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Water in asteroids

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“Ensimmäinen nainen kuussa.”

—ellaella

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Asteroids have been studied for over 200 years and most asteroids have been found in the last two decades. Before 1801, all the celestial objects known to man were fairly large objects visible using optical telescopes: stars, planets and comets. The first asteroid Ceres was found in 1801 and three more were found in the following six years. Asteroids are explored due to various reasons such as threats to the Earth and gaining knowledge on the history of the Solar System. Asteroids are believed to be remnants of planetesimals that were the building blocks of planets and other small bodies. According to current theories, asteroids could be the main source of water on the Earth. Water is the precondition for life on the Earth as we know it, but the origin of the Earth’s water is still unknown.

Asteroids are studied by ground-based observations, space-based missions, and by studying meteorites. Ground-based observations focus on an asteroid’s reflectance spectrum. Different minerals have their own distinct spectral features that can be observed in visible and mid-IR regions. Space weathering alters the surface of asteroids, thus altering the observed spectrum. This can be a significant problem in ground-based observations and rendezvous missions. Space-based missions can be divided into rendezvous and sample-return missions. Rendezvous missions can only observe the surface of the asteroid, which can be strongly altered by space weathering and other events. Sample-return missions collect samples from the surface of the asteroid and deliver the collected samples to the Earth for closer analysis, which is done by spectral analysis of the sample. Meteorites are shattered pieces of asteroids that have travelled through the Earth’s atmosphere and hit the ground. During their journey to the Earth, these objects sustain changes in their composition which can change their original mineralogy.

Water can be found throughout the Universe and during the accretion of the planets, the Earth could have obtained large amounts of water ice that then would have melted during alteration processes. A great amount of this water can be found in the Earth’s mantle and core but the young Earth could have lost almost all the surface water. We know that almost 70 percent of the Earth’s surface is covered in water and it is possible that large amount of it could be from asteroids.

Avainsanat — Nyckelord — Keywords
Water, asteroids, astronomy

Säilytyspaikka — Förvaringsställe — Where deposited

Muita tietoja — övriga uppgifter — Additional information

Contents

1. Introduction

The first few asteroids were found in the 19th century, but most of the known asteroids have been found in the past two decades. Until the beginning of the nineteenth century, all celestial objects known to man were stars, planets, and comets. The new types of object, asteroids, did not have all the necessary qualifications to be any of them, so a new type of classification needed to be made.

Asteroids, also called minor planets, are rocky, icy, or metallic objects without an atmosphere. Asteroids in the Solar System orbit the Sun as planets do. Their orbits have higher inclinations and eccentricities than the planet's. Asteroids are found in different groups around the Solar System and most of them are located in between Mars and Jupiter in the Main Asteroid Belt.

Asteroids differ from planets due to their small sizes and varying shapes, although they have the same building blocks, planetesimals. Planetesimals are celestial bodies that existed in the very early Solar System. These objects collided and interacted with each other and formed the planets and other celestial bodies now present in our Solar System. Some of these planetesimals shattered through collisions. These fractured pieces exist in the Solar System as asteroids and other small bodies. The first asteroids were further on shattered into smaller pieces due to collisions, thus forming asteroid families.

The first asteroid Ceres was found in 1801. It was first thought to be a star or a planet because of its position between Mars and Jupiter, and because it was fairly big and bright. In the beginning of the 19th century, scientists thought that a planet was missing between the two planets.

Naming these new objects took time. The name chosen for asteroids came from a greek word aster, meaning a star-like. As many objects in the sky, asteroids can look a lot like stars from a far, because they reflect the light of the nearby star as planets and other small bodies do.

Observing asteroids is important due to the threat they pose on Earth and also because they are useful for learning about the history of the Solar System. Because asteroids are made of the same planetesimals that formed the planets, they share the same elemental composition. Many of them consist of water or other hydrated elements, and it is fairly possible that the Earth's water is from asteroid and meteor collisions.

Water is the precondition for life on the Earth. It acts as a solvent for a carbon-based life. Without water, life on the Earth would not be possible. Water covers 71 percent of our blue planet's surface. Even humans contain up to 60 percent of water. It is one of the key elements for forming life.

Since the Earth is located in the habitable zone of the Solar System, it is at the perfect distance from the Sun for liquid water to exist. The Earth is the only planet in the Solar System that has water in liquid form. However, all terrestrial planets show evidence of the existence of water.

The origin of the Earth's water is still an unknown question, and any of the theories have not been proven. There are a few theories for the origin of the Earth's water, but the leading hypothesis is that the water was brought to the Earth by asteroid collisions.

Water is not only found on the surface of the Earth. It can be found in the Earth's atmosphere, mantle, and core (Hanslmeier, 2010; O'Brien et al., 2018). Saline water, oceans, cover 96.5 percent of the Earth's known water supply, and the rest are fresh water supplies. Only a small fraction of the fresh water supply is in liquid form. The amount of water in the Earth's mantle, and core are not known for certain. The amount of water in the Earth's oceans, crust, and atmosphere have been estimated to around $2.4 \cdot 10^{-4} M_{\oplus}$, where

$M_\oplus = 5.97219 \cdot 10^{24}$kg is the mass of Earth (O'Brien et al., 2018). The estimation for the water in the Earth's mantle is between $0.8 - 8 \cdot 10^{-4} M_\oplus$ to even $2 \cdot 10^{-3} M_\oplus$ (O'Brien et al. (2018)). The difference between the estimations is quite large. It is the same with the estimation for the Earth's core. The Earth's core holds up around 60 percent of all The Earth's hydrogen, which is the key element in hydrous minerals and water (Wu et al. (2018)). The Earth's core could hold water up to 7.5 times the mass of the oceans due to the observed amount of hydrogen. Another approximation for the mass of water in the Earth's core is $\sim 3.2 \cdot 10^{-4} M_\oplus$ (Ohtani, 2021). Hydrogen oxidizes easily so when talking about the Earth's water supply, it is often measured as the amount of hydrogen reservoirs on the Earth.

Water on the Earth's surface and crust includes all the visible and accessible water. The oceans, lakes, rivers, ice, snow, ground water, swamps, and atmosphere are examples of the water on the surface or in the Earth's crust.

The question of my thesis is whether the Earth's water could be from asteroids? Also is it possible that all asteroids contain water or hydrated minerals or at least have at some point of their life? My thesis focuses on the origin of the Earth's water and the methods for observing hydrated minerals and water on asteroids.

Chapter 2 focuses on asteroids as objects. First I will start with the definition of an asteroid and how they differ from the other objects in the Solar System. In Section 2.2 I will focus on the on the evolution of the Solar System and how the asteroid's orbits changed during this time. Section 2.3 is focused on the properties of asteroids such as size, shape, composition, and differentiation during their lifetime. Lastly, in Section 2.4 I will focus on the classification of asteroids.

Chapter 3 focuses on water in asteroids but I will also explain how water reservoirs are distributed within Earth. I will focus deeper on the physical properties of certain asteroids and focus on the alteration done by water and hydrated molecules. I will explain the difference between water and hydrated molecules, different ways of observing both on asteroids, water and hydrated molecules already found on asteroids, and also focus on the question that can we be certain that not all asteroids contain water or hydrated molecules.

In chapter 4, I will discuss asteroid observation. I will go through the history of the observation, and the main ways to observe asteroids. I will go through ground-based observations, samples from meteorites, and previous and ongoing space missions. I will talk about each method's pros and cons, and discuss what to expect from the future research. I will explain how water or hydrated molecules can be observed using each of these methods and how we could get the best results doing so.

In chapter 5 I will combine all the previous chapters and give my own conclusion and answer the questions of my thesis.

2. Introduction to asteroids

In this chapter I will first go through the definitions for asteroids and other small bodies in the Solar System. I will explain what they are and how they differ from each other by their physical properties. In Section 2.2, I will go through the locations of asteroids in the Solar System and how the orbits changed during the history of the Solar System. In Section 2.3, I will move on to their properties such as size, shape, and composition and differentiation during their lifetime. Finally, in Section 2.4 I will discuss different ways of how asteroids are classified either by the groups they belong to, composition, observed spectra, or by studying and observing meteoroids and meteorites.

2.1 What are asteroids

Asteroids are rocky, icy or metallic celestial objects without an atmosphere. Asteroids are sometimes called minor planets due to the similarities in composition and orbits between the first discovered asteroids and planets. Asteroids are believed to be left overs from the formation of the Solar System about 4.6 billion years ago ((NASA, f)). The sizes and shapes of asteroids vary significantly from irregular to almost spherical and from a diameter of only 10 meters to even almost 1000 kilometers ((NASA, f)). Smaller objects than that are usually called meteoroids or even space dust ((NASA, f))

The biggest and first asteroid found is Ceres, which is now also classified as a dwarf planet like Pluto ((NASA, a)). The radius of Ceres is 476 kilometers and it is located in the Main Asteroid Belt.

To give an even clearer image on the sizes of asteroids, the approximated mass of all asteroids in the Solar System is less than the mass of the Earth's moon, which is $m_{Moon} = 7.348 \cdot 10^{22}$ kg ((NASA, g)). Most of the asteroids in the Solar System are located in the Main Asteroid Belt between Mars and Jupiter. More than 1,3 million asteroids have been found. When an object, asteroid, meteoroid or a comet approaches close to the Earth, with a perihelion distance of q<1.3 au, where au $= 1.496 \cdot 10^{11}$kg,it is called a near-Earth object (NEO) or a near-Earth asteroid (NEA). Au is the abbreviation for the astronomical unit. The small mass of all the asteroids found can be explained by their low densities and porosity due to collisions, small sizes, and by the orbital changes in the early history of the Solar System.

Asteroids differ from other celestial objects like comets and meteoroids due to their size and composition. Meteoroids are fragments of their parent asteroids, and their sizes range from dust particles to meter-scale asteroids. Comets are icy asteroid-like objects that are formed far away from the Sun. When they enter the Sun's proximity they start sublimating and expelling gas and dust, which forms their tail. The sizes of comets can vary from a couple of kilometers to less than a hundred kilometers (NASA, b). Most comets are located a great distance from the Sun in the Kuiper belt and in the Oort cloud (NASA, b).

2.2 Asteroids and their orbits in the Solar System

When stars are born, a protoplanetary disk forms around them. This disk is full of dense gas, ice, and dust particles. These small particles interact with each other and accrete into planetesimals. These planetesimals then keep on colliding and form the protoplanets, which in time form the planets. The left over planetesimals, protoplanets, that never grow large enough to form a planet, are shattered to smaller pieces and left in the Solar System as asteroids, and other small bodies like comets.

The Solar System has gone through various changes since the formation of our planets and small bodies. The first big change according to the Grand-tack theory, that shaped the main belt and moved some objects outside and inside of it, was the migration of the giant planets. According to the Grand-tack theory, Jupiter first moved closer to the Sun through the protoplanetary disc, scattering some of the inner disc planetesimals out of the disc, and then outwards after gaining mass, due to the interaction and drifting into orbital resonance with the growing Saturn, moving some of the outer disc planetesimals into the inner disc (Michel et al., 2015b; Alexander, 2017; Rubie et al., 2015).

According to the Nice model (Tsiganis et al., 2005), after around 500 million years and after the protoplanetary disc was removed, the giant planets migrated again (Michel et al., 2015b). There was a large disc of planetesimals located in the outer part of the Solar System (Fig 2.1). These planetesimals interacted with the giant planets pushing Neptune, Uranus and Saturn outwards as the planetesimals moved inwards. As the planetesimals moved inwards due to the interaction with the giant planets, they pushed the planets out of their way into a further orbit in relation to the Sun. Everytime the planetesimals interacted with a planet, some of them drifted away from the disc. After interacting with all the giant planets, enough planetesimals had been pushed out of the disc for the force of the planetesimals to be too insignificant to push Jupiter outward. This caused Jupiter to move inward towards the Sun, and pushed out many of the remaining planetesimals (Tsiganis et al., 2005).

Lastly the Nice model could also explain the origin of the Late Heavy Bombardment, which could explain the cratering on the Moon, Vesta, and other small bodies, but also the size and collisional history of other asteroids. Late Heavy Bombardment is a theory where the movement of the giant planets disturbed the orbital balance of the planetesimals which then drifted through the Solar System crashing into anything that was on its path.

