Solar System

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1 Introduction

Our solar system is a wide and wonderful place, full of a wide variety of planets, moons, and other celestial bodies, with countless important earth science processes that take place on them.

2 Mercury

Mercury is the closest planet to the sun, and also the smallest and second densest.

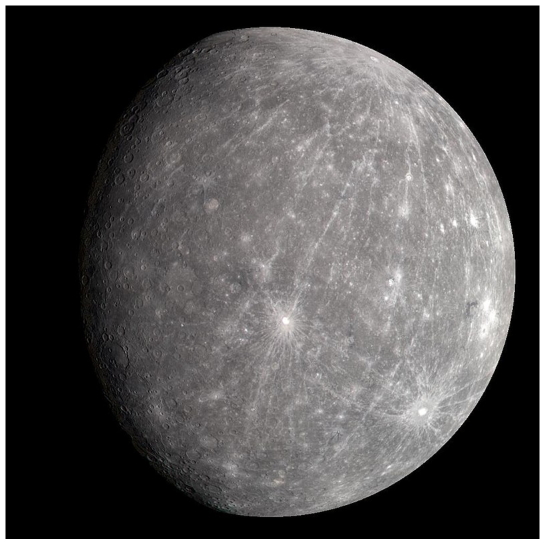


Figure 1: An image of Mercury (Source: Wikipedia)

2.1 Composition

Mercury's crust and mantle are both solid and made out of silicates. It has a deeper liquid iron core, and a solid iron core underneath that. It is without an atmosphere. The core is exceptionally large in volume compared to the other planets, and is also the highest in iron. It is thought to be the most enriched because it likely formed from a similar source as early chondrites (meteorites that have remained relatively unchanged since their formation). The surface is similar to that of the moon due to the lack of an atmosphere.

2.2 Orbital Parameters

Mercury has the most eccentric, or least circular, orbit out of any of the planets in the solar system. Because of this, Mercury was used as a test for Einstein's theory of general relativity. It also has the highest orbital inclination out of all of the planets. However, it has a small axial tilt, rotating nearly vertically. Mercury also has a unique 3:2 spin-orbit resonance, meaning it rotates three times for every two orbits around the sun. Each Mercury year is 90 days, while each Mercury day is 60 days.

2.3 Magnetic Field

Mercury has a much stronger magnetic field than would be expected for its size, likely because of a similar dynamo effect to Earth (where spiral flow in the molten core generates a magnetic field). Mercury's magnetic field is able to deflect the solar wind. Interestingly, Mercury has interesting twisting magnetic field surfaces which occasionally allow for the solar wind to breach the magnetic field.

2.4 Tidal Locking

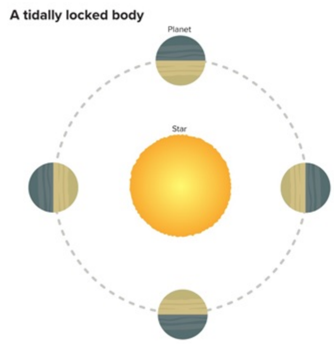


Figure 2: An illustration of tidal locking (Source: Astronomy Magazine)

While Mercury is not tidally locked, the long rotation period means one side faces the sun for a long time, and the other side does not. This leads to an extreme temperature dichotomy where the sunny side reaches 430 degrees Celsius while the cold side reaches down to -180 degrees Celsius. While there are some zones with intermediate temperatures, especially in craters near the poles, the temperature is extreme in most parts of the planet.

2.5 Weird Terrain

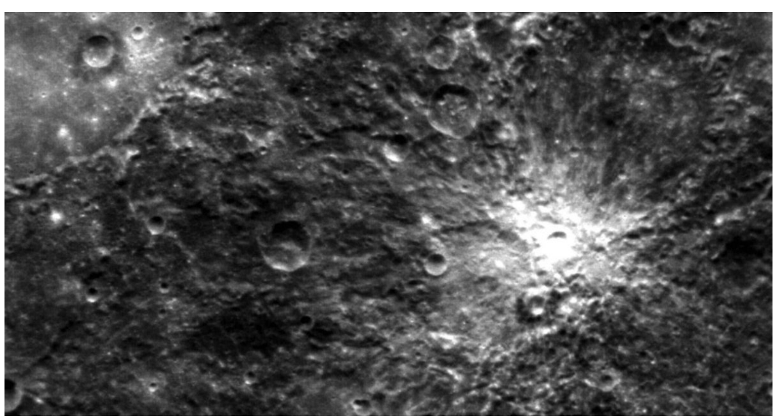


Figure 3: An image of the weird terrain (Source: The Planetary Society)

This terrain is jumbled and hilly, and is also present on the moon. It is thought to have been formed from shockwaves from an ancient impact that led to the surface being fractured at the antipodal point from the impact.

3 Venus

Venus is the second-closest planet to the sun, with the hottest surface temperatures as the result of a runaway greenhouse effect.

