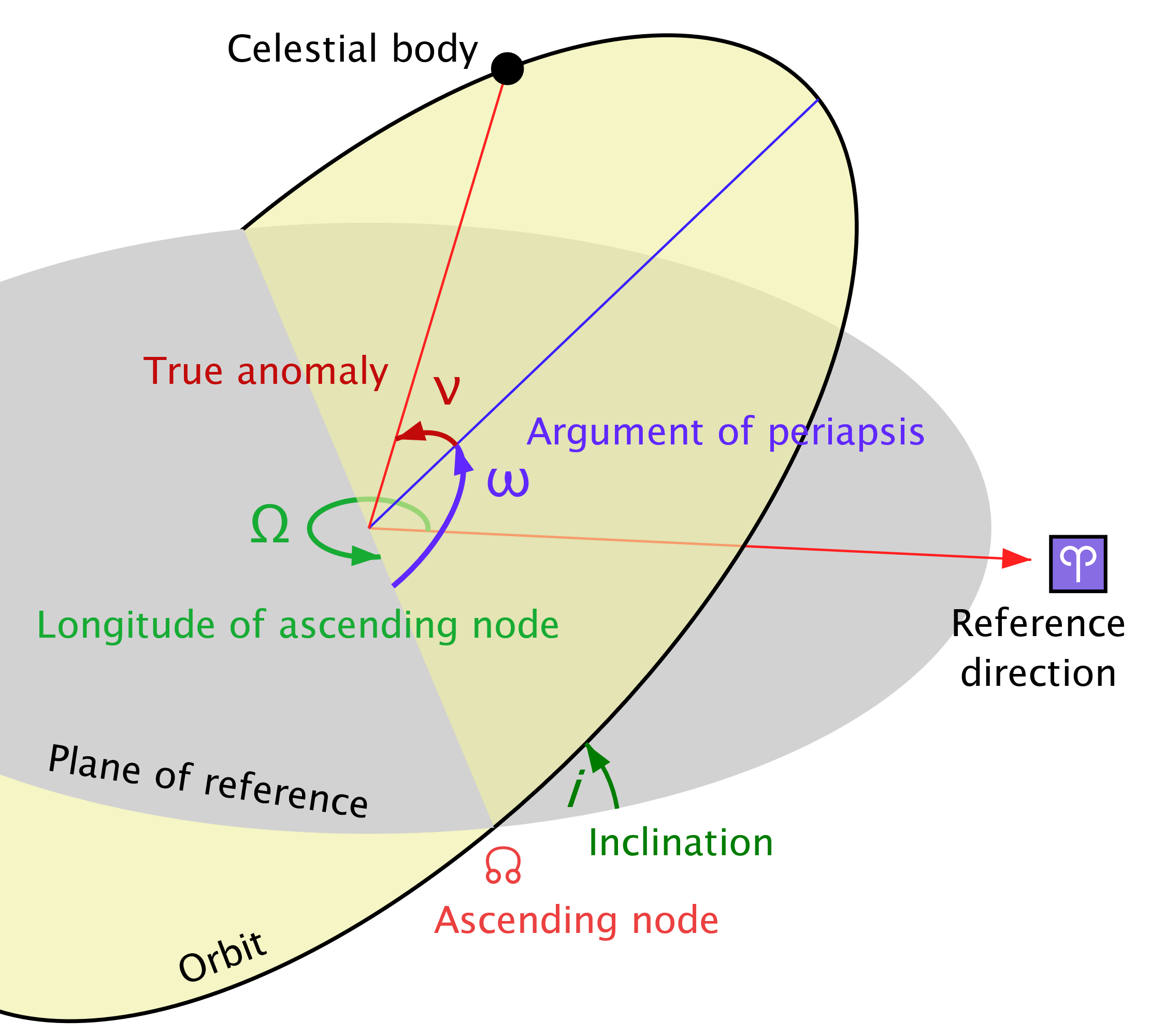


Figure ‑

The 2-elements that define the orbit shape and size are the eccentricity *(e)* and the semi-major axis (*a)*. The other two elements that define the orbital plane orientation in an embedded ellipse include the inclination *(i)* and the longitude of the ascending node *(Ω)*. [ref]