All of these changes could further on explain the depletion of mass in the asteroid belt, the missing mantle problem, and the mixed asteroid families and groups. It could also explain the differences between the inner- and outer-belt asteroids and the eccentricities

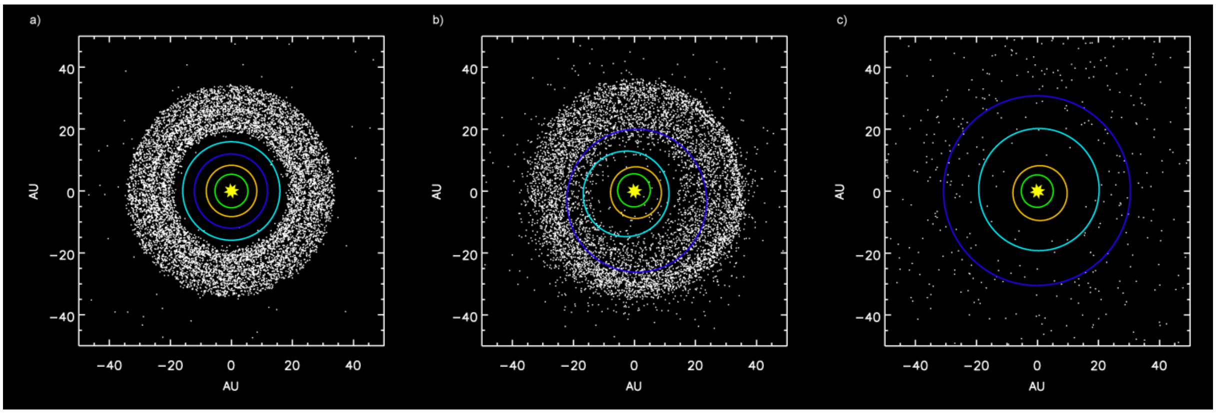

Figure 2.1: The changes in the giant planetary orbits and planetesimals according to the Nice model. The dark blue orbit is Neptune, light blue Uranus, orange Saturn and green Jupiter. en:User:AstroMark, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

and inclinations of the orbits of planets and small bodies. Nesvorný (2018); Tsiganis et al. (2005); Michel et al. (2015b) The mass of the Main Asteroid Belt is lower than expected, and the depletion of mass likely happened in the early history of our Solar System, as the giant planets migrated (Clement et al., 2019). The missing mantle problem refers to the lack of olivine-dominated material in asteroids and meteorite samples, which is the dominating material of the mantles of rocky planets (Rider-Stokes et al., 2025). The mixed asteroid families and groups can be explained by the migration of the planetesimals and their interaction with the giant planets. A great amount of the planetesimals were moved into new orbits, mixing the families, and many of them were shattered outside of the Solar System. These changes factored in to the eccentricities and inclinations of the planets and small-body objects orbits, leaving the planets and small-body objects, like asteroids, to orbit the Sun in elliptical orbits with varying eccentricities and inclinations.

Now most of the asteroids in the Solar System orbit the Sun between Mars and Jupiter in the Main Asteroid Belt (Elkins-Tanton, 2010). Main Asteroid Belt contains more than one million asteroids. The mass of the Main Asteroid Belt is less than the mass of the Earth's moon $M_{Moon} = 7.3 \cdot 10^{22}$kg. The estimation for the mass of the Main Asteroid Belt is $M \sim 12 \cdot 10^{-10} M_{\odot}$ (Pitjeva and Pitjev, 2018). The Main Asteroid Belt starts from around

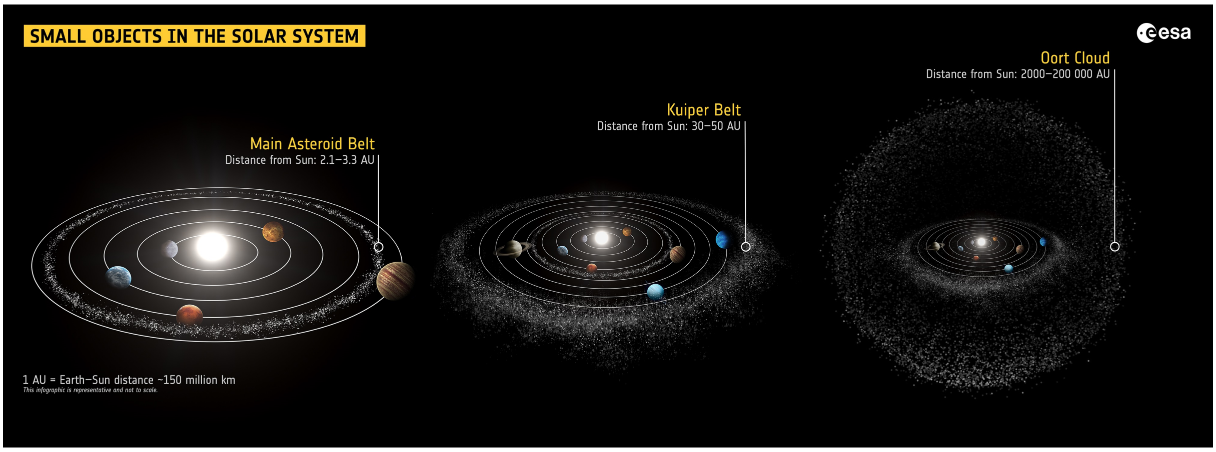

Figure 2.2: Distance between small bodies locations in the Solar System(not on scale). ESA (acknowledgement: work performed by ATG under contract to ESA

the distance of 1.8 au and continues to 3.5 au in relation to the Sun, with the densest part around 4:1 to 2:1 orbital resonances with Jupiter (Fig. 2.4) (Pitjeva and Pitjev, 2018). For reference Mars' orbit is around 1.5 au from the Sun and Jupiter's around 5.2 au.

Even though most of the asteroids are located in the Main Asteroid Belt, there are also many asteroids outside the main belt's limits. For example Hildas are asteroids that are located before Jupiter's orbit but behind the Main Asteroid Belt and Trojans are asteroids that share their orbit with Jupiter.

Hildas are located just outside of Jupiter's orbit at a distance of around 4 au from the Sun (Fig. 2.3). There are two groups of asteroids that are located in Jupiter's orbits gravitationally stable Lagrangian points. They are the Jupiter Trojans (Fig. 2.3). The Nice model explains the origin of these asteroids and how they got stuck within the Jupiters' orbit when the giant planets migrated due to the interaction with the planetesimals.

Kuiper belt is located in the outer Solar System, after Neptune, at distance of ~ 40 au to ~ 50 au, between the orbital resonances of 3:2 to 2:1 with Neptune (Fig. 2.2). Some small bodies have been scattered outside the 50 au limit and they are called scattered disc objects. These objects have high eccentricities and inclinations and have orbits that are as far as 90 au (Pitjeva and Pitjev, 2018). Kuiper belt is mostly full of comets and other

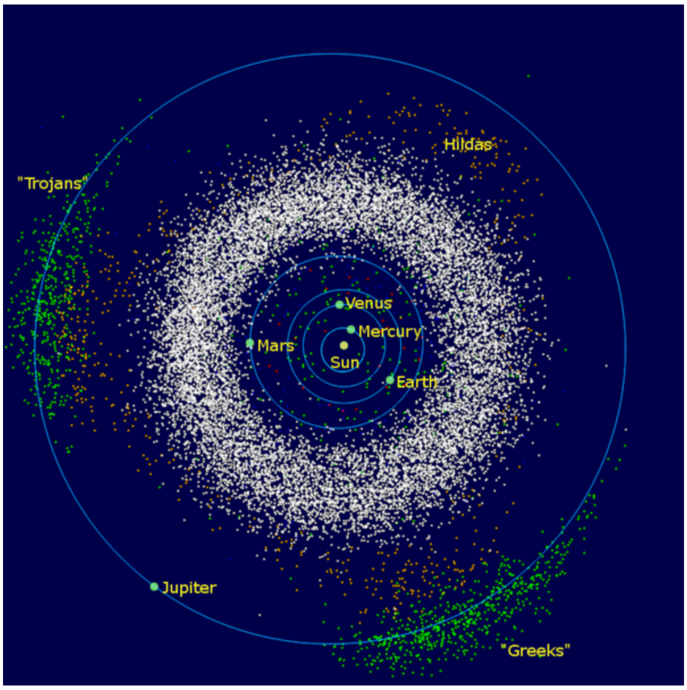

Figure 2.3: An image of the inner Solar System. In the picture you can see the Main Asteroid Belt between Mars and Jupiter and the Trojan asteroids in the Jupiters orbit. https://upload.wikimedia.org/wikipedia/commons/f/f3/InnerSolarSystem-en.png

small bodies. Dwarf planet Pluto is located in the Kuiper belt. The estimated mass of the Kuiper Belt is $M_K \sim 2 \cdot 10^{-2} M_{\otimes}$ (Pitjeva and Pitjev, 2018). Objects that are located on orbits beyond the planet Neptune are called trans-Neptunian objects. They are located at the distance of 30 auto 48 au from the Sun.

As mentioned before, the orbits of planets and the Solar System belts are in orbital resonance with each other. This is due to the gravitational forces with the celestial bodies and keeps the orbits somewhat stable. In Fig, 2.4, you can see the orbital resonances within the asteroid populations. Asteroids can be in stable orbits in the Lagrangian points of an object. The stability is not a certainty and changes in the resonance and gravitational forces can unbalance the whole system. This was seen in the early Solar System as planetesimal migration where planetesimals interacted with the giant planets and changed the orbits of planets and ejected a lot of planetesimals outside the Solar System limits.

Asteroids exist also outside the Solar System. Asteroids outside our own the Solar

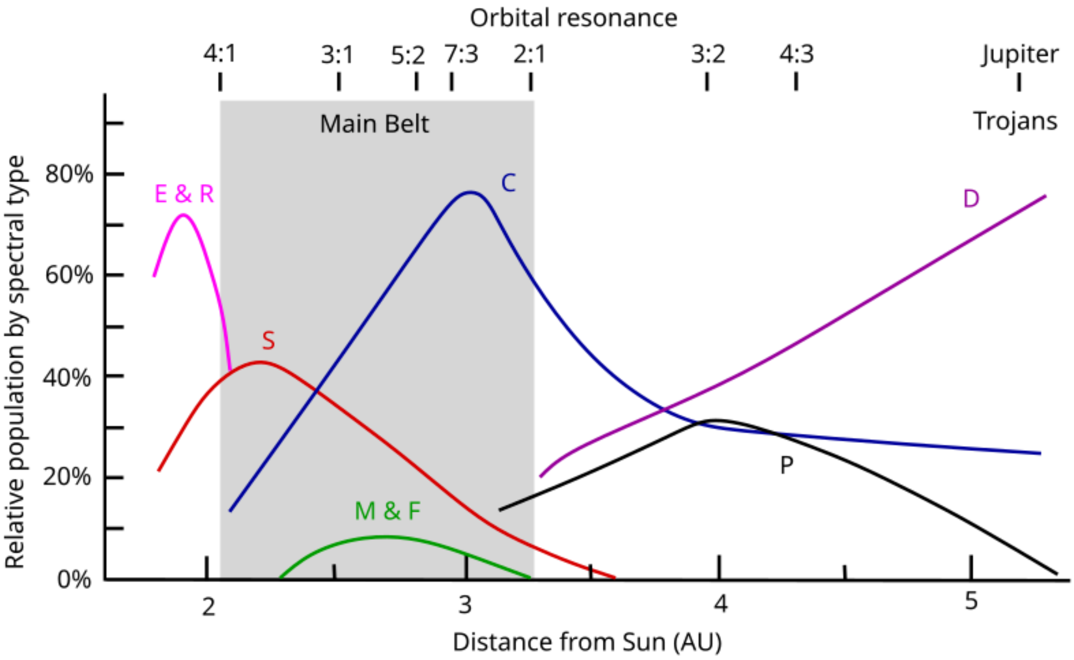

Figure 2.4: Asteroid populations with orbital distance and resonance and observed spectral type according to Tholen taxonomy. Praemonitus, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

System's limits are called exoasteroids, with exo meaning extrasolar. These objects are similar to our own asteroids and are parts of disintegrated exoplanets and planetesimal from the star-planet systems.