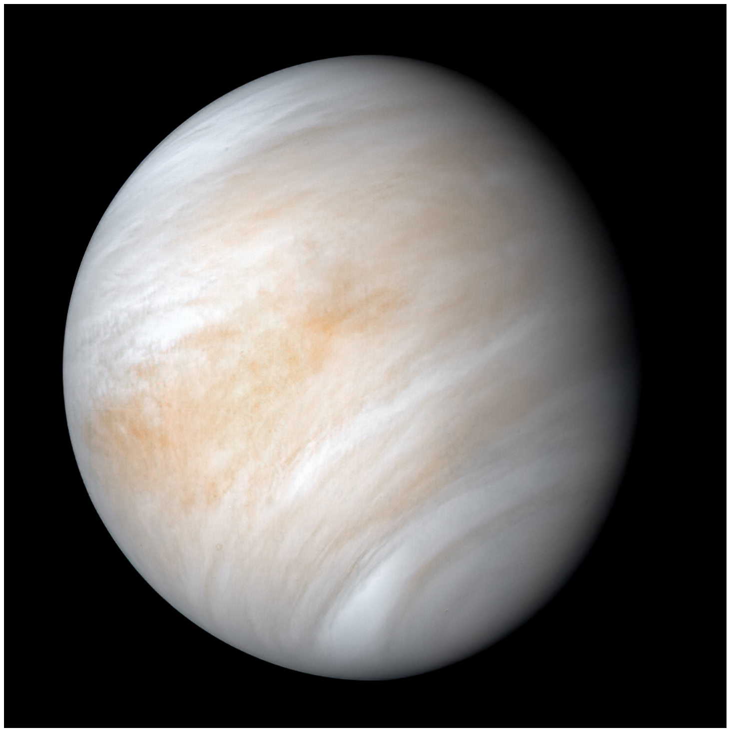


Figure 4: An image of Venus (Source: Penn Today)

3.1 Composition

Venus is very similar in mass and radius to Earth. The internal structure of Venus is poorly known, but it likely also has a core, mantle, and crust as well, and is partially liquid. However, there are no plate tectonics on Venus, nor does it have an internal magnetic field. Venus periodically has major resurfacing events, where liquid rock comes gushing over and covers large sections of the planet.

3.2 Spin

Venus' spin is retrograde, meaning it rotates in the opposite direction of its orbital motion. By convention, "north" and "south" are defined so that a planet always rotates west to east. Thus, Venus' retrograde spin means it has a north pole below the ecliptic.

3.3 Winds

The temperatures on Venus's surface are nearly constant, leading to very little variation because of the thick atmosphere. However, there is still enough to generate one-cell zonal flow. This zonal flow is tied to the sunspot cycle. It also likely has a large polar vortex around each of its poles.

3.4 Volcanism

Venus has a large number of volcanoes, because of its considerably older surface. Some of these are active, leading to changes in gas levels. These may erupt intensely during the resurfacing events.

3.5 Atmosphere and Greenhouse Effect

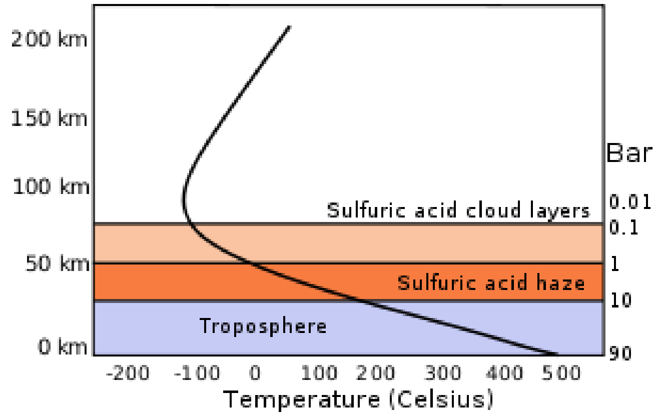


Figure 5: Venusian atmospheric profile (Source: Wikipedia)

Venus has a dense, carbon dioxide heavy atmosphere, and the atmosphere is much more massive than that of Earth's, leading to much hotter temperatures and pressures. This is thought to be due to the smaller mass of the planet which allowed water to escape easier, preventing crucial feedback loops and allowing for this runaway effect. There was a possible though debated detection of phosphine, a compound only known to be created through biotic processes, in the Venusian atmosphere. There are thick sulfuric acid clouds in the upper layers of the atmosphere that make the surface invisible in the visual. There are no seasons on Venus due to a small axial tilt.

3.6 Planetary Evolution

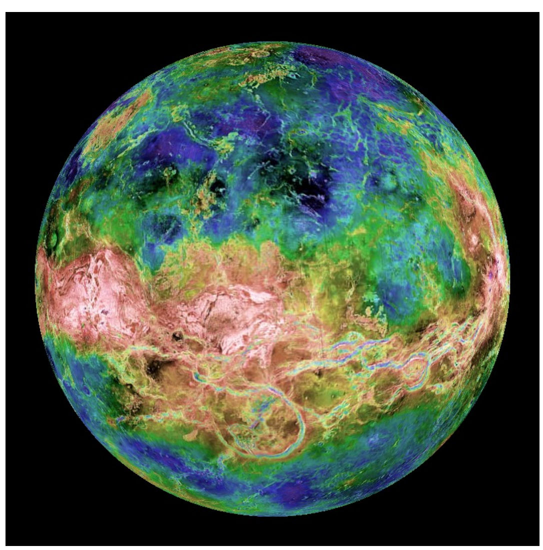


Figure 6: Venusian topographic map (Source: NOAA)

The two key events in Venusian planetary evolution is the resurfacing events, as well as the removal of light gases from the atmosphere. The resurfacing event occured about 300 million years ago, and was fairly abrpt, and caused a decrease in volcanic and an end to tectonic activity. The removal of light gases happened much sooner, due to the planet's smaller mass than Earth.

4 The Moon

The moon is the object in the solar system nearest to us, and the one that has the most daily influence on our planet.

Figure 7: An image of the moon (Source: Space.com)

4.1 Composition and Structure

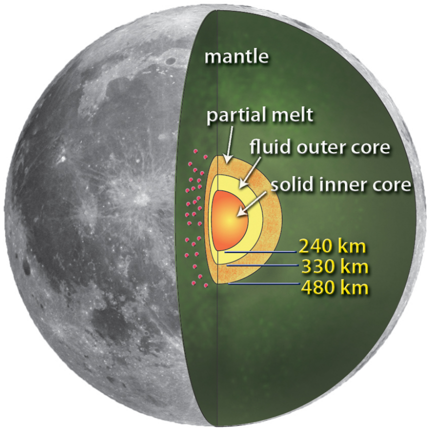


Figure 8: A diagram of the lunar interior (Source: NASA)

The moon has a crust, mantle, and core, likely formed through fractional crystallization (a process by which mafic minerals tend to crystallize first; refer to the "Rock Formation and Processes" handout for more information). It is largely anorthositic. Partial mantle melting formed large basaltic provinces called mares that are extremely flat. The moon's core is tiny, and likely iron. The inner core is solid, and the outer core is liquid.