|  |  |  |
| --- | --- | --- |
| **Name** | **Units** | **Description** |
| Semi-major axis (*a*) | au | Half the length of the long axis (diameter) of an elliptical orbit represents a measure of the orbit’s size. Also, it is defined as half of the sum of the pericentre and the apocenter. The pericentre is the point on the orbit where the asteroid is closest to the Sun (central body). At the same time, the apocenter is the furthest point in the orbit away from the Sun. *q* is a notation used for the pericentre and sometimes used instead of the *a.* |
| Eccentricity (*e*) | - | *e* defines the orbit shape and computes the orbit’s variation from a circle (e=0). It is the ratio between the focus distance from the orbital ellipse centre and the *a.* It takes values ranging from 0<*e*<1. When *e* = 1, it describes a non-bound orbit in the form of a straight line. If *e>*1, it becomes a hyperbolic orbit. |
| Inclination (*i*) | deg | *i* is the angle between the orbital plane of an asteroid and the ecliptic plane. It ranges from 0°<*i*<180°. A prograde orbit ranges between 0°<*i*<90°, and the asteroid moves anticlockwise to an observer located at the ecliptic North pole. A retrograde orbit has a clockwise motion, and its *i* ranges from 90°<*i*<180°. Planets in our solar system have a direct orbit. When the orbital plane intersects the reference plane, it’s creating two points known as the ascending and descending nodes. |
| Longitude of the ascending node (*Ω*) | deg | *Ω* determines the angle between the vernal equinox (first point of Aries) and the ascending node (where the orbital plane intersects the plane of the ecliptic). It is positively defined around the z-axis of an ecliptic coordinate system with the vernal equinox. The vernal equinox defines the z-axis of the same ecliptic coordinate system. The *Ω* ranges from 0°< *Ω* <360° |
| Mean anomaly (*M*) | deg | *M* is the angular distance from the perihelion (closest point of the orbit to the Sun or orbiting object), denoted by the letter *“q”* to the current body’s location, which lies in motion direction. |
| The argument of the perihelion () | deg | defines the angle between the ascending node and the perihelion (the Sun is the central body), measured counterclockwise along the orbit plane. It describes the orbit’s orientation in its orbital plane and ranges from 0°<<360° |
| Perihelion (*q*) | au | *q* defines the closest point of the asteroid’s orbit to the Sun. |
| Aphelion (*Q*) | au | *Q* defines the furthest point in the orbit of the asteroid from the Sun. |
| Epoch | - | Epoch defines the date on which the orbital element is obtained. |
| True Anomaly (*V*) | deg | It is an angle that specifies the orbital position of an asteroid based on its specific epoch. The perihelion passage *T* is mostly used instead of the true longitude. In some special cases, the *M* is used to specify the orbital position when an element with linear time dependency is observed. |

## Asteroids Dynamics

Dynamics covers all the processes that affect an asteroids rotation and orbital characteristics. A study on the dynamics can show how asteroids from the MBA cross into Earth’s orbit and eventually producing meteorites. Understanding the dynamics is key to study the propagation of the asteroids and serves as a link of meteorites with their parent bodies and the evolution of the solar system.

### Asteroid families

Collisional events led to the formation of asteroids families from the MB. It is also the cause of the abundance of small asteroids. Other influences from collision include change of asteroid orbit, rotation change, and material and shape formation. A study on the collisions is done in laboratories where experiments and numerical simulations are conducted [ref]. The experiments focus on the analysis of the impacts at varying magnitudes. Others include the numerical study to study the collisional events of Vesta [ref].

Asteroid families are remnants of past asteroid collisions involving the parent body that led to forming a group of asteroids. These families were first observed in 1918 by the astronomer Kiyotsugu Hirayama [ref]. His analysis was on the property of orbital elements representing the average values of their original body over long time scales. He then proposed that those smaller asteroids that share similar orbital elements have a common collisional historical event. Over the years, his findings have been refined, and further numerical methods have led to more accurate asteroid families [ref]. The families include [ref].