2.3 Properties of asteroids

Asteroids have sustained a lot of changes during their lifetime due to differentiation, collisional history and space weathering. They are composed of different types of rocks, metals, ice, and even organic matter. They vary in shapes and sizes and by their mineralogical and chemical compositions. The sizes of asteroids vary from the size of a dwarf planet (Ceres) to objects with diameter of only a meter to ten meters (Fig 2.5). Some asteroids are big enough to have an almost spherical shape. If an object is massive enough, its gravitational forces will force it into a sphere. Because most asteroids are fairly small, their shapes have stayed irregular. Collisions have also altered the shapes of asteroids.

The mass and density of an asteroid varies with the asteroid's mineralogy, porosity, composition, and evolutionary history. Asteroid density estimations are somewhat difficult to construct because we can only see the composition of the surface and the craters. If the mass and volume of the asteroid are known, a rough estimate can be calculated for the density from the formula $\rho = \frac{m}{V}$, where m is the mass and V is the volume of the object. The estimated density for asteroids in the main belt is $\rho = 2.2 \mathrm{g/cm}^{-3}$ (Pitjeva and Pitjev, 2018). It is clear that asteroids with metallic composition have much higher density than stony silicate asteroids with a grainy structure, so the density estimate is a best fit for the silicaceous asteroids. The mass estimations for asteroids are easier to measure than the density. The masses can be derived by gravity-based methods.

Looking at an asteroid's surface, you can see a lot of craters from past collisions. The amount of craters depend on the history of the object. The older the asteroid is, the more craters it likely has. The age of an asteroid is often predicted by the observed density of existing craters and their size. Different forces shape the object's surface and might change the properties of the craters. The collisional and dynamical evolution is an important part of the asteroid's evolution and collisions have shaped the asteroid's mineralogy and structure during its lifetime. The observed craters do not always have clear edges and a round shape because of space weathering decay and other modifying effects on the asteroid's surface. The older the crater is, the more it has been modified during the asteroid's life, and the harder it is to identify as one (Marchi et al., 2015).

The depths of the craters vary depending on the force of the impact and by the size of the asteroid. By observing the craters, we can get a lot of information about the physical and mineralogical properties of the asteroid, and also the asteroid that it collided with. The crater opens up the asteroid's surface and lets us see below it. This is a great way to explore the asteroid's inner mineralogy (Marchi et al., 2015).

Collisions have also shattered bigger asteroids into smaller ones. These pieces from the same parent body form an asteroid family. That is why asteroid families have the same observable properties and classifications.

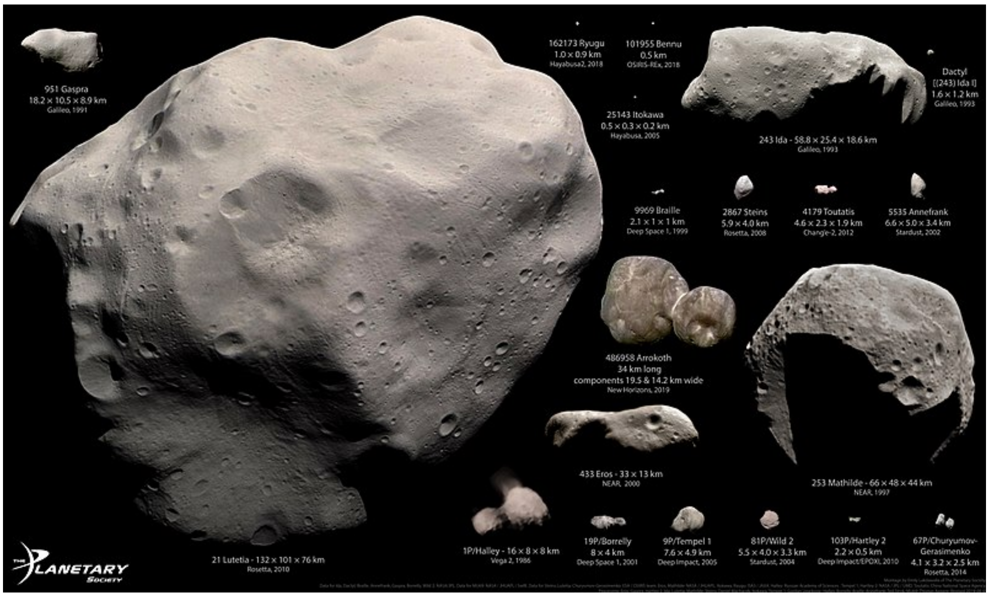

Figure 2.5: The varying shapes and sizes of asteroids can be seen on these asteroid's visited by sppacecrafts. Montage by Emily Lakdawalla for The Planetary Society. Data from NASA / JPL / JHUAPL / SwRI / UMD / JAXA / ESA / OSIRIS team / Russian Academy of Sciences / China National Space Agency. Processed by Emily Lakdawalla, Daniel Machacek, Ted Stryk, Gordan Ugarkovic / Thomas Appéré, https://www.planetary.org/space-images/asteroids-and-comets-visited-2018

Asteroids do not have an atmosphere to protect them from space weathering. The lack of an atmosphere makes them strongly affected by space weathering which alters the surface of the asteroids. Changes on the asteroid's surface, on the other hand, affects the optical properties of that asteroid and can thus change the observed spectrum, and make meteorite-asteroid parent body identifications difficult. Space weathering includes, irradiation by ions from solar winds and flares, micrometeorite bombardment, and cosmic rays (Brunetto et al., 2015). Space weathering on the Moon has darkened the observed spectrum in the visible and near-infrared wavelengths and also reddened the spectrum, making the observed spectrum more sloped (Brunetto et al., 2015). The same happens with asteroids. The distance from the Sun affects the intensity of the space weathering effects. Space weathering can also create hydrated minerals (OH) and water on asteroids when solar wind protons interact with the asteroid's surface minerals.

The first bodies that were accreted from the planetesimals contained short-lived radio nuclides of ^{26}Al, which is a radioactive isotope of Aluminium. ^{26}Al drove the internal heating and differentiation in the planetesimals and other celestial bodies. This heating changed the mineral composition of the objects by melting them from the inside (Alexander et al., 2018). Alteration via heating and melting during the object's evolution has affected its physical properties. Some asteroids show evidence of internal differentiation that happened on their parent body in the early time of their life. Bodies that were not large enough did not experience heating and/or melting because they cooled down too fast for the differentiation to happen. Vesta is a great example of an asteroid that shows evidence of differentiation because of its inner composure. Vesta formed at the same time as the Earth and can be considered as a planetesimal or a protoplanet that did not accrete large enough to become a planet (Johansen et al., 2023a). Vesta sustained similar differentiation as the Earth due to ^{26}Al decay, collisions and water differentiation (NASA, h). Vesta was the target of the Dawn mission (NASA, h).

2.4 Classification of asteroids

There are multiple ways to classify asteroids. It can be done by dividing them into asteroid families, or by their observed spectra. Asteroids are thought to bear resemblance to chondritic meteorites and thus some meteorite samples can be connected to asteroid families or a single parent bodies. Meteorites can be roughly divided into chondrites and achondrites, and asteroids can be connected to these meteorite classes. Most of the known asteroids are thought to be ordinary chondrites.

Ordinary chondrites are silicate-rich bodies that have not experienced any significant melting or differentiation due to their small size. These asteroids contain or have contained chondrules that are round grains which contain crystal and glass (Elkins-Tanton, 2010). Chondrules can be seen on the inside structures of some meteorites. Chondrites are made of a primitive material, which means that their chemical composition, if hydrogen and helium is not taken into account, is close to that of the Sun. These bodies were most likely formed in the early Solar System because its' temperature needed to be first very high and then cool down rapidly to form chondrulas (Elkins-Tanton, 2010). Chondrites often contain minerals such as olivine and pyroxene. They can also contain hydrated minerals or even water ice (Elkins-Tanton, 2010). Chondrites are further divided into groups by their compositions. These groups are ordinary chondrites, carbonaceous chondrites, and enstatite chondrites.

Achondrites are bodies that have sustained melting and differentiation which has changed its chemical composition and mineralogy. Achondrites do not have chondrules and contain metals. Like chondrites, achondrites are divided into groups which are primitive chondrites, which are closest to the composition of chondrites, asteroidal chondrites, and martian and lunar meteorites.

Figure 2.6: An image of chondrules inside a meteorite. You can notice the round shapes inside the stone which are chondrules.

https://www.flickr.com/photos/47445767@N05/50887737568/

Asteroid families are asteroids that have similar orbits and most likely come from the same parent asteroid that has shattered due to a collision or collisions (Masiero et al., 2015). These asteroids have similar properties, such as albedo and observed spectra. By observing these asteroids, you can tell a lot about the parent body. If and when the parent body collided violently with another object, some of the remnants might have traveled quite far and thus be far away from the rest of the family but still belong to it. The changes in the dynamics of the early Solar System has moved around and mixed the asteroid families. This explains the often mixed groups of asteroids, and for example the diversity of the Jupiter Trojans.

Asteroids classified by their observed spectra are divided into three main complexes (DeMeo et al., 2015). The three main complexes according to Tholen and later on Bus-DeMeo taxonomy are C-complex, S-complex and X-complex. Also, a fourth group is added for the asteroids that do not fit any of the previous groups. This group is called the end members (DeMeo et al., 2015). Each of these complexes are then further divided into different classes or types according to their spectra. There are 24 of these classes in the Bus-DeMeo taxonomy.

There are clear differences in the observed spectra for each of the classes (Fig. 2.7). The shape of the observed spectra depends on the mineralogy of the asteroid. Different minerals reflect light in their characteristic ways and have their own spectral features. Thus the asteroids mineralogy determine this classification. All minerals and their mixtures have their own spectral features and these features can give clues on the mineral composition of the object.

S-complex asteroids are silicate-rich objects that were formed in the inner Solar System. They are rich in pyroxene and olivine which is shown in their spectra. S-complex asteroids are linked to ordinary chondrite meteorites. They are quite dense and have stony and grainy mineralogy. S-type objects are common in the asteroid belt and have a moderate albedo. Some of the S-complex asteroids can be fairly bright.

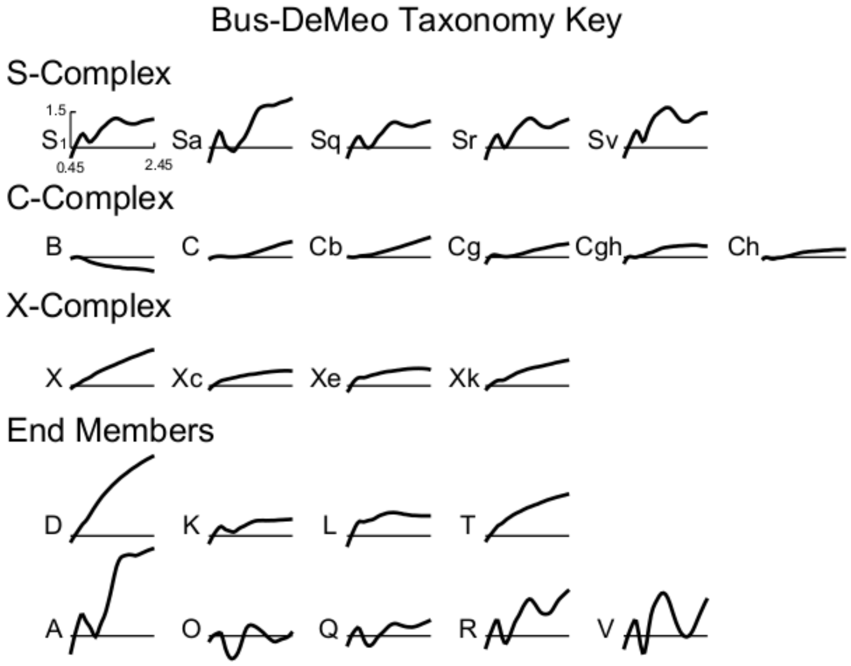

Figure 2.7: Spectral classes in the Bus-DeMeo taxonomy DeMeo et al. (2009)

C-complex asteroids are dark and carbonaceous and therefore have a low albedo. Their spectra is similar with carbonaceous chondrite-meteorites (Rivkin et al., 2015). C-complex asteroid are fairly interesting because many of them contain hydrated minerals (Rivkin et al., 2015). Most of the known asteroids in the main belt are asteroids belonging to the C-complex.

Asteroids with X-complex are further broken down in to three groupsvary depending on the objects albedo (Rivkin et al., 2015). This group has the highest variety of albedos and consists of the brightest and darkest of asteroids. The X-complex asteroids are metallic objects with fairly featurles spectra. The X-complex comprises the E, M, and P asteroid classes (Fornasier et al., 2011).