4.2 Surface Geology

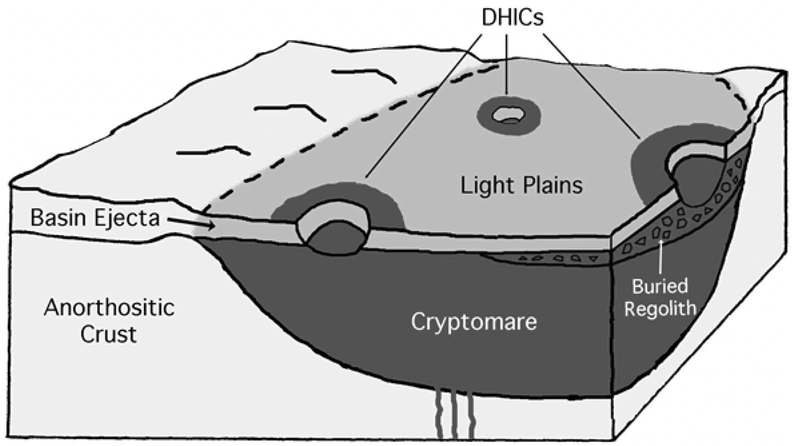


Figure 9: An image of the lunar surface (Source: Lunar and Planetary Institute)

The moon formed about 4.5 billion years ago and was entirely molten. The surface of the moon is comprised of lighter lunar highlands called terrae that are anorthositic and better reflect the interior composition, and basaltic maria. The maria are generally younger, forming 3-3.5 billion years ago in large floods. Some of the lunar rocks are vesicular, and the highlands have some pyroclastc deposits. The lunar surface also has rilles from lava channels, forming linear, sinuous, or arcuate shapes. There are also many wrinkle ridges, grabens, and domes.

4.3 Moonquakes

Moonquakes are earthquake-esque quakes thought to be caused by the build up and release of tidal forces on the moon, although they are weaker. Moonquakes have also been crucial for probing the internal structure of the moon. Moonquakes often occur in swarms of moonquakes, although the cause of these swarms is unknown.

4.4 Eclipses and Phases

The moon is tidally locked to the Earth, and causes ocean tides. The moon goes through a series of phases ranging from full, waning gibbous, third quarter, waning crescent, new, waxing crescent, first quarter, waxing gibbous, and back to full. It also is capable of eclipsing the sun or being eclipsed itself due to slight variations in the moon's nodal lines that follow the Saros cycle (which simply predicts the timing of solar and lunar eclipses).

4.5 Formation

The moon is thought to have been formed through the impact of a Mars-sized planetesimal named Theia with Earth during the late heavy bombardment, leading to a large amount of magma and debris having been ejected and reformed to create the moon. The event would have liquefied the Earth. There are still some unresolved issues with this theory regarding the moon's composition.

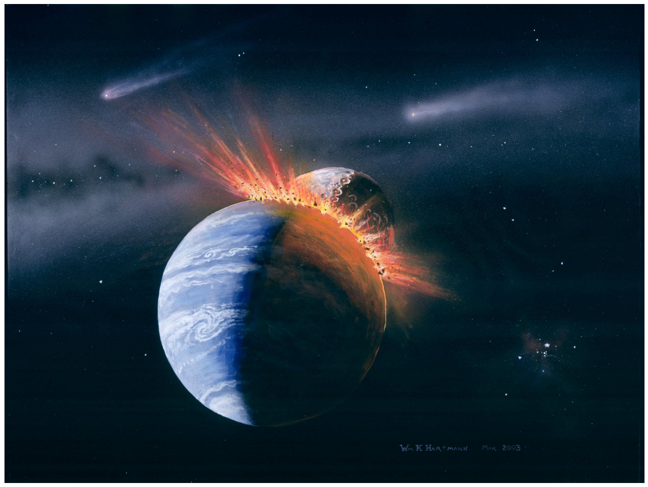


Figure 10: An artist's rendering of the formation of the moon (Source: Smithsonian)

5 Mars

Mars is the furthest out of the terrestrial planets, and is the next best studied planet (after Earth).

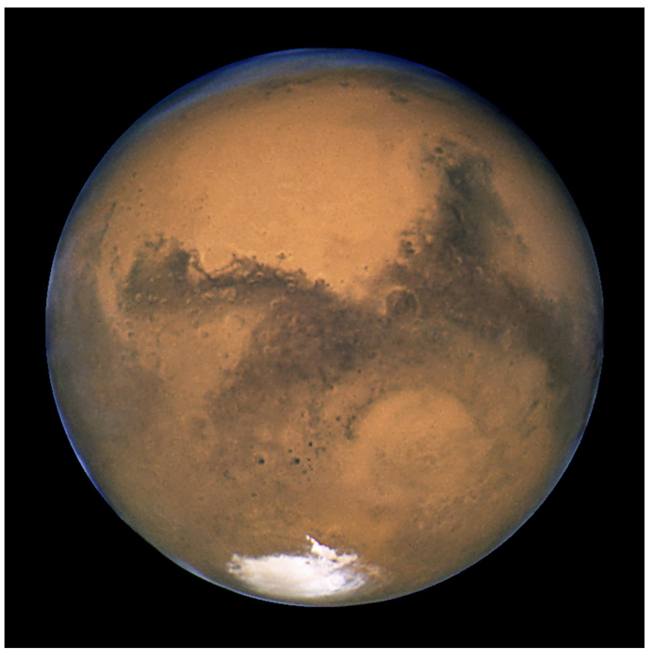


Figure 11: An image of Mars (Source: NASA)