1. The Eos family, named after 221 Eos and has 9789 known members
2. The Eunomia family, named after 15 Eunomia and has 56770 known members of type S asteroid.
3. The Flora family, named after 8 Flora, is the third largest family with 13,768 known members.
4. Hungaria family, named after 434 Hungaria and has 2965 known members. Class E asteroids.
5. The Hygiea family, named after 10 Hygiea and has 4854 known members,
6. The Nysa family, named after 44 Nysa and is the largest family with 19,073 members.
7. The Themis family, named after 24 Themis, has 4782 known members.
8. The Vesta family, named after 4 Vesta, is the second-largest family with over 15252 known members. These are V class asteroids
9. The Hila family has 409 known members.
10. The Schubart family has 352 known members
11. The Eurybates family has 218 known members.

The asteroid taxonomy class is presented on table 2.2.

### Resonances

Planets Jupiter and Saturn play a significant role in the shape and dynamics of the MBA due to their gravitational forces. They result in the MB having gaps that Kirkwood first discovered in 1866, and the gaps were named after him. These gaps reveal the motion resonance with Jupiter.

Fig. 2.8 shows the MBA bounded Kirkwood gaps. The most prominent Kirkwood gaps are located at 5:1 (at 1.780 au), 4:1 (at 2.065 au), 3:1 (at 2.502 au, home to the Alinda group of asteroids), 5:2 (at 2.825 au),7:3 (at 2.958 au), 2:1 (at 3.279 au, Hecuba gap, home to the Griqua group of asteroids.), 3:2 (at 3.972 au, home to the Hilda asteroids.) and 4:3 (at 4.296 AU, home to the Thule group of asteroids) [ref]. The blue histogram presents the inner MB; the yellow presents the intermediate MB, and the green present the outer MB. Asteroids with a mean motion resonance have a shorter period than Jupiter. Therefore, asteroids with a mean motion of 5:2 would orbit the Sun five times while Jupiter would have completed two-orbit revolutions. If an asteroid enters, any resonance region will have an increased orbit eccentricity and can cross planet orbits within a brief period of the order of 1 to 2 million years [ref]. Most resonances remove materials from the MB since the beginning of the solar system. This could explain why some asteroids, when ejected, would end up as meteorites[ref].

A screenshot of a computer

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Figure ‑. Histogram displaying the known Kirkwood gaps. [ref]

Secular resonance is synchronous of the precision of the perihelion of Saturn. These resonances are less chaotic than the motion resonance and can cause asteroids eccentricities to either increase or decrease. These resonances have complex 3-D shapes of the asteroids. Most of the gaps have been depleted due to the overlapping V5 and V6 secular resonance and mean motion resonances. Another reason is that when both Jupiter and Saturn are near the 5:2 resonance, the depletion is accelerated, especially when both planets have their orbits close together [ref]

### Yarkovsky and YORP effects

The Yarkovsky effect is a force that acts on a rotating object, resulting in thermal energy emission from the surface. It was discovered in 1900 by polish engineer Ivan Osipovich Yarkovsky. He theorised that the constant heating of the Sun on a rotating object would produce a small force that, with time, would change the objects orbital properties [ref]. The effect is eminent on small bodies like asteroids. Over time the rotating asteroids in motion around its orbit would gradually accelerate and expand their orbit or have a retrograde spinner that will spiral the orbit inwards.

It is composed of two components. The diurnal effect, which has an asteroid spin axis, stays nominally perpendicular to its orbital plane. The seasonal effect has the spin axis nominally parallel to the asteroids orbital plane. Thermal inertia is an intrinsic property causing the delay of absorption and emission of the Sun’s thermal energy. The importance of the Yarkovsky effect is the delivery of an asteroid impact fragment into a mean motion and secular resonance, causing some to enter Earth’s orbit and end up as meteorites.

![From University of Belgrade [Универзитет у Београду](RS)(CZ) via Sky &amp;  Telescope: “Karma Asteroid Family Might Be Sending Members Near Earth” |  sciencesprings](data:image/jpeg;base64,)

Figure ‑:Yarkovsky Effect. [ref]

Fig. 2.9 shows the asteroids in their orbits around the Sun, with the surface facing the Sun getting warm. Due to rotation, the heated-up sides start to cool. However, there is a delay in the emission of thermal energy due to the thermal inertia inherent in the asteroid. The same effects happen on Earth, causing the afternoons to be the warmest. In a prograde rotation, the Yarkovsky force is in line with the direction of the orbital motion increasing the *a* and the eccentricity to some extent. Over time, this slight change would lead to substantial changes in the orbit. For a retrograde motion, the Yarkovsky force is opposite the direction of the orbit motion causing a decrease in the semi-major axis and eccentricity.