There are also asteroids that do not fit into any of the main complexes and have spectra with more visible features. These are the end members. The spectra of the end members show more distinguish features than in the previous groups (Fig. 2.7).

S-complex asteroids have a spectra with moderate slopes, the spectra of C-complex asteroids is fairly flat and the spectra of X-complex asteroids changes depending on the observed albedo and composition. The end member asteroids have spectra that do not fit any of the previous complexes and have more distinct features. (Fig. 2.7)

Asteroids can also be classified into taxonomy groups by their physical properties and mineral composition. These groups are C-, M- and S-groups. The letters come from the words carbonaceous, metallic, and silicaceous, which describe the observed mineral composition of the asteroids. Silicaceous group can also be called the stony asteroids. These groups are also classified by the observed asteroid's spectrum, as in the Tholen and Bus-DeMeo taxonomy.

C-type asteroids are the most common asteroids in the main belt. They are connected with carbonaceous chondrite meteorites. They have low albedos and consist of carbon, silicates, and hydrated minerals. S-type asteroids are rocky asteroids that have been connected to stony meteorites. They are the second common asteroid type and have a moderate albedos. S-type asteroids are fairly dense due to their silicate mineralogy. M-type asteroids are metallic asteroids with higher albedos and densities. These asteroid are connected with iron meteorites.

Meteorites are fragments of disintegrated asteroids, so parent asteroids can be connected to some meteorite classes. The challenge with this is that the parent asteroid has been formed in a different time and most likely different region of the Solar System and has thus sustained alteration due to space weather, collisions, heating and melting. It is sometimes hard to link the found meteorite to the right parent body. While traveling to the Earth, meteorites sustain changes during their trip due to their high speed and interaction with the Earth's atmosphere. Most meteorites fraction or even burn due to the force of the atmosphere and later on the impact to the Earth's surface. Some meteorites can sometimes be hard to distinguish from the Earth rocks due to their similar appearance and composition and thus not all meteorites are found.

From the main belt asteroids, C-type and S-type asteroids have been the most interesting for observing water and hydrated minerals due to their mineral structure and porosity. Same goes with asteroids that are located further away from the Sun's proximity. They are interesting due to the distance from the Sun's effects. The focus should also be on other asteroid classes as well because water has been observed also on M-type asteroids.

3. Hydration in asteroids

In this chapter, I will explain the definition of hydrated minerals and where they are found in the Solar System. I will go through different types of minerals that contain water or hydrated minerals, and discuss how hydrated minerals or water affect the composition of the object. I will go through different ways of determining if the object has had, or has water or hydrated minerals. I will also explain, if we can exclude, that all asteroids could contain water, or that they have at some point of their life. I will also go through the locations of water reservoirs on the Earth. In chapter 4 I will explain different methods for observing water on asteroids and other small bodies.

3.1 What are hydrated minerals

Water is composed of molecules with one oxygen and two hydrogen atoms. Hydrated minerals are minerals that contain water H_2O or molecules with both hydrogen and oxygen atoms (OH). These are called hydroxyl bearing minerals (Rivkin et al., 2002). Helium (He), hydrogen (H) and oxygen (O) are the most abundant elements in the Solar System, therefore it is not a surprise that minerals containing water H_2O or (OH) compounds are quite common as well (Rivkin et al., 2002). Water in different forms can be found throughout the Solar System on planets, asteroids, comets, and meteoroids.

Water can be bound to minerals in different forms. As we know, temperature affects the state of water. It is either in solid, liquid, or gas form. The Earth is the only planet with water in liquid form. When the first Solar System objects formed, they contained water ice, which then melted in some objects causing aqueous alteration and possibly stayed in the ice form in some objects.

Hydrated minerals can be divided into silicates and non-silicates. Silicates are rock-forming minerals that are composed of silicon and hydrogen atoms. Non-silicates on the other hand are minerals that are mixtures of carbonates (salts), oxides and hydroxides. In other words, they are minerals that do not contain silicon. Metals such as iron and copper belong to non-silicates.

When silicates interact with water, the water can alter the mineralogy by hydrating the existing silicates. The melting of water ice in the forming and heating protoplanets, caused aqueous alteration, altering the body's original mineralogy. These aqueously altered silicate atoms within those objects formed for example phyllosilicates. Phyllosilicates are silicate minerals that are hydrated. They are also called clay or sheet minerals due to their structure. Phyllosilicates are common in the main belt asteroids and meteorites that are disintegrated from these asteroids, but also on the Earth. Phyllosilicates are divided into different groups by the number of hydrogen-oxygen (OH) groups between the silicon-dioxide (SiO_2) layers (Rivkin et al., 2002). The strength between the different silicate layers depend on these shared atoms. If the layers share an oxygen atom, they are held together more tightly.

Hydrated non-silicates are non-silicates that have been altered by water and thus have oxygen and hydrogen atoms in their chemical composition. Brucite ($Mg(OH)_2$), goethite ($\alpha - FeO(OH)$), hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) and sulfide tochilinite are examples of non-silicate hydrated minerals. All of them contain either H_2O or OH. Hydroxysulfides are minerals mixed with sulfides and hydroxides and they belong to the non-silicate group.

Asteroids rarely contain water as H_2O form, but due to aqueous alteration, the water has altered the original mineralogy of the object, forming for example phyllosilicates such as clay, where the water is stored as OH form. The oxygen in OH often further reacts with metals like Fe and this oxidation process might lose some hydrogen (Alexander et al., 2018).

Anhydrous minerals do not contain hydrogen or oxygen atoms but they can be hydrated in the presence of water. These minerals can still have traces of water and aqueous alteration. Depending on the heating and differentiation processes some objects have sustained hydration and then dehydration processes.

Observing hydrated minerals can help to identify asteroid parent bodies for meteorites, and give clues about the heat sources of planetesimal differentiation, the amount of mixing within the planetesimals and also the water distribution in the Solar System. Hydrated minerals have absorption features in the visible and near-infrared bands, which helps to identify objects that contain hydrated minerals or water.

3.2 Water in asteroids

During the formation of the Solar System, icy planetesimals were likely formed inside the snow line (Drążkowska and Alibert, 2017). The snow line or the water frost line is the minimum distance from the Sun, where water ice is stable enough to form planetesimals (Rivkin et al., 2015). In the Solar System the snow line is located within the Main Asteroid Belt, but it has moved during the Solar System's evolution. When planetesimals formed and accreted within the snow line, icy planetesimal accreted more easily than silicate planetesimals due to ice being stickier than stone (Drążkowska and Alibert, 2017). These planetesimal then formed bigger objects like protoplanets and planets, which consisted of water ice and stony and/or metallic minerals. The accreting bodies also accreted other volatiles during this time. Due to ^{26}Al decay and collisions, these bodies were heated from the inside and this melted the water ice, which then altered the mineralogical composition (Alexander et al., 2018). This is called aqueous alteration.

More precisely, aqueous alteration happens, when the minerals inside the object react with a hydrous material, changing the original mineralogical composition. Magnetite, carbonates, phyllosilicates and Fe-sulfides are minerals that are formed in an aqueous alteration, so observing and studying these minerals in an asteroid or meteorite body can give some clues on the alteration processes in the parent body (Sridhar et al., 2021). Aqueous alteration is mainly found in chondrite asteroids and meteorites. Melting of the water ice is necessary for the aqueous alteration to happen. Some objects did not have enough ^{26}Al to heat the body or the collisions did not bring enough energy to heat and/or melt it internally. Due to this, the aqueous alteration is not as prominent in some asteroids as in others. If the temperatures got high enough, all the water could have been lost from the body and thus they would seem anhydrous. Bodies accreted earlier and closer to the solar nebula sustained intensive heating that could have left them dry and volatile poor.

Aqueous alteration on asteroids depend highly on their location in the Solar System. Asteroid parent bodies closer to the Sun in the inner and mid asteroid belt have sustained more heating and thus aqueous alteration during their lifetime. Different types of asteroids have different types of mineralogical structures and these minerals and mineral compounds react to hydration in their characteristic ways. For example iron oxidizes easily, breaking the chemical structure of water leaving hydrogen or deuterium behind. Observing the deuterium-to-hydrogen ratio can give some clues about the origin of the water in an object.

Deuterium-to-hydrogen ratio is a tool for determining the origin and thermal history of water molecules (Ohtani, 2021). In the D/H ratio, H stands for hydrogen and D stands for deuterium, which is an isotope of hydrogen that has double the mass of the nucleus of one hydrogen atom (Lis et al., 2019). The D/H ratio is a good tool for answering the question of the origin of the Earth's water. The observed D/H ratio is compared to that of the Earth's oceans (standard mean ocean Water) ($D/H_{oceans} = 1.56 \cdot 10^{-4}$) which is the base value when comparing the D/H values in different celestial bodies ((Lis et al., 2019)). The D/H value is expressed as permil (‰), meaning the amount of deuterium per the amount of hydrogen. Because the value for the Earth's water is the base value, $\delta D = 0$.

The isotopic signatures of oxygen and the D/H ratio can give clues about the origin of water in different bodies. The Oxygen isotopic variation depends on the oxidation state of different minerals. When anhydrous minerals that tend to be ^{16}O-rich, interact with water and form hydrated minerals, the isotopic signature of the water and the minerals is passed on to the aqueously altered minerals (Alexander et al., 2018). The D/H ratio also depends on the alteration processes the body has sustained, and the D/H ratio of different bodies can be compared to each other.

Water and hydrated minerals have strong absorption features, especially in the visible and infrared band; thus, they are a good way to determine the compositions of low-albedo asteroids which otherwise do not have any strong noticeable features. Water and hydrated minerals are also a good tool, when determining the density of asteroids. Usually the lower the asteroids density is, more aqueous alteration it has sustained. Most of the porous and silicaceous asteroids like C-type asteroids, contain hydrated minerals.

Asteroids are all fragments of a larger parent bodies of planetesimals, that were disrupted due to a large-scale collisions early in the Solar System history, and during the giant planet migration. These fragments of the parent bodies that formed the asteroids further on disrupted and formed the asteroid families. The aqueous alteration that took place on the larger parent body can still be seen on the asteroids. The existence of hydrated minerals like phyllosilicates, organic compounds and the lack of anhydrous silicates are all evidence of the aqueous alteration (Lauretta et al., 2024).

S-type asteroids dominate the inner Main Asteroid Belt (Raymond and Izidoro, 2017). Most asteroids in the outer belt are on the other hand C-type asteroids, but other classes are also present. S-type asteroids are relatively dry with a water mass of only less than 0.1 percent, C-type asteroids have a water mass of 5-20 percent. Water has also been discovered on other asteroid types, like on X-complex asteroid. Most evidence on aqueous alteration is found on C-type asteroids especially ones that are connected to carbonaceous chondrites. These asteroids are composed of phyllosilicates and other hydrated minerals.

If the heating processes were not prominent enough to melt the water ice, aqueous alteration did not take place in the body. On the other hand if the temperatures got too high, the water was likely lost from the body (Alexander et al., 2018). The formation time of an asteroid can affect the level of aqueous alteration and hydration on asteroids. The asteroid bodies that formed earlier, could have sustained more heating than bodies accreted later on. Bodies formed in the inner disc when the solar nebula was still present were likely dry due to the high temperatures. After the dissipation of the solar nebula and due to the movements of the giant planets, hydrous planetesimals that were formed beyond the snowline, travelled inwards towards the Sun.