5.1 Composition and Structure

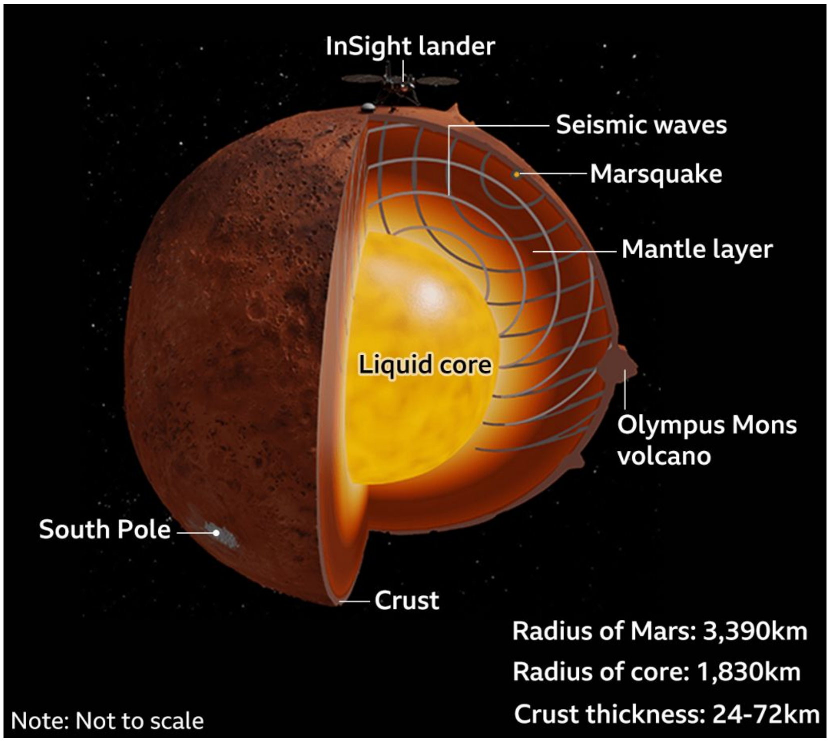


Figure 12: A diagram showing the internal structure of Mars (Source: Universe Today)

Mars has an iron-nickel core and a silicate mantle like Earthm as well as past volcanic and tectonic features, although those are dormant. Mars' core appears to be entirely liquid, with a solid mantle, and a zone similar to the asthenosphere between them. Despite having a liquid core, there is no current global magnetic field, despite having indications of past activity.

5.2 Surface Geology

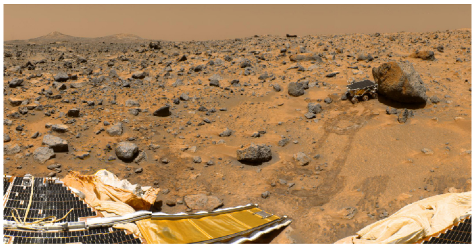


Figure 13: An image showing the Martian surface (Source: UCF)

The Martian surface is mainly tholeiitic basalt, with significant concentrations of hematite, olivine, K-spar, and silica glass. The surface is covered in iron (III) oxide, giving it its distinctive red color. The soil is slightly basic and rich in light elements. There are also clear signs of past mass wasting, lava flows, and fluvial erosion. Despite the small amount of liquid water on the surface, there is a significant erosion caused by this. The surfaces of the two hemispheres on Mars are quite different, with the southern regions being significantly more weathered and elevated compared to the northern ones.

5.3 Dust Storms

Dust storms are caused by the large amount of loose soil on Mars and a thin atmosphere. They can cover the whole planet, tend to raise the temperature, and occur near perihelion.

5.4 Climate

The loss of the Martian magnetosphere has led to significant atmospheric stripping due to the solar wind. The current Martian atmosphere is incredibly thin, and primarily carbon dioxide. The seasons are Mars are similar to Earth, but double the length, and have higher temperature variations.

5.5 Planetary Evolution

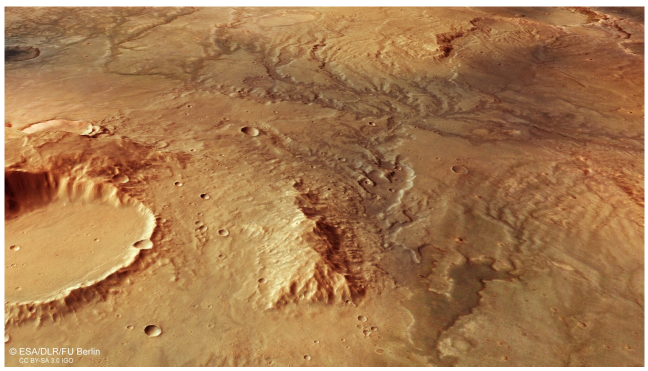
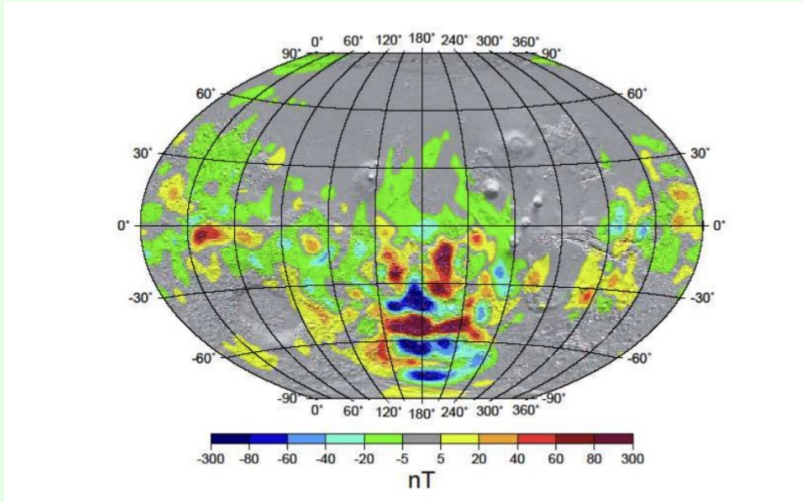