The YORP (Yarkovsky O’Keefe Radzievskii Paddack) is a Yarkovsky effect that influences the asteroid rotation rate[ref]. YORP is a result of heating and reemission of thermal energy. Asteroids with a non-symmetrical shape experience a net torque. The torque can increase or lower the rotation rate of the asteroid. YORP effects do not directly alter the orbit, but their effects influence the Yarkovsky effect. An asteroid with infinite spin rate could cause YORP to increase the rotation rate, but this would minimise the Yarkovsky effect.

### Small body mechanics

The various regions that the asteroids occupy in the solar system cause them to move at varying speeds. They move at an orbital velocity () that governs them to be in a gravitational orbit around the Sun. if the velocity is circular, then it is represented by the equation:

Where is the universal gravitation constant, is the Sun’s mass, and is the heliocentric (orbital radius) distance. The asteroid’s angular speed () is equal to the speed relative to Earth and divided by the distance away from Earth (). With the being the difference of the orbit velocity to that of Earth. Therefore, an asteroid in a near opposition would make the heliocentric distance (in au) subtracted by 1 au (distance of Earth from the Sun) and can be obtained in the equation below.

gives an estimate of how these asteroids are moving as viewed from Earth. Its advantage is trying to point out that objects are in motion during observations. Table 2.1 shows calculated orbital and angular speeds with orbits assumed to be circular.

Table : Distinct groups of asteroids and their orbital and angular speeds.

|  |  |  |  |
| --- | --- | --- | --- |
| **Asteroid group** | ***r (au)*** | ***(m/s)*** |  |
| NEA/NEO | 1.5 |  | 0.9 |
| MBA | 2 |  | 0.7 |
| KBO | 40 |  | 0.05 |

### Rotation

Asteroid’s rotation is the most important property and one that is the focus of the thesis. The rotation provides information about an asteroid origin, its material composition due to its shape, and the dynamic interaction from effects such as Kirkwood gaps. The data of an asteroid’s rotation can be obtained from techniques such as ground optical telescopes and radar [warner], space telescopes, and in situ methods from space missions [ref]. The data has been useful in maintaining the population of asteroids and the emergence of new ones. Other findings include a spin rate barrier, for which rubble pile asteroids rotate about eleven revolutions per day. The prevalence of a binary asteroid system and YORP effects that change the primordial Maxwellian distribution of spin rates are findings from the period. Further details on the rotation are discussed in chapter 3.

### Vestoids

The vesta family was formed as an outcome of the asteroid’s collision. The vesta family is the largest of asteroids families. The family consists of oof the brightest V-type asteroids (visual), this the name, Vestoids. Vesta is the second-largest asteroid with a mean diameter of 530 km and contains other smaller asteroids below 10 km in diameter. The brightest of the vesta family include the 1929 Kolla and 2045, having H = 12.2.

Fig. 2.9 shows the Vesta family location and characteristics of the Vesta family. The circles are proportional to the mean diameter of the asteroids. The top plots represent proper orbital elements of inclination vs semi-major axis (top left) and inclination vs eccentricity (top right). The bottom plots are zoomed-in plots containing the Vesta family (in red) using the HCM method analysis [ref]. The same analysis method was used to identify the outer family members (in purple) but are less certain to be members [ref]—the numbered asteroids in general (small blue dots) from the AstDys database. The location of asteroids that are large and explicitly named on the plot is shown by a light cross within the circle.

Chart, diagram

Description automatically generated

Figure ‑ The Vesta Family. [ref]

The vesta family is bound by an orbital space of 2.26 au < *a* < 2.48 au, 0.075 < *e* < 0.122, and 5.6°< *i* < 8.3°. At 2.36 au contain the highest density of the vesta family. The Vesta family is believed to have originated from a tremendous impact of Vesta at its south pole around one billion years ago [ref]. The impact resulted in the formation of the Rheasilvia basin. More materials were ejected into the region of space and near Vesta. Much of the ejected material would be lost due to neighbouring resonance, proving that more material was ejected than the current number [ref]. The Vesta family also includes the J-type asteroid that is believed to have come from the deep layers of the vesta crust and bears similarities with diogenite meteorites.