The accretion timing of an object can be predicted from the amount of water and other volatiles detected. On the other hand, the amount of aqueous alteration and the elemental and mineralogical composition can give clues on the topic. Asteroids that formed less than two million years after the birth of the Solar System lost most of their volatiles due to intensive heating during the early stages of their life. S-type silicaceous asteroids belong to this group. Hydrated C-type asteroids were likely accreted around $\sim 3.5 - 4$ mega years after the birth of the Solar System. The temperatures were low enough for water to stay in the body and to drive aqueous alteration due to internal heating processes. Asteroids that accreted later than this did not have sufficient internal heating to melt the water ice and drive aqueous alteration in the body. Alexander et al. (2018)

The accreting asteroid's distance from the Sun affected the degree of aqueous alteration as well. As mentioned, asteroids that accreted inside the snowline accreted more water ice than the asteroids outside it. Asteroids closer to the Sun likely formed earlier and lost their volatiles due to the high inner temperatures. Asteroids farther from the Sun, around the mid-snowline accreted more water ice and sustained aqueous alteration. The snowline has moved during the evolution of the Solar System due to the movement of the planets, and also the dissipation of the gas disc, and falling temperature of the star.Alexander et al. (2018)

Because the planets migrated during their lifetime, they moved smaller bodies like asteroids to new orbits. Objects that formed outside the Main Asteroid Belt travelled inwards during the giant planet migration, and are now found in the main belt. Same way some of the asteroids might have moved outwards, and some of these objects could be captured by Jupiter. The bodies that were scattered to the inner Solar System could have brought more volatiles to the forming planets. Alexander et al. (2018)

It is possible that at first anhydrous bodies, that did not accrete water but contained organic compounds, were aqueously altered through the decomposition of organic matter in the body (Hirakawa et al., 2021). The decomposition processes needed the body to be heated for a long enough period and likely an orbit inside the snowline. This could be how S-type asteroids obtained their water.

Achondrites are thought to be fairly anhydrous but they can contain traces of water. They could have obtained their possibly existing water reservoirs from collisions with hydrous bodies or they could have accreted water ice from the solar nebula.

One possible way to obtain water on asteroids surface is space weathering. Space weathering can produce water on the surface of asteroids and other airless objects. The solar wind protons bombard the surfaces of asteroids, affecting the chemical bonds in the surface minerals creating water and hydroxyls which can be detected while observing the asteroid.

3.3 Water reservoir on asteroids and the Earth

Asteroids were formed from planetesimals and the location of the growing planetesimal affected the composition and mineralogy of the body. Asteroids born beyond the snow line accreted more water ice due to the water ice being stable enough for it to be accreted into planetesimals.

The degree of the aqueous alteration depends on the internal heating of the body and the amount of energy it sustained from the collisions and the decay of short-lived isotopes of aluminium like ^{26}Al. If the body was not heated internally to the point where the water ice melted and interacted with the other minerals in the object, aqueous alteration did not happen. At the same time if the internal heating was intensive enough, all the volatiles could have been lost from the body.

Space weathering, especially solar wind protons effect on the surface of the asteroid, could potentially form water or hydrated minerals that could then be trapped into places where the Sun's warming effect do not melt it straight away. This could be a way for asteroids to have water that is visible with spectral observations, but does not ensure that the asteroid is aqueously altered.

Chondritic asteroids are known to contain water and their D/H ratio is similar with the Earth's oceans. Most of the asteroid studies regarding water and hydrated minerals are done on chondrite asteroids and meteorites. Hydration can still be found on other asteroid types, like silicaceous S-type asteroids. The amounts are just more insignificant. Collisions between water- or OH-rich asteroids and anhydrous asteroids, could transport water between objects. This could be then seen in the asteroid's spectrum.

It is possible that all asteroids have had volatiles at some point in their life but they could have been lost to space during their evolution.

The Earth's mantle is composed of various hydrous and anhydrous minerals that contain hydrogen and thus water (Fu et al., 2019). Anhydrous minerals such as olivines that do not contain hydrogen nominally in their chemical formula can still have water dissolved in them (Fu et al. (2019)). The present estimation for the water budget in the Earth's mantle is between $1.3 \sim 6.9$ times the ocean's mass (Ohtani, 2021). The amount varies between the different layers of the mantle. Most of the water is estimated to be located in the mantle transition zone. The upper mantle is believed to be relatively dry and the lower mantle could possibly contain around the same amount of water as found in the Earth's oceans (Ohtani, 2021).

The Earth's core is thought to be composed mainly of oxidized metals such as iron and nickel and lighter elements such as hydrogen and carbon. The core is divided into the inner and outer core. The outer core is about 2200 kilometers and the inner core only around 1220 kilometers. The outer core is composed of liquid metal and is extremely hot. The inner core on the other hand is dense, even though the high temperature would propose otherwise (Geographic). According to the current theory, the Earth's core contains most of the hydrogen reservoir found on the Earth (Ohtani, 2021).

The Earth's atmosphere is composed of mainly of nitrogen ($\sim$ 78 percent) and oxygen ($\sim$21 percent). The remaining 1 percent is composed of argon ($\sim$0.9 percent) and other gasses ($\sim$0.1 percent) (Wallace and Hobbs, 2006). Water vapor belongs into this remaining 0.1 percent. The amount of water vapor in the atmosphere depends on the day due to the water cycle. Therefore, the amount of water vapor in the atmosphere can vary between 0-5 percent at an altitude of 105 kilometers (Wallace and Hobbs, 2006). The amounts of different gasses also vary depending on the height and the atmospheric layer.

The D/H ratio of the Earth's mantle and core can not be measured directly, so when determining the bulk D/H ratio of the Earth's water, this must be taken into account.

4. Detecting water in asteroids

In this chapter I will go through the history of the asteroid observation and different ways of observing asteroids. In section 4.1 I will focus on the history of asteroids and asteroid observation. In this Section I will go through when and how the first asteroids were discovered and how these new types of objects got the name asteroid. In Section 4.2 I will focus on the various reasons of why asteroids are observed. Section 4.3 is divided in to three different parts where each part represents a different way of observing asteroids. In subsection 4.3.1 I will discuss observations done by using telescopes. In subsection 4.3.2 I will go through meteorite studies and what these meteorites tell about their parent asteroid. In the end of subsection 4.3.3, I will discuss observations via space missions. In Section 4.3 I will mainly focus on detecting hydrated materials using each observational method. In Section 4.3.3 I will also discuss previous and ongoing space missions. In Section 3.4 I will focus on the future of asteroid observation, and focus on future space missions. In the last Section of the chapter, I will summarize the chapter, and again go through all of the ways to detect hydration on asteroids.

4.1 History of observation

The first asteroid was found by accident in the beginning of nineteenth century on the 1st of January 1801, when an Italian catholic priest and astronomer Giuseppe Piazzi was revising an existing star catalog (Jedicke et al., 2015). He noticed a star that had not been observed earlier, and when trying to observe it the following night, he noticed that it had moved. He kept observing the star in the following nights, and noticed that it moved each night. Piazzi did not report his discovery straight away but waited for a half a year before finally announcing his find. Cunningham (2015); Elkins-Tanton (2010).

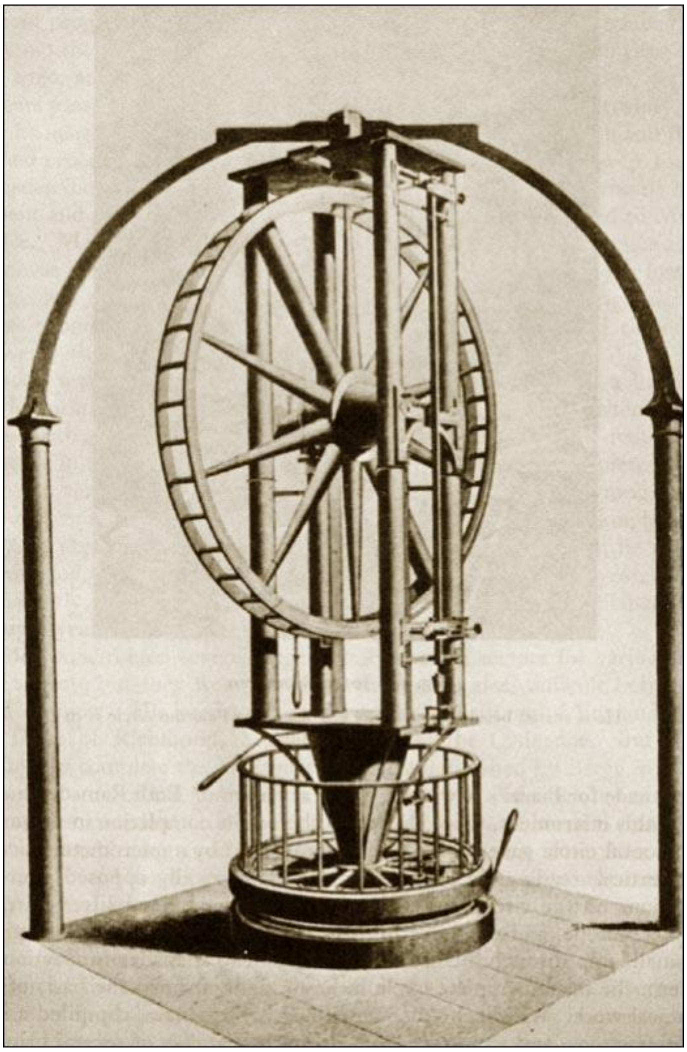

Figure 4.1: The Palermo Circle telescope which Giuseppe Piazzi used to discover the first found asteroid Ceres. https://w.wiki/BWWg

All the known celestial objects at this time were stars, planets, and comets. Ceres was first thought to be a star or a comet. But it could not be a star because it seemed to be moving on the night sky. On the other hand, it did not move like a comet nor had a tail. Because of its properties and its position between Mars and Jupiter it had to be a planet, which existence was predicted by Titius-Bode's law. It was believed at the time that the large distance between the planets of Mars and Jupiter would contain a planet (Michel et al., 2015a) (Bottke et al., 2002) (Cunningham, 2015). Titius-Bode's law predicted that the distance between planets in the Solar System should be twice the distance from the Sun compared to the distance of the previous planet (Bottke et al., 2002). This meant that the distance between Mars and Jupiter should fit a planet that had not been found. The formula for Titius-Bode's law was:

$a = \frac{n+4}{10}$, where a is the planets average distance from the Sun (au) and n = 0, 3, 6, 12...

The discovery of Ceres started a boom of asteroid study and observation. In just a bit over a year, another object was found. On 28th of March 1802 a German astronomer Wilhelm Olbers found the second asteroid Pallas (Bottke et al., 2002). Pallas had similar properties as Ceres but higher inclination and eccentricity. It was also smaller than Ceres but also seemed to have an orbit between Mars and Jupiter. Couple of years later, on the 1st of September in 1804 a German astronomer K. L. Harding discovered the third asteroid Juno (Bottke et al., 2002). Olbers found his second asteroid Vesta on the 29th of March in 1807, after six years of finding Ceres (Bottke et al., 2002). All of these objects had orbits between Mars and Jupiter which puzzled the community of astronomers.

William Herschel was the first to propose that these new objects could be new types of celestial bodies that had not been observed before (Bottke et al., 2002). He proposed a name for these new class of objects; Asteroids (Bottke et al., 2002). The first asteroids were big and rather bright so they were possible to find by naked eye, and by using optical telescopes. Most asteroids are relatively small so it is not a surprise that it took almost 40 years for a new asteroid to be discovered after the discoveries of Ceres, Pallas, Juno and Vesta (Bottke et al., 2002).

4.2 Reasons for asteroid observation

All the planets, dwarf planets, asteroids, natural satellites, meteoroids, and other small bodies were formed from planetesimals in the beginning of the birth of the Solar System.

To get a clearer picture of what happened in the early times of the Solar System, we need to study the planetesimals that have sustained the smallest changes and differentiation since those times (Johansen et al., 2015). Chondrite asteroids are the missing pieces for this puzzle. Since chondritic asteroids and fragments of those bodies have not sustained any large-scale changes in their composition and mineralogy, they are the perfect objects for getting the answers to our questions.

In addition, observing asteroids can give answers about the history of the Solar System and tell us about the very early conditions. Asteroids consist of hydrated molecules, water and organic matter and they could give us information about the beginning of life on the Earth. As any other planet or celestial object, the Earth has suffered endless asteroid and meteorite collisions in the early times of its formation even until now. The Moon is believed to have formed from one large collision between two protoplanets, that fragmented the Moon from the Earth. These collisions could have delivered water and organic molecules to the Earth, which then made the life on the Earth possible.

Asteroid and meteorite collisions pose a quite serious safety hazard on the Earth. An asteroid that has a diameter of only 1 km can cause a destruction that has global effects. The Solar System is full of asteroids with different orbits around the Sun. Asteroids interact with each other and other celestial objects as well. It has been important to map all the asteroids that could pose a threat on the Earth and many asteroid missions are focused on this. Almost 80 percent of all life on the Earth became extinct when an asteroid with 10-15 kilometer diameter hit the Earth around 66 million years ago.