Figure 14: An image showing the effects of past fluvial erosion on Mars (Source: ESA)

Mars is thought to have been significantly impacted by the late heavy bombardment, including a possible impact by a large planetary body that created the hemispheric divide. Since then, there have been three main periods on mars, the Noachian, Hesperian, and Amazonian. There was significant liquid water erosion as well as volcanic activity and impacts in the Noachian. The Hesperian period is marked by large plains of lava. The Amazonian is marked by the formation of Olympus Mons and other lava flows.

Example 5.5.a (USESO Open Round 2022) Though Mars does not currently generate a magnetic field, parts of its crust are magnetized. The map shows the remanent magnetization present on Mars's surface. Which of the following does the map suggest?



I) The lack of magnetization in impact basins is attributed to large impacts and thermal events erasing preexisting remanent magnetization.
II) The northern lowlands are thought to have experienced sedimentary or volcanic resurfacing.
A. I only
B. II only
C. I and II
D. None

Solution: The impact basins appear gray on the image, indicating little magnetic field due to large impacts. The Northern Plains also have little magnetic field as well, suggesting that new crust overlays the older magnetized crust. Similarly, sedimentary and volcanic resurfacing overlays the old magnetized crust in those areas. Thus choice C is the answer.

6 Jupiter

Jupiter is the most massive planet in the solar system, and is thought to be crucial to lowering the risks of catastrophic asteroid collisions with Earth.

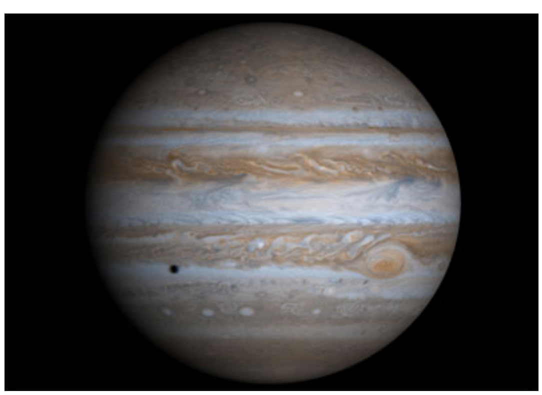


Figure 15: An image of Jupiter (Source: NASA)

6.1 Structure

Jupiter has a mostly hydrogen upper atmosphere, with a significant amount of helium that increases going towards the center. There are traces of other gases. Near the center, the pressure is so intense the the hydrogen becomes metallic hydrogen through a large region of the planet that conducts and generates a magnetic field. There is not a sharp divide between the metallic hydrogen core and the mantle. There are also rains of noble gases.

6.2 Storms

Figure 16: An image of the Great Red Spot, an especially prominent storm on Jupiter (Source: NASA)

Jupiter has several large storms, most famously the Great Red Spot. These storms are large atmospheric eddies that can exist for a while unimpeded by fiction. Storms on Jupiter also follow the Coriolis effect, with storms in the southern hemisphere rotating counterclockwise. Large storms often have a cooler "eye" in the center similar to storms on Earth. These storms can also be significantly hotter than their surroundings. However, the dynamics are very different.

6.3 Magnetosphere

Jupiter has a very strong magnetic field, which generates a significant bow shock and large auroras. There are also often "sheaths" of plasma that get trapped within the magnetosphere.

6.4 Effects on Earth

Jupiter's large mass is thought to help shield Earth from large meteorites and other possible impact bodies. It also creates the Kirkwood gaps in the asteroid belt due to resonance effects.

7 Io

Io is the most volcanically active body in the solar system, and also is the Galilean moon closest to Jupiter.

Figure 17: An image of Io (Source: NASA)

7.1 Volcanism

Io is the most volcanically active body, with huge mostly basaltic lava flows, as well as significant plums of gas and sprays of pyroclastic material. These plumes can reach significant heights, and can be relatively long-lived. It is famous for the paterae depressions that look like insides of pots. The paterae often have lava flows from rights on the floor, and are often rich in sulfur.

7.2 Tidal Heating

Tidal heating is caused by the counteracting forces of Jupiter on each side of the planet, leading to a significant compression that heats up the inside of the moon and causes large melting, enough to keep a large reservoir of molten rock.

7.3 Atmosphere

Io has a very thin atmosphere of sulfur dioxide and other sulfur compounds, mainly generated by volcanic plumes. Gas from the atmosphere regularly is removed and becomes part of a surrounding cloud, as well as a large torus of plasma that surrounds Io's orbit, and is generated via magnetization of the plume gas. Some of the plume gas also condenses onto the planetary surface to form ice during the dark. It can also form aurorae.

7.4 Magnetic Interactions

Io helps provide ions for Jupiter's magnetic field because of its plumes. Io is surrounded by a cloud of gas and plasma, in the shape of a torus.

8 Europa

Europa is another Galilean moon with a sub-surface ocean and thought to be the best candidate for life in the solar system.