### Resupply of NEOs

A vast number of asteroids have dynamic life of about ten million years, which is shorter than the age of the solar system. A handful of these NEOs are observed from trajectories that are due to either the MBA changing their ***a*** from collisional events or because of Kirkwood gaps. These gravitational effects lead to either the asteroid ejection from the solar system or injecting them into new orbits that could come near planets.

Apart from gravitational forces, the resupply can also be because of other non-gravitational forces. The Yarkovsky effect tends to change the *a* of an asteroid and drifts it to orbits resonating with other larger objects such as planets. Drift here is size depended on the *a* of the asteroid and changed proportion to the inverse of the asteroid’s diameter. Continuous drift would cause the orbits eccentricity and inclination to change, thus causing a planet-crossing or Sun colliding trajectories. This would increase the population of NEOs over time.

## Asteroid taxonomies

Spectrometry is the measurement of the interaction between light and matter and the reaction of radiation intensity and wavelengths. It is also the study and measure of a specific spectrum [ref]. Therefore, an asteroid spectral type is based on the colour, emission spectrum and albedo. The study of spectrometry has led to the implementation of asteroid taxonomy. The study and measurement have evolved so much. The most used taxonomy classes include:

1. Tholen classification was proposed in 198 and is most widely used. Developed by David J. Tholen, its classification uses a broad band spectrum of 0.31~1.06 μm and with a combination of albedo measurements [ref7]. It includes a total of fourteen types of classes.
2. SMASS (Small Main-Belt Asteroid Spectroscopic Survey) is a more recent taxonomy created by Schelte Bus and Richard Binzel in 2002. It includes 1447 asteroids of smaller range wavelengths of 0.44 ~ 0.92 μm [ref9].
3. Bus-DeMeo was developed by Schelte Bus, Francesca DeMeo, and Stephen Silvan in 2009. It is based on the reflectance spectrum on the wavelength 0.45~2.45 micrometres of 371 asteroids. It has twenty-five classes, with the 25th addition being the *Sv*-type [ref6].

The taxonomy has 25 classes from the analysis of the visible (V) and near-IR (Infrared) spectral data, at a wavelength range of 0.45 ~ 2.45 microns [ref].

|  |  |  |
| --- | --- | --- |
| **Class** | **Description** | **Asteroids** |
| A | Rare inner MBA. Spectra indicate the presence of olivine. | (246) Asporina,  (289) Nenetta. |
| B | An uncommon class of carbonaceous asteroids found in the outer MB. Spectra show the presence of clays, carbon, and organics. | (2) Pallas,  (431) Nephele,  (25143) Itokawa. |
| C, Cb, Cg, Cgh, Ch | Carbonaceous type is common in the outer MB. | (1) Ceres,  (10) Hygeia,  (19) Fortuna,  (45) Eugenia,  (253) Mathilde |
| D | The spectrum of these outer MB objects may indicate organic-rich carbon and anhydrous silicates, and ice. | (624) Hektor,  (944) Hidalgo |
| K | Silicaceous or stony uncommon MBAs. Spectra indicate the presence of olivine and orthopyroxene. | (221) Eoa,  (233) Asterope. |
| L | Uncommon asteroids with featureless  spectra. | (387) Aquitania,  (728) Leonisis. |
| O | - | (3628) Boznemcova |
| Q | Inner MBAs. Spectra indicate the presence of olivine and pyroxene. | (1862) Apollo. |
| R | These are moderately bright inner MBAs with the presence of olivine, pyroxene, and plagioclase. | (349) Dembowska. |
| S, Sa, Sr, Sq | Moderately bright, stony, chondritic asteroid class dominating the inner MB. | (6) Hebe, (433) Eros,  (15) EuNomia. |
| T | These are low albedo inner MBAs of unknown composition with featureless, moderately red spectra. | (114) Kassandra. |
| V | Like S-class asteroids. But they contain a form of pyroxene known as augite. | (4) Vesta. |
| X, Xe, Xc, Xk | Metallic asteroids. Spectra indicate the presence of troilite (iron sulphide), enstatite, and hypersthene. | (44) Nysa,  (64) Angelina,  (87) Sylvia,  (2867) Steins. |