Lastly, we live on a planet which has limited amounts of raw materials such as minerals which are used for example electronics, batteries and just to keep our infrastructure afloat. With this consumption and growth rate we will run out of those materials sooner or later. Asteroids, on the other hand, contain those minerals such as lithium, cobalt, copper and graphite. Therefore a possible solution for this shortage could be asteroid mining, which could be done using the same methods as in sample-return missions.

For my thesis, I am focusing on the observation of hydrated materials and water on asteroids.

4.3 Observing water in asteroids

Asteroid observation can be divided into ground-based and space-based observations. Ground-based studies include observations done by telescopes and meteorite studies. Space-based studies can be divided into mapping asteroids, rendezvous missions and sample-return missions. In this section I will go through different ways to study asteroids and the benefits and drawbacks of each method. I will explain how water and hydrated minerals are detected using each method and how future missions can give us more information on the topic.

4.3.1 Telescopes

At first, all the knowledge on asteroids was obtained by ground-based surveys, first using the naked eye, and later using telescopes. The first asteroids found were large enough to be seen using the naked eye. Most asteroids are not large enough to be seen visually, with a diameter of only 10 meters or less. This can explain, why it took a relatively long time to understand the large amount of asteroids that exist in the Solar System. The first asteroid, Ceres, was identified visually by Giuseppe Piazzi, and the few first asteroids found after Ceres were also identified this way.

Before photographic asteroid discovery, less than 500 asteroids were detected. Photographic imaging was performed by comparing images taken minutes apart and then checking if the object had moved between the images. Photographic surveys used manually operated blinked comparators and stereomicroscopes to obtain and visually compare the images. The first asteroid found this way was Brucia, and it was discovered in 1891 by Max Wolf, who later on found 320 more.

The modern era of asteroid surveys began with the use of charge-coupled devices, CCDs. CCD imaging was first used on Spacewatch asteroid survey. CCD imaging provided more accurate detection of asteroids. It used the same idea of comparing the position of the object on several images, but the need to do the comparison visually was ceased due to an automated analysis done by a software. CCD imaging also provided more details on the observed object like estimates for the size, orbital characteristics and distance from the Earth. Ratcliff (1992); Jedicke et al. (2015)

Asteroid observations were first mostly done to map all the near-Earth objects that could pose a threath to the Earth. In 1998, NASA set a goal to find 90 percent of all the NEOs with a diameter of more than one kilometer. This goal was expanded later on to find all the NEOs with a diameter of more than 140 meters. Space-based observations were later on used with this goal due to the advantages on ground-based observations. For example Spacewatch (started in 1983),Catalina Sky Survey (CSS) (started in 1992), Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) (started in 2010) are ground-based NEO-surveys funded by NASA. Now asteroid surveys are also done to understand the history of the Solar System and to study the properties of asteroids already discovered. Objects further away are also easier to observe due to their slower movements in the sky compared to NEOs (Jedicke et al., 2015).

Most asteroids have been discovered through ground-based surveys, and the follow-up observations are done the same way, asteroid discoveries and the knowledge on asteroids have been aquired using this observational method. Without first discovering the asteroids using telescopes, space-based follow-up would not happen.

Ground-based observations are a good way to detect asteroids and hydrated minerals on them. These observations are focused on the visible, near-infrared, mid-infrared, and three micrometer regions. As mentioned before, water and hydrated minerals have strong absorption features in all of those bands and hydrated minerals can be easily detected in these regions. Thus these regions are the main focus when observing hydration on asteroids.

The visible and near-IR region contain the wavelenghts of $\sim 0.4 - 0.8\mu m$. These

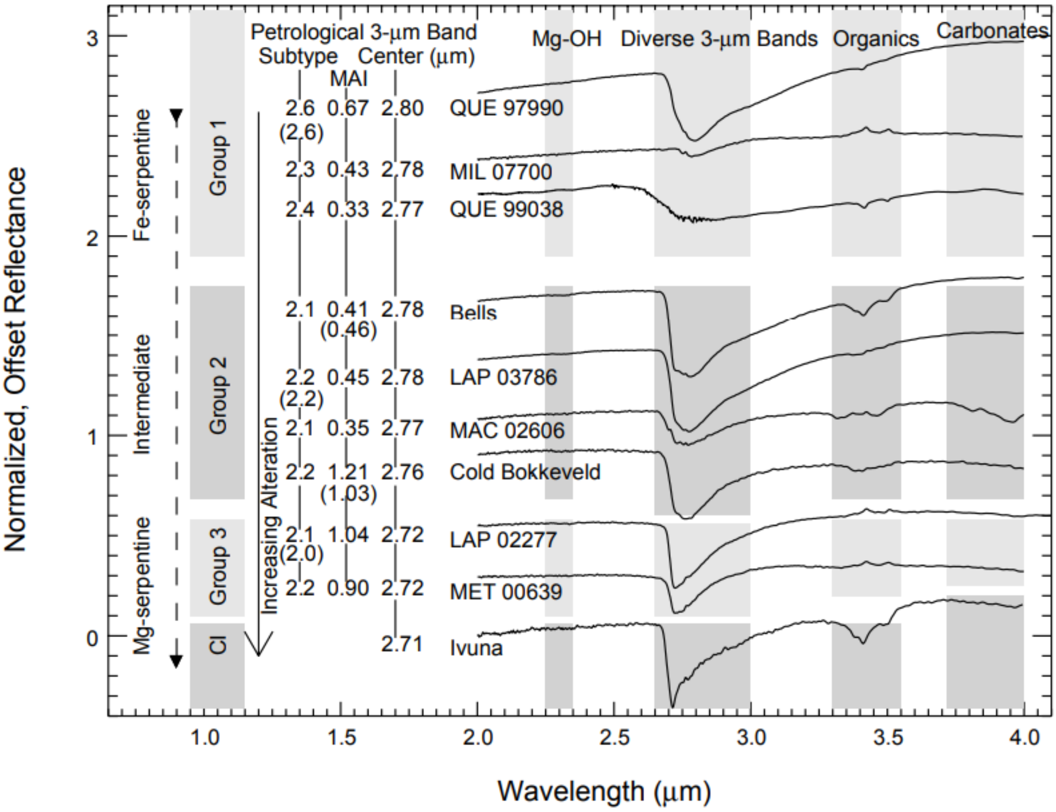

Figure 4.2: Spectral features of carbonaceous chondrites. figure form Takir et al. (2013)

wavelenghts show absorption bands generic for phyllosilicates like saponite and serpentine. Phyllosilicates can contain both H_2O and OH. Most of the asteroid studies regarding water are done on chondrite asteroids and meteorites due to the fact that these asteroid and meteorite types are known to contain water or hydrated minerals. Carbonaceous chondrite asteroids have defining characteristics in the $0.7\mu m$ band, but this band is not found on the carbonaceous chondrite meteorites. The $2.2 - 2.4\mu m$ region is used to identify water and hydrated minerals on the Earth and Mars but the presence of opaques can hide these bands thus obtained spectrum does not always show evidence of this band. The $1.4\mu m$ and the $1.9\mu m$ bands are possible to use for detecting hydration on asteroids but it is somewhat difficult to observe asteroids in these bands through the atmosphere. The $1.4\mu m$ absorption band is the first overtone of the OH band at the $2.7-2.8\mu m$ and the $1.9\mu m$ band is due to the combination of the H_2O bending and OH stretching mode. Thus these could be useful in space-based observations.

The $3\mu m$ region shows strong absorption features for water, hydroxyl and other volatiles. The hydroxyl band position varies due to the exact mineral composition of the body but it is usually around the $\sim 2.7 - 2.8\mu m$. Carbonaceous chondrite meteorites and asteroids have a absorption band around the $2.7\mu m$ due to existence of hydroxyl bearing minerals. The bodies that have absorption features around the $2.7\mu m$ band contain phyllosilicates, and have been aquaously altered. The Earth's atmosphere poses a challenge when observing water due to the water in the atmosphere. Water and hydroxyl have fairly different band shapes and positions, and water ice can thus be distinguished from hydrated minerals. Water ice has absoprtion bands at the $3\mu m$ regions between the $3 - 3.2\mu m$ depending on the structure and temperature of the water ice. The asteroids thermal emissions can interfere with the observed spectral features and needs to be taken into account. The thermal flux can fill in the band for some asteroids. Just like other celestial objects, asteroids warm and cool depending on their distance from the Sun, which can cause the thermal flux to affect the observations. Rivkin et al. (2015)

The mid-IR region $5 - 50\mu m$ is not generally used for mineralogy observations on asteroid due to the low spectral contrast, high flux and the variability of the Earth's atmosphere's thermal emissions (Rivkin et al., 2015). Still, the mid-IR region can be used to detect hydration when the conditions are favourable. H-O-H or X-O-H bending vibrations can be detected around $6.25\mu m$ and Si-O bend and stretch modes in $8 - 12\mu m$ and $15 - 25\mu m$. Phyllosilicates have absorption bands in these bands and can be detected using the mid-IR region.

The spectral observations are done by using reflectance spectroscopy. The detected spectrum is then analyzed and can tell a lot about the mineralogical composition and hydration level of the asteroid's surface. As mentioned before, different minerals have their own distinguished spectral features that can be then detected from the spectrum. Because only the surface can be observed, the observed spectra can be faulty due to the effects of space weathering, collisions, and aging has on the asteroids surface. The detected albedo can be lower than the objects true albedo, and the spectrum on the other hand redder. Only the surface mineralogy of the asteroid can be detected, thus the true mineralogy and hydration level can hide below the surface layer. It is possible that the hydration is not detected, but the object does contain hydrated minerals below its surface. Space weathering can create water on the asteroids surface, which can be detected, but the rest of the asteroid could be anhydrous. One way is to observe the newest craters and the parts with the highest albedo to possibly get a general idea of the mineralogy of the object.

4.3.2 Meteorites

Meteorites are fragments of their asteroid parent bodies, which were formed from the solar nebula planetesimals, and survived the collision with the Earth. Because Meteorites are fragments of their parent asteroids, they can give information about their parent body's properties such as mineralogy, thermal history, and the level of aqueous alteration. Meteoroids were born when collisions between asteroids formed asteroid families (Carbognani and Fenucci, 2023). These meteoroids were moved into orbits that made them travel through the Earth's atmosphere, and if they survived, they crashed into the ground.Because meteorites are fragments of asteroids, they can tell quite a lot about its parent object. More than 50 000 meteorites have been found and almost all are from asteroids (NASA, d). Some meteorites found on the Earth are lunar or martian rocks that are shattered parts from the Moon or Mars.

Meteorites can give information about the thermal and aqueous alteration processes in the early Solar System, but also give specific information about minerals found in asteroids. Meteorites are affected by the Earth's atmosphere and could reabsorb water on their way to the Earth's surface. This could change the original composition of the meteorite. Most minerals found in meteorites can also be found on the Earth, but some meteorites contain minerals that cannot be found here naturally (Elkins-Tanton, 2010). Meteorites show evidence of the alteration processes through the minerals found in them. They are studied for example by obtaining their spectrum, while trying to separate the spectral properties caused by possible contaminants like volatiles such as water absorbed from the atmosphere and/or the ground.

Each of the meteor group is thought to be a parts fractured from one parent asteroid. DeMeo et al. (2015) Meteorites are often linked to a parent asteroid by studies on both bodies. When there is no mineralogical samples of the parent asteroid, the comparison is based on only the observed spectrum. The observed spectra is not always accurate do to microscopic and macroscopic effects such as space weathering, collisions, and aging on the parent body. Also the distance of the asteroid can cause inaccuracy on the obtained spectrum. It is sometimes possible that the observed body does not have any recognizable absorption bands. Observations done on rendezvous missions do not give much more precise results but can give information about the homogeniety of the asteroid's surface. Aqueous alteration can be seen in meteorite samples by studying the mineralogy of the object. Different minerals like phyllosilicates are formed during aqueous alteration of the parent body and these minerals can be then found on the meteorite. Meteorites can tell a lot about the history of the Solar System and the conditions, especially the thermal conditions and history in the early Solar System. They have given us information on minerals found on asteroids, and also on the processes of aqueous alteration of the bodies in the early Solar System.