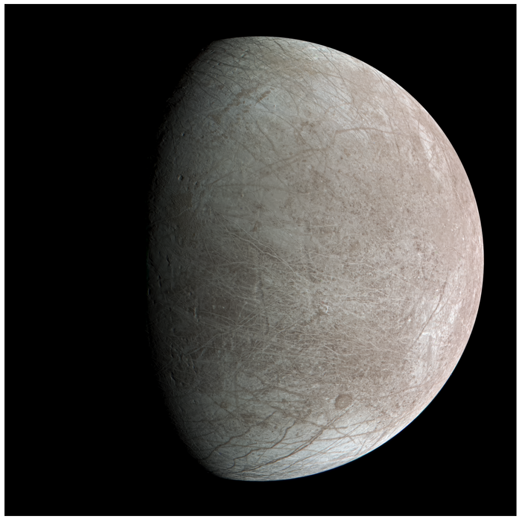


Figure 18: An image of Europa (Source: Wikipedia)

8.1 Surface

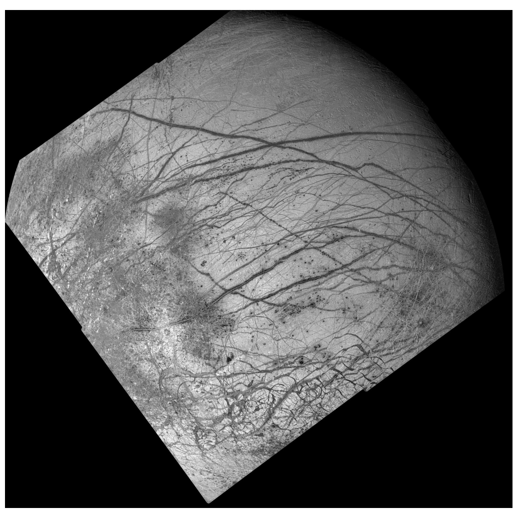


Figure 19: The lineae on the Europan surface (Source: Wikipedia)

Europa has a very smooth surface, indicating freuqent resurfacing. However, it does have large spikes near the equator known as penitentes which from from ice sublimation. It also possesses prominent lineae, or lines, which are likely similar to volcanic ridges but instead made of warm water.There are also similar circular and smooth features.

8.2 Ocean

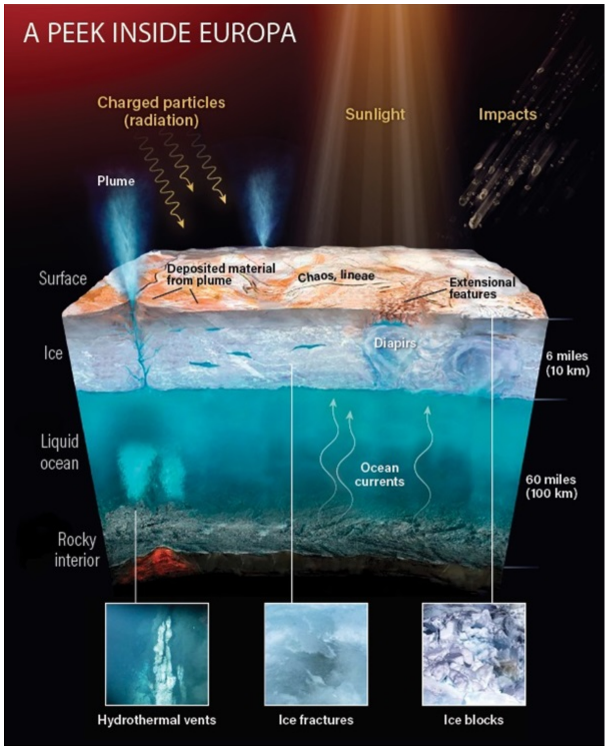


Figure 20: A diagram showing the internal structure of Europa (Source: Astronomy Magazine)

Europa has a subsurface ocean that is liquified because of tidal heating. There is a thick layer of ice on top of the ocean, and a rocky mantle and metallic core beneath it. Little is directly known about the ocean, but it is likely rich in sulfate salts, and may have hydrothermal vents similar to those found on Earth. There are also occasional plumes of water from the ocean that spew out through the icy crust as a result of tidal flexing, or tidal force effects that force apart parts of the thick ice layer.

8.3 Atmosphere

Europa has an extremely thin oxygen and water vapor atmosphere. There is an interestingly movement of atmospheric particles, where the radiation is strong enough to split them. Similar to Io, there is a torus of gas around Europa too.

8.4 Possibility of Life

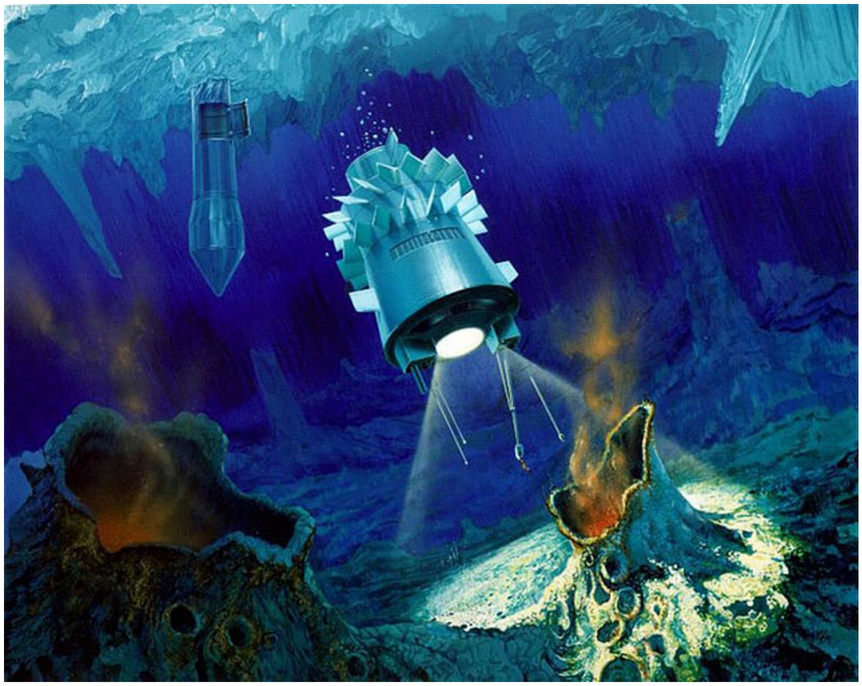


Figure 21: An artist's rendering of life on Europa (Source: Wikipedia)