## Impacts of NEO

As fascinating as studying asteroids and their potential to provide resources and support life on Earth from material compositions and water, they also threaten our planet. The Chicxulub asteroid caused the famous event that happened sixty-six million years ago. Its impact on Earth caused a mass extinction of life, also known as the Cretaceous-Paleogene extinction event. Many living organisms and species were wiped out from the impact. A small population of the winged ones survived [ref].

Therefore, there have been campaigns to raise awareness of the potential dangers of asteroids, and agencies are trying to prevent what happened with the dinosaurs. Large asteroids impact has a low probability of collision chance. Still, the smaller ones are populated across the solar system (from the MB). They can cause damages and loss of lives if an impact event occurs. Most smaller asteroids enter the atmosphere as meteors. Many of them burn in the atmosphere, and only a few make it to the surface as meteorites. The Chelyabinsk event in 2013 was due to an asteroid burning and disintegrating in Earth’s atmosphere upon entry. The asteroid was about twenty meters in diameter and had an airburst of around five hundred Kilotons. This burst was an explosion that was thirty times that of Hiroshima. But it caused explosive air bursts that create shockwaves causing damage to buildings and shattering glasses. People nearby the building got injured. [ref]

The European Space Agency (ESA) created a planetary defence office that governs space safety and security activities. The observation campaigns mark risky asteroids, perform orbit propagation, and create impact warnings and means of mitigations. Its goals are:

* to create awareness of current and future positions of NEOs,
* create estimates of impacts,
* assess the level of impact and its consequences,
* relay findings to other agencies and astronomers’ communities,
* and develop means and methods of deflecting asteroids heading towards Earth.

The planetary defence office is divided into three main work areas.

### Observation, Detection and Tracking

Observation is key to understanding the motion of the asteroids and cataloguing them in databases. Most observations are conducted using telescopes, and more details about them are discussed in the following paragraphs.

The Flyeye telescope is a network of telescopes that scan the skies every night and automatically detect any asteroid that poses a risk of collision and feeds this information to the agency. The Flyeye works by splitting every captured image into sixteen smaller images, increasing the sky coverage observed and the FOV (Field of View). They are placed on both the north and south hemispheres, scanning 48 hours of the night sky. Flyeye is effective as it can detect more than one-meter asteroids.

The Test-Beds Telescopes (TBTs) consist of two 56cm telescopes that test the data processing on development for the Flyeye telescopes. One of the telescopes is commissioned in Madrid, and the other will be in La Silla in Chile. In La Silla, the telescope will be under the control of the European Southern Observatory (ESO).

The optical ground station in Tenerife has a one-meter diameter telescope and is majorly used for follow-up asteroid observations. Most observations are done around four nights before the new moon for NEO observations. This is due to reduced reflection from the moon, allowing less bright NEOs to be easily detected.

ESA participates in sponsoring other telescopes in Europe. One of them is the Klet Observatory in the Czech Republic and others in Germany, Spain, and Tauten burg. ESA also works together with the Telescope Joan Oro (80cm optics) in the Spanish Pyrenees, *Observatoire des Makes* (60 cm optics), at Saint-Louis on Réunion Island, and with the International Scientific Optical Network (ISON). [ref]

Near-Earth-Asteroid Tracking (NEAT) is the first automated one meter-telescope from NASA. NEAT lies on the Maui Space Surveillance Site on the crater of the extinct Haleakala volcano, Hawaii. Between 1996 and 2007, NEAT has discovered 442 NEOs up to the year 2007, and more than 1500 designations of minor planets, and 26000 MBA detections [ref].