Some meteors never become meteorites and are perished on their way to the Earth's surface. Also some meteorites that fall on the Earth are never found. They either fall in to the ocean, shatter into millions of small pieces, or are good at disguising themselves as the Earth rocks. Asteroids with low density materials are unlikely to survive the atmospheric entry, so meteorite records do not include samples from these types of bodies. This can make the meteorite records less detailed than hoped. Meteorites absorb water on their way to the Earth form the Earth's atmosphere but this water can be removed in the laboratory to obtain the true spectra of the object. The absorption bands in the $3\mu m$ region are broader in the minerals than in the atmospheric water so the error due to the contamination of the meteorite samples can be minimized.

4.3.3 Space missions

Space missions can be divided into rendezvous missions and sample-return missions. Rendezvous missions use imaging as a tool same way as ground-based missions. Sample-return missions on the other hand collect material from the asteroids surface and deliver the samples back to the Earth for a closer observation that is usually done by studying the sample for example by obtaining the sample's spectrum.

Rendezvous missions collect observational data from closer to the asteroid than ground-based observations, and without the effect of the atmosphere and the distance all together. Still, as mentioned earlier, the asteroid's surface has sustained changes during its lifetime, and the observed spectrum from the surface mineralogy, can be quite different compared to the mineralogical composition of the asteroid. The best way to image an asteroid, is to find the newest collision crater, because the collisions expose the minerals under the differentiated surface. Of course, the mineralogy can be mixed with the colliding asteroid's mineralogy.

Spectrum obtained by a rendezvous mission can give better information about the homogeneity of the observed asteroid's mineralogical composition due to the possibility to observe the asteroid from all angles. Still, rendezvous missions do not give any clearer image on the spectrum of the asteroid. Collisions, aging, and microscopic effects such as space weathering and regolith depth do change the asteroid's surface. These changes can mask the features that reveal the mineralogical composition of the asteroid.

Sample-return missions on the other hand give precise knowledge on the actual mineralogical composition of the asteroid, but these missions are more prone to errors due to the difficulty of the missions, and are more expensive. The collected sample needs to be secured from any outside variables that could contaminate it. Sample-return missions are the only way to obtain the true mineralogical spectra of the observed asteroid in case the sample stays uncontaminated. The results of the sample analysis can then be compared to the previously observed spectra and can show the degree of the alteration done by aging and/or space weathering. Of course the changes on the asteroids surface depend on its location, mineral composition etc. but this could be helpful when observing asteroids that belong in the same families/groups or have similar properties.

Below I will go trough a few space based missions and the results obtained from these missions. I will also dive further into the differences between the data obtained from rendezvous missions and sample-return missions.

The first missions to collect samples from an asteroid was JAXA's (Japan Aerospace Exploration Agency) Hayabusa mission. It was launched in May 9th 2003 to collect samples from asteroid (25143) Itowaka, which is an S-type asteroid. This mission was a test mission for future sample-return missions and, although they encountered various problems, the samples were returned to Earth in 2010. The spacecraft mapped and imaged Itowaka from distance of 20 km and collected some samples from the asteroid's surface.

Hayabusa measured the asteroid's diameter and density, and made some spectral observations. The measured properties were in a good agreement with the measurements made ground-based. There was a slight difference between the optical albedo and near-IR spectrum which can be explained by space weathering which darkens the observed albedo and reddens the observed spectrum. The differences in the surface albedo could be explained by the darker regions being more altered by space weathering and the brighter regions could have been newly exposed to shaking by impacts.

Hayabusa2 was JAXA's sample-return mission to a C-type asteroid (162173) Ryugu. It was launched in 2014 and it returned the collected samples back to the Earth in 2020. The samples were taken from two different location, one next to a crater to get the most accurate results. The sample was stored in nitrogen gas and did not experience any notable contamination. The spectrum of the sample was obtained and the spectrum showed an absorption feature at the $2.72 \mu m$ region, which indicates the presence of hydroxyl OH. There was evidence of aqueous alteration on Ruygu, which was expected. The spectrum obtained from the samples was in an agreement with the spectrum obtained by ground-based observations. It showed a low albedo which is common in C-type asteroids. Yada et al. (2021)

NASA's sample-return mission OSIRIS-REx to another C-type asteroid (101955) Bennu was launched in 2016, and it returned the collected samples from the body in 2023. Bennu showed evidence of hydrosilicates, aqueous alteration, and possibly primitive carbonaceous composition (Lauretta et al., 2024). OSIRIS-REx first used its visible and infrared spectrometer (OVIRS) to obtain spectra between $0.4 - 4.3 \mu m$ from Bennu's surface. It mapped the asteroid's surface for two years before the sample collection sites were confirmed. The spectrum was then obtained especially from the sample collection sites. Kaplan et al. (2021) The spectra obtained from rendezvous studies could this way also be compared to the spectra obtained straight from the samples.

Hydrated phyllosilicates, magnetite, which is oxidized iron, carbonates, and organic compounds were detected by the remote sensing of Bennu's surface (Lauretta et al., 2024). All of these were confirmed from the sample. Some anhydrous silicates were also detected using both methods but the amount was small which could be due to the aqueous alteration the parent body sustained. The sample also consisted of hydrogen, nitrogen, and oxygen isotopes which could be compared to samples from meteorites and other asteroid studies. Bennu was particularly interesting due to its primitive carbonaceous composition, aqueous alteration and the slight possibility it could collide with the Earth at some point (Lauretta et al., 2024). The samples from Bennu resemble the samples obtained from Ryugu and previously studied carbonaceous chondrites.

When the sample's spectrum was compared to the spectrum obtained by OVIRIS, it was noticed that the sample appeared to have a redder more positive slope compared to the spectra obtained by OVIRIS, and the $2.7\mu m$ feature was also narrower and weaker compared to the OVIRIS data Lauretta et al. (2024). On the other hand around $1.1-1.2\mu m$ the samples albedo matched fairly well to the asteroids. The differences could be due to space weathering and the location of the sample collection site in the Hokioi crater. The Hokioi crater "Nightingale site" is possibly one of the latest impact crater,, and thus would have the least space-weathered material on the surface of Bennu (Lauretta et al., 2024).

Lucy and Psyche are two ongoing rendezvous missions to asteroids in the main belt and in the Jupiters' orbits Lagrangian points. Lucy's main goal is to observe Jupiter Trojans, and Psyche is observing a main belt asteroid called Psyche.

Lucy is a mission which was launched in 2021 to observe Jupiter Trojans. Lucy will fly by three main belt asteroids and eight Trojan asteroids on its twelve-year mission. Lucy is the first mission to observe the Trojan asteroids. It has already studied the three main belt asteroids Dinkinesh and its moon Selam on first of November 2023 and Donaldjohanson on 20th of April 2025. Trojan asteroids are particularly interesting due to the variety of different types of asteroids close by each others. These asteroids are likely remnants of bodies that formed all over the Solar System and were trapped in the lagrange points of Jupiter's orbit as the giant planets migrated. By observing the Trojan asteroids, we could get important information about the formation of the Solar System (NASA, c; Levison et al., 2021).

Psyche is a spacecraft that was launched in 2023 to study a main belt asteroid (16) Psyche. Psyche is an extremely metal-rich M-type asteroid that orbits the Sun in the outer part of the Main Asteroid Belt. Psyche is an irregular shaped asteroid with a very high density, due to it being metal-rich and containing more metals than rock or ice (NASA, e; Dibb et al., 2023). The main goal of the mission is to learn more about how planets are born and how they evolve. Psyche could be a partial metallic core of a planetesimal and thus could give answers on the core formation and give an opportunity to study an asteroid that resembles a metallic planetary core (NASA, e). The spacecraft will reach the asteroid in summer 2029.

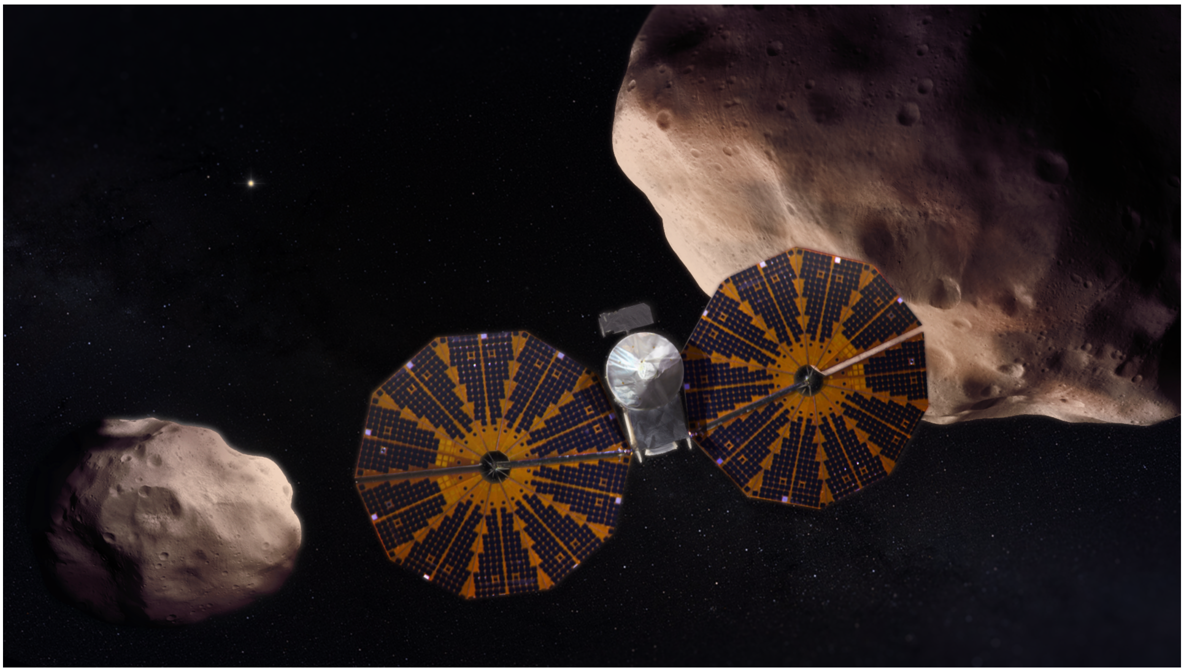

Figure 4.3: Lucy spacecraft with binary asteroids Patroclus and Menoetius (NASA's Goddard Space Flight Center/Conceptual Image Lab/Adriana Gutierrez, https://science.nasa.gov/solar-system/planets/jupiter/nasas-lucy-mission-a-journey-to-the-young-solar-system/

Sample-return missions can be the only way to get a closer look on objects that are composed of low density materials. As mentioned in the meteorite subsection, these types of objects do not survive their journey to the Earth's surface and thus are not included in meteorite records. This is one of the reasons why sample-return missions are important to get knowledge on the different types of objects with different mineralogies and evolutionary history in the Solar System. On the other hand, while it is known that space weathering and aging can change the surface properties of the asteroid, this can be taken into account when making spectral observations.

4.4 The future of asteroid observation

The latest sample-return missions were to C-type asteroids, that are known to contain hydroxyl or water. Sample-return missions to other types of asteroids, could broaden the knowledge on the mineralogy and the level of hydration on other asteroid classes.

The Lucy mission could broaden the view on this topic. The results obtained from Lucy mission, can bring extremely important information about the history of the Solar System, due to the diversity of the objects and the primitive nature of the bodies. These objects have been orbiting in the Lagrange points of Jupiter's orbit from very early on. The physical and mineralogical properties and the existence of aqueous alteration could give clues about the differences in thermal evolution of the bodies.

Psyche will encounter the asteroid Psyche in 2029. If the asteroid is truly a partial core of a protoplanet that has been disintegrated, it could let us observe a core like object closer than ever before and obtain knowledge on planetary core formation. It is impossible to study a planets core this way, close up.

These future missions could give interesting information on the history of the Solar System, differentiation of the celestial bodies in the early Solar System and help to keep us safe.

4.5 Overview on the detection methods

Every method has their own benefits and drawbacks. Most of the observational methods can not collect data past the asteroids surface, and all the knowledge on the object is based on this small part of it that can be detected using that method. Because asteroids are airless bodies, their surface can be strongly altered due to different processes. Thus the inner composition can vary from the surface composition due to different alteration processes. Asteroid's surface is prone to changes due to collisions and space weathering, which can cause challenges in the observations. Although hydration is not be detected on the surface of the asteroid, the insides of the object could contain hydrated minerals and/or aqueous alteration. If space weathering can produce water on the surface of the asteroid, this water could be detected using spectral observations, but it is possible that the rest of the body could be relatively anhydrous.