Europa is considered to be the best possible candidate in the solar system for extraterrestrial life, because of the presence of large quantities of liquid water and energy. These are thought to be likely single celled, simple organisms living around deep sea vents, though there is the possibility for more advanced lifeforms and even full-fledged ecosystems. It would be extremely difficult to know this without a mission to the Europan surface that included a drilling rig and an autonomous underwater vehicle.

9 Other Jovian Moons

Jupiter has several dozen moons, and the list is still growing. Some of the most important other Jovian moons include the remaining Galilean moons, Ganymede and Callisto, and three of the Amalthean moons, Metis, Thebe, and Amalthea.

9.1 Ganymede

Figure 22: An image of Ganymede (Source: Wikipedia)

Ganymede is the largest moon in the solar system, larger than mercury by volume. It likely has an internal ocean, similar to that of Europa. However, the ice is likely thicker, and the world colder. There are more craters, as well as a layer of ice under the ocean. The upper layer is hexagonal ice, and the lower one tetragonal ice.

9.2 Callisto

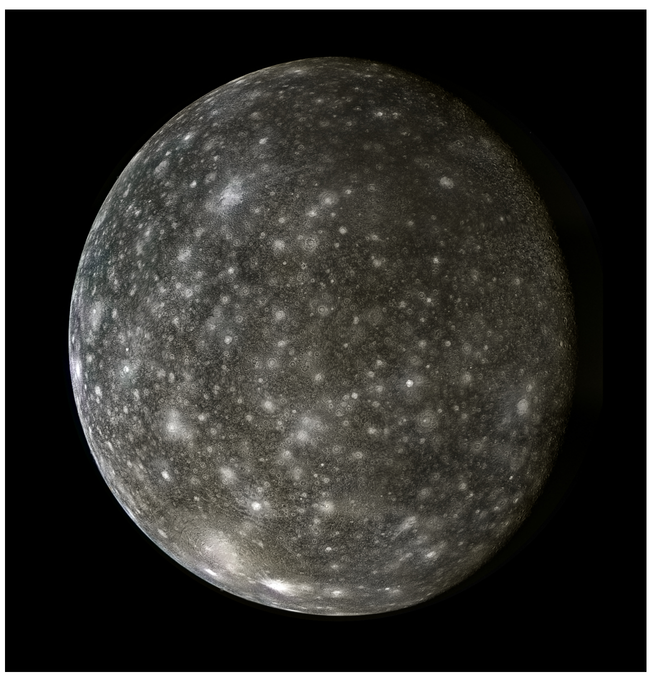


Figure 23: An image of Callisto (Source: Wikipedia)

Callisto is not part of the orbital resonance similar that the other Galilean moons are part of, and is heavily cratered as well. Similar to Ganymede and Europa, it also has an internal ocean, and is surrounded by layers of ice.

9.3 Metis

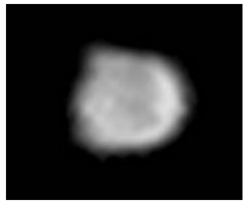


Figure 24: An image of Metis (Source: Wikipedia)

Metis is the closest moon to Jupiter, is tidally locked, and elongated.

9.4 Thebe

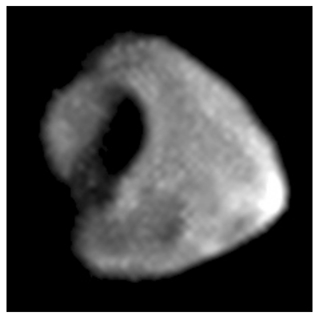


Figure 25: An image of Thebe (Source: Wikipedia)

Thebe is a misshapen satellite, and rotates synchronously.

9.5 Amalthea

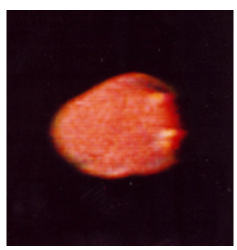


Figure 26: An image of Amalthea (Source: Wikipedia)

Amalthea is a red moon, likely due to sulfur and is fairly rigid. It also likely is fairly icy body and full of rubble.

10 Saturn

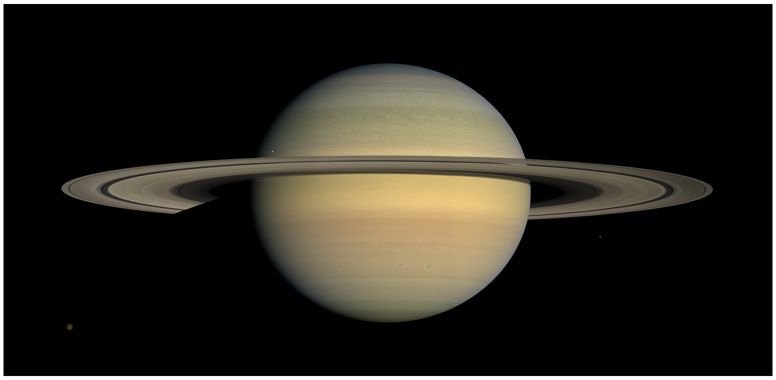


Figure 27: An image of Saturn (Source: Wikipedia)

Saturn is another gas giant planet famed for it its rings and low density (Saturn would float in water!)