Catalina Sky Survey (CSS) is a high-rate NEO discoverer. CSS has the observatory code of 703. NASA funded it to support the Near-Earth Object Observation (NEOO) under the Planetary Defence Coordination Office (PDCO). The CSS consists of three telescopes, one located in the Siding Spring Observatory in Australia and the other two in Tucson, Arizona. CSS has been successful in its sky coverage survey and detection and has had innovative software to help create an alert on PHAs and follow up processes. The CSS has discovered more than 8,500 NEOs [ref].

Lincoln Near-Earth Asteroid Research Program (LINEAR) is an MIT program and collaborates with NASA and the United States Airforce. Its observation code is 704. It consists of a pair of telescopes in Socorro, New Mexico. LINEAR has discovered 2,641 NEOs. It was responsible for most of the discovery but was later overtaken by the CSS [ref]

Spacewatch is a project by the University of Arizona, whose operations started in 1984. Its telescopes have apertures of 0.9, 1.8, 2.3 and 4.0 meter-diameter. These telescopes are placed on the Kitt Peak Mountain, Arizona. It uses observation code 691. Spacewatch studies minor planets, including both asteroids and comets. So far, it has discovered over a thousand minor planets [ref].

Wide-field Infrared Survey Explorer for Near-Earth Objects (NEOWISE) is a NASA spacecraft mission [ref]. It was extended for few months due to its success. NEOWISE produces images of the sky in four infrared wavelength bands using a 0.4-meter-diameter telescope, always 90° from the Sun. The images captured asteroids and comets that were close to Earth’s orbit. The spacecraft characterised 158000 minor planets and 35000 newly discovered objects, including twenty comets [ref].

Chart, bar chart

Description automatically generated

Figure ‑NEOs population from various detection projects. [ref]

Panoramic Survey Telescope and Rapid Response System (PanSTARRS) was developed and is operated by the Institute for Astronomy at the University of Hawaii. PanSTARRS goes by the observatory code of F51. Located in Haleakala, Maui, PanSTARRS consists of astronomical cameras and telescopes, with a computing facility that is continuously survey moving objects. PanSTARRS output its data in the form of astrometry and photometry of the detected objects. It has discovered more than four thousand NEOs [ref].

### Data Provision

Asteroid Data collected from radar systems and telescopes is passed to the MPC, which operates with support from the International Astronomical Union (IAU) in Cambridge, Massachusetts. The MPC is a central database for asteroids and comet observations.

These measurements in MPC are gathered from ESA’s Near-Earth Object Coordination Centre (NEOCC). NEOCC offer to coordinate observations of small bodies in the solar system and evaluate imminent threats from these objects to come near Earth. NEOCC is based in Frascati, Italy. It is the centre of all networks of European asteroid data source operation and information providers. They use this information coming across many channels to create orbit determination, monitor impacts, create data provisions, and perform risk analysis.

The Centre for Near-Earth Object Studies (CNEOS) is NASA’s centre dedicated to the computation of orbits for NEOs and their probability of earth impact. Their main goal is to predict close approaches of NEO’s to Earth and create probabilistic models that span over years to come. The NEO data is constantly updated. The discovery, calculations and statistics are available at the Small-Body Database (SBDB) [ref].

### Mitigation means

Once an asteroid is considered potentially dangerous, agencies worldwide and informed, discussions, and support are offered from the NEOCC and other organisations on how to mitigate the asteroid. Therefore, new means of mitigation are being developed, and some are ongoing.

Chart, scatter chart

Description automatically generated

Figure ‑: Impacts of Small asteroids on the Earth’s atmosphere. [ref]

Among the mitigation measure is the fireball camera. The camera is under ESA’s development and will use tools to simulate impacts on Earth and further research on deflection methods. Fireballs are small-sized NEOs, like bright meteors, with diameters ranging from centimetres to meters. Due to their small size, they do not survive re-entry and disintegrate in the atmosphere causing bright trails. One in every1200 meteors become brighter than -5 mag, while one in every 12000 achieves a -8 mag brightness [ref]. Most metros have an apparent magnitude of -3 using the zenith position. Zenith magnitude is applied when it is visible to observe the meteor if it appears in the zenith observation site. The apparent brightness decreases with the square distance of the meteor and the observer. At the same time, the light absorption is proportional to the optical path length. The zenithal magnitude is calculated using eq(), where *M* is the zenithal magnitude, *m* is the apparent magnitude, and *h* is the elevation above the horizon.