Asteroids are the key to the evolutionary history of the Solar System, so they can explain various processes that happened during its history. Spectral observations are a great way to study the composition of the asteroids, although there might be some differences with the asteroid's spectrum. Spectral observations can be done from the Earth, and it is the most ecological and sustainable way to do so. Space missions need a lot of planning, and to get an approval and funding for a missions can take time. If the asteroid has some interesting spectral features, it could be a great target for a future rendezvous or even sample-collection mission.

It is clear that sample-return missions get the most precise data, but the missions take time themselves. To get the best image of the whole object, rendezvous missions can be the only way to do so. It is possible to map the whole surface of the asteroid during a rendezvous mission and study the homogeinity of the surface this way. But again these missions do take time.

Meteorite studies on the other hand are a simple way to obtain knowledge on the parent body, but these objects have experienced alteration during their journey to the

Earth. It is possible to eliminate the contaminants effects such as water's effect on the body. Due to the differences on asteroid parent body's mineralogy and composition, some meteorites do not survive to the Earth because they disintegrate on their way here. This means that the asteroids with the most delicate composition are not represented in the meteorite records. Not all meteorites are found or identified depending on their landing site. Meteorites can resemble the Earth rocks, and thus are not found. Aqueous alteration on meteorites can be studied by studying the mineralogy of the meteorite. Carbonaceous chondrite asteroids and meteorites are known to be aqueously altered, but these are objects with a fragile composition, that often do not make it to the Earth.

There is not a one single best way to observe asteroids and hydration on them. All the observational methods have their own limitations but they all give important information. The best way is to combine the observational methods and then compare the results obtained from each method. This is the way to get the best picture on the object and also understand how different variables can affect the data obtained.

Johansen et al. (2023a,b,c, 2021)

5. Conclusion

Water is found throughout the universe. It can be seen in stars spectra or even in the interstellar medium (Lecuyer, 2014). To understand the possible origin of the Earth's water, it is important to understand the evolution of the Earth from the planetesimal accretion, through the protoplanet face, through differentiation and asteroid impacts, to the blue planet that is still the only one with proven life. The theories for the Origin of the Earth's water is often based on the D/H ratio observed in different parts of the Earth; either in the crust, mantle or the core, compared to other bodies in the Solar System.

The solar nebula and later on planetesimals that formed from the matter of the nebula's gas disc, contained large amounts of water ice and hydrogen. That water ice accreted into the planetesimals and further on into the newly born proto-planets, and shattered into smaller objects like asteroids. These objects then sustained heating due to thermal energy from collisions and the decay of short-lived isotope of aluminium ^{26}Al, which changed the objects inner and outer composition and mineralogy. These heating events changed the original water reservoirs from the solar nebula and planetesimals. Thus, even though the planetesimals could have brought significant amount of water, even four times the amount that is found in the Earth's oceans, to the proto-Earth, large amount of it could be lost due to the changes within the young planet (Wu et al., 2018). The temperatures were extremely high during the period of first two million years, and the accreting bodies could have been very dry due to the surrounding temperature and intensive inner heating processes (Alexander et al., 2018).

The internal heating from the ^{26}Al decay and collisions, caused the water ice to melt and metal-silicate differentiation, which caused the metals to separate from the silicates. The melted water ice interacted with the silicate minerals, forming hydrated phyllosilicates such as clay. This intensive heating formed a magma ocean inside the proto-Earth, where the metal and silicate minerals stayed in an equilibrium for a while due to the high pressure. These metal atoms then further on reacted with the oxygen atoms in the melted water ice from the planetesimal accretion. The oxygen in the melted water ice, oxidized iron atoms, forming even heavier elements, which then sank to the middle of the body, and later on formed the Earth's core (Rubie et al., 2015; Wu et al., 2018). These metals could have stored a great amount of hydrogen within them from this oxidation event. This could explain the high amounts of hydrogen in the core. With each collisional event, more melting happened, and the larger the magma ocean grew. Each time even more heavier atoms sank to the core, forming the Earth's growing metal core. The formation of the magma ocean enabled the creation of the Earth's core and mantle distribution (Johansen et al., 2023a).

Oxygen, hydrogen, sulfur, and nitrogen all have a tendency to react strongly with iron and to create iron compounds like oxidized iron (FeO). Because of this high binding characteristics between these elements, they tend to combine with the iron melt rather than with the silicate melt inside the magma ocean (Johansen et al., 2023b). The surplus of volatile materials such as carbon, hydrogen, oxygen and nitrogen, that can not combine with either silicate or iron compounds, are outgassed from the magma ocean. These outgassed elements further on form the primordial atmosphere, where they are found in different compounds such as water, carbon dioxide, molecular nitrogen, and N_2 and methane (Johansen et al., 2021, 2023b,c; Lichtenberg et al., 2023). The primordial-atmosphere worked as a thermal blanket which kept the temperature high enough to sustain the magma ocean (Wu et al., 2018). The partitioning of the volatiles in between the core, mantel and atmosphere are determined by the volatiles solubility in the magma ocean Suer et al. (2023). This primordial-atmosphere was not advanced enough to keep the volatiles and water on the

Earth.

After the dissipation of the solar nebula, the cooling temperatures caused the magma ocean to crystallize gradually. The gradual crystallization in the magma ocean formed dense cumulates, dense igneous rocks that are formed from crystallized plasma, which sinked close to the core-mantle limit. Some cumulates with lower density mixed with the unmelted underlying mantle Wu et al. (2018).

Collisions and accretion of planetesimals accreted the Earth's mass until it reached about 60 percent of its current mass around 100 million years after its formation. The last $\sim$ 40 percent of its mass was likely acquired from the Moon Forming impact. According to one theory, Earth collided with almost same-sized planet Theia around 4.5 billion years ago. This strong impact fused the two planets together, destroying Theia. The collisional matter that was thrown into space, formed our Moon. Theia likely formed in between of the Earth and Mars and had similar composition and accretional history than Earth. Earth and the Moon have similar isotopic composition, which can be explained by Theia and the Earth being formed from the same planetesimal. Because of the impact, even 60 percent of the Moon's mass could originate from the Earth. Just like on asteroids, space weathering affects the Moon's surface modifying its chemical composition and observational characteristics. The Moon forming impact with almost same sized planets was so powerful that it could have melted almost all of the magma ocean and removed a large amount of the Earth's water reservoirs. Rubie et al. (2015)

Most of the Earth's surface water was likely gained after the Earth had accreted most of its mass (Rubie et al., 2015). Large amount of the water was brought via the planetesimal accretion, but large amount of it evaporated due to the internal heating and chemical reactions.

One possible source for the Earth's water is thought to be comets but comets have higher D/H ratio, even as high as $300 \cdot 10^{-6}$. The Earth's oceans D/H ratio is $150 \cdot 10^{-6}$ (Wu et al., 2018). Most comets are originated from the Kuiper belt and Oort cloud which

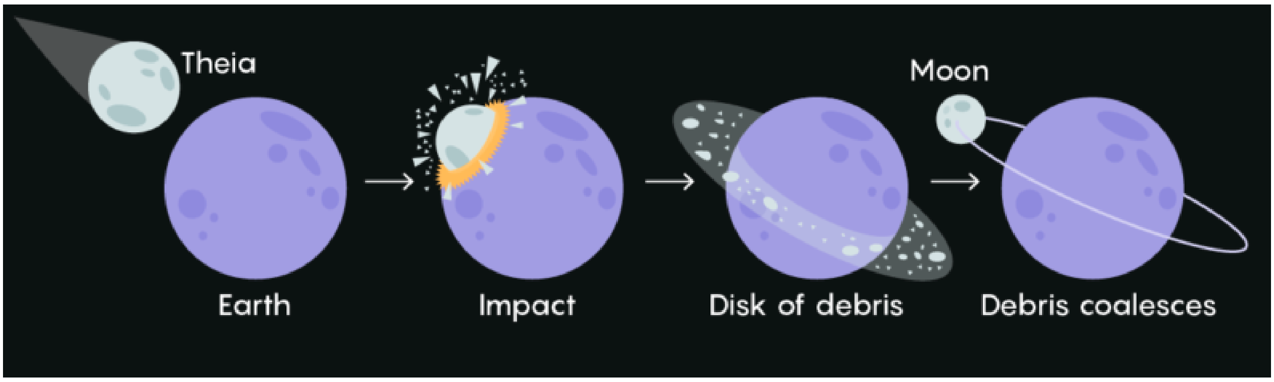

Figure 5.1: A simple model of the Moon forming impact. Citronade, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

are located far away from the Earth, after the orbits of the Giant planets. Comets contain ice and other volatile matter, which makes them somewhat fragile. Due to being far away, comets are not very likely to collide with the Earth.

When measuring the D/H ratio and amount of other volatiles, primitive chondrites are believed to be the main source of the Earth's water, especially the C-type carbonaceous chondrite asteroids from the outer belt (Alexander, 2017) (Wu et al., 2018).

When it comes to the solar nebula, the D/H ratio of the nebula is much lower $\sim 21 \cdot 10^{-6}$ than compared to the Earth's (Wu et al., 2018). Although some of the water could be from the nebula, chemical reactions inside the Earth and the internal heating have either dissipated the water or changed the D/H value.

Although, only observing the D/H ratio of the object is not going to give any precise answer. It is possbile that when deuterium interracts with metals, it fractions and separates into lighter hydrogen which then could grow the D/H ratio in the area (Wu et al., 2018). The D/H ratio can vary between similar objects due to inner differentiation. It is important to remember that the volatiles and water reservoir is a summary of all the planetesimals and objects that the Earth accreted from. This is why it is important to observe also the bulk composition of each volatile and its isotopes on the Earth.

Asteroids are interesting objects with a key to the knowledge about the history of the Solar System. Asteroids differ from each other, depending on various things like thermal, collisional, and differentiational history of the object, location in the Solar System and where it was originally formed. Everything started with the same building blocks, planetesimals, which contained water ice. This water ice either melted, vaporized and/or differentiated the object or stayed as ice form due to the low temperature changes in the object.

The Earth accreted, experienced differentiation due to the heating by collisions and ^{26}Al decay, and the melting of the water ice. The Earth accumulated water from the Solar nebula and planetesimals formed in it, but also from a huge amount of asteroid collisions. The collision with the planet Theia could have also brought a large amount of water on the Earth. This could explain why the Moon has water ice. It is almost impossible to tell whether all the water is from asteroid collision but the Earth's water reservoirs could be both from the collisions, and the Solar nebula. The D/H ratio shows that asteroids could have brought most of the Earth's surface water but the inner reservoirs could be collected already from the solar nebula and planetesimal accretion.

Because asteroids are important tools for explaining the processes that took place in the early Solar System, the results from future asteroid missions such as the Lucy and Psyche could bring answers on the origin of the Earth's water. These missions study a large variety of asteroids with varying properties and spectral classes, which have not been studied close up before.

The uncertainties in the amount of water, OH, and hydrogen in the Earth's mantle and core, make answering the research questions fairly difficult. The water and hydration in the atmosphere and within the crust can be easily studied because it is accessible, but directly studying for example the Earth's core is not possible. The D/H ratio varies due to how hydrogen reacts with other minerals and elements and can vary even within the body. If the origin of the Earth's water is only based on this value, the theory can be faulty. The results from the Psyche mission can possibly shed light on the formation processes and elemental abundances of metallic cores of stony planets. This could give clues on the composition and differentiation history of the Earth's core.

On the other hand, the Lucy mission studies Jupiter Trojans, which are a diverse group of asteroids, that has stayed on their orbits likely since the giant planet migration. Hydration and aqueous alteration have been observed on these bodies, and if confirmed, the presence of these aqueously altered minerals could give clues on the alteration and heating processes further in the Solar System. The variety of the objects can shed light on how different types of asteroids have been altered during their evolution and if hydration can be expected on similar bodies. This can explain if the existence of water can be excluded from some types of asteroids.

If only comparing the bulk D/H ratio of the Earth's water and the chondritic asteroids and meteorites, the connection between these objects and the origin of the Earth's water can be made, but the truth can be more complex. Since water has already existed in the Solar nebula and the accreted planetesimals, some of this water can still possibly be found on the Earth. Also since asteroids are fragments of the planetesimals, that accreted water ice, most asteroids have contained water, but this water could have been lost from the body. These now anhydrous bodies could have contained hydration earlier in their life. Hopefully the future mission can give more precise answers to these questions.

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