10.1 Structure

Saturn is mainly hydrogen, with a metallic hydrogen and rocky core. Saturn's interior is warmer than expected, possibly due to the settling of helium in Saturn. Saturn is relatively oblate for a planet.

10.2 Ring System

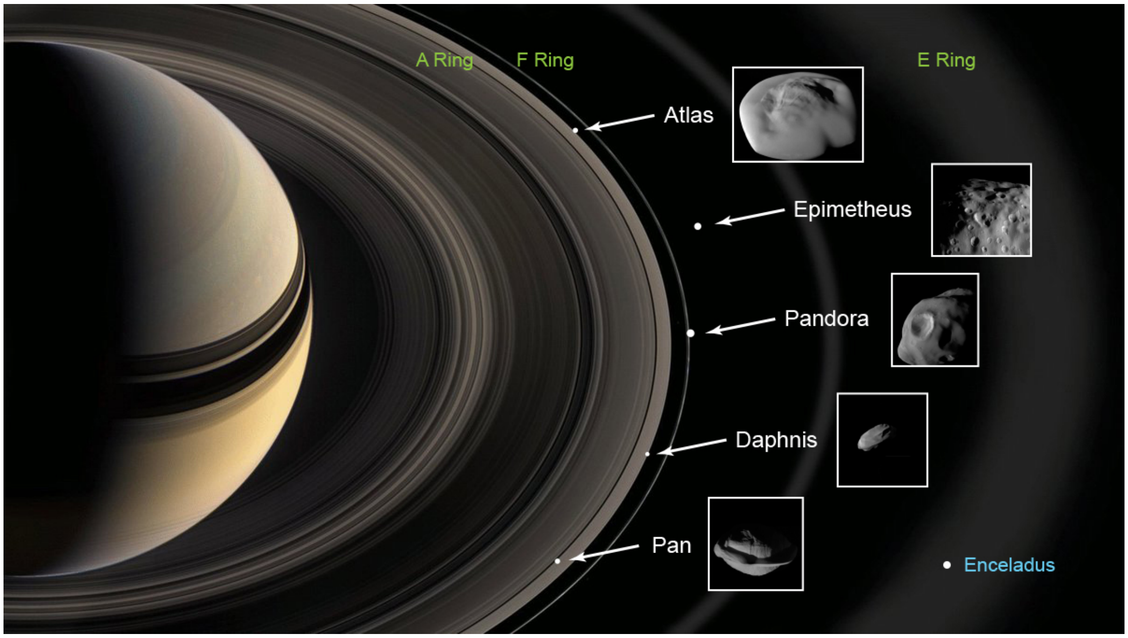


Figure 28: An image of Saturn's rings (Source: NASA)

Saturn is surrounded by a large an complex series of rings, primarily made up of ice and a small amount of rocky material. The rings are highly reflective, and grouped into individual sub-rings and gaps, often controlled by resonances satellites of Saturn.

10.3 Ring Formation

The ring formation process is unknown, and still hotly debated. They are generally thought to have formed a long time ago, but that is not certain. One theory proposes that they were formed as the result of a moon ripped apart by tidal forces, another that they were formed by moons crashing into each other. Another theory is that it could have been caused by significant outflows from others.

10.4 Ring Process

Many different process effect rings, most primarily resonances with larger bodies that prevent them from existing in various parts of the ring. Drag effects are also very important, as well as the Poynting-Robertson effect, an effect where particles absorb and re-emit light causing particles to fall inwards.

10.5 Atmosphere

Saturn's upper atmosphere is hydrogen, with ammonia crystals, and few storms.There is a cycle of eddies that exist, as well as bands similar to that of Jupiter. Most famously, Saturn has a hexagon shaped polar vortex at the north pole, likely formed by a standing wave. It is thought to have a clear eyewall.

11 Titan

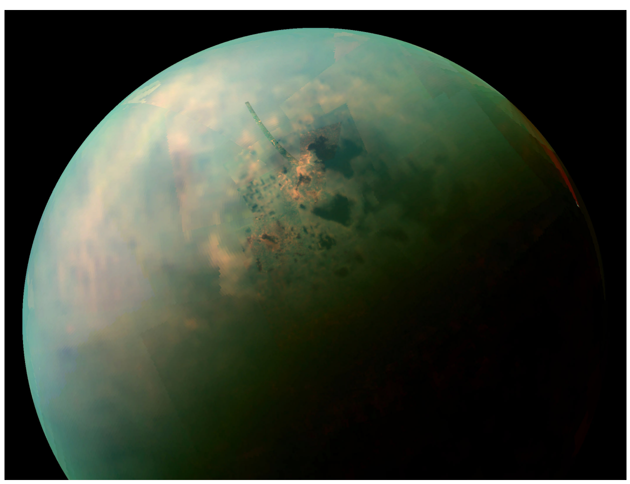


Figure 29: An image of Titan (Source: Universe Today)

Titan is one of the most fascinating moons in the solar system, with lakes and rain made out of hydrocarbons!

11.1 Atmosphere

Titan has a significantly dense nitrogen rich atmosphere. The atmosphere is fairly opaque, and has significant methane amounts, as well as other hydrocarbons. These forms from photolyses of organic chemicals. It also has significant clouds.

11.2 Surface

Titan's surface is very young, and has significant tectonic activity and channels. There are also many methane lakes, rivers, and seas, and the expected weathering features that would correspond.

11.3 Climate

Titan is very cold, but much warmer than would be expected because of the very small amount of light that reaches the surface of Titan. However, Titan experiences a strong greenhouse effect, warming it much more. Cloud formation is tied to the seasons on Titan.

11.4 Lakes