Fireball study can help provide valuable information on the NEO population, especially the small asteroids and their compositions.

The Hera mission is the most popular one and one that was featured in the 2021 asteroid day. Named after the Greek goddess of marriage, Hera will be the first satellite to rendezvous with Didymos pair (an asteroid with a satellite) [ref]. Didymain has a diameter of 780 m and is orbited by Didymoon with 160m.

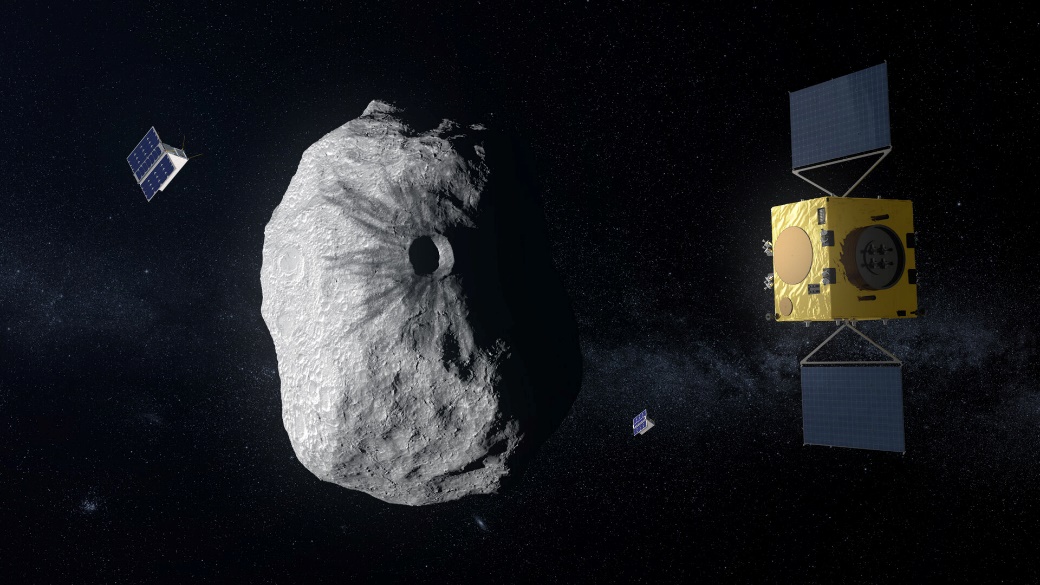


Figure ‑Hera in orbit scanning and analysing the impact from DART. [ref]

Hera is due to launch in October 2024. Hera contributes to the Asteroid Impact Deflection Assessment (AIDA) cooperation as the first planetary defence mission. This mission is backed up by NASA developing the Double asteroid Redirection test (DART) mission who will first create a kinetic impact on Didymoon in 2022. The impact on the moon would help us understand how the asteroid can be deflected. Hera follows with a post-impact on Didymain. Hera would also autonomously navigate around the asteroid, scanning and collecting data of the asteroid and its impact on its moon. It will aid in understanding the structure and material composition that will be useful for future missions. This mission is a grand-scale project that will be repeatable for future planetary defence missions. [ref]

## Conclusion

The formation of our solar system has its formation weighing heavily on asteroids and comets, linking to the occurrence of organic matter and water on Earth. And water is a key element for sustaining life; asteroids did aid in that development. Therefore, space exploration will be possible with mining these resources from the asteroid and reducing costs on mission launch and mass. Asteroid mining is the next step to space exploration. Lots of research is put into it, with companies like Deep Space industries pioneering the race.

The study of asteroids gives us insights into the evolution and physical features of our solar system. More study is put on observation to track and identify new asteroids and potential hazardous ones. Each year on June 30, astronomers and space agencies celebrate asteroid day and gives the public the awareness of asteroids and share in on discoveries. One of the most invested research is the mitigation of PHAs, where agencies devise means of deviating an asteroid from its determined course to deflect and avoid a collision event with Earth. Other studies include harvesting asteroid material and performing return missions so the materials can be analysed on Earth. There is a lot to discover. Each step, each discovery, each observation, and each asteroid mission brings us closer to better understanding asteroids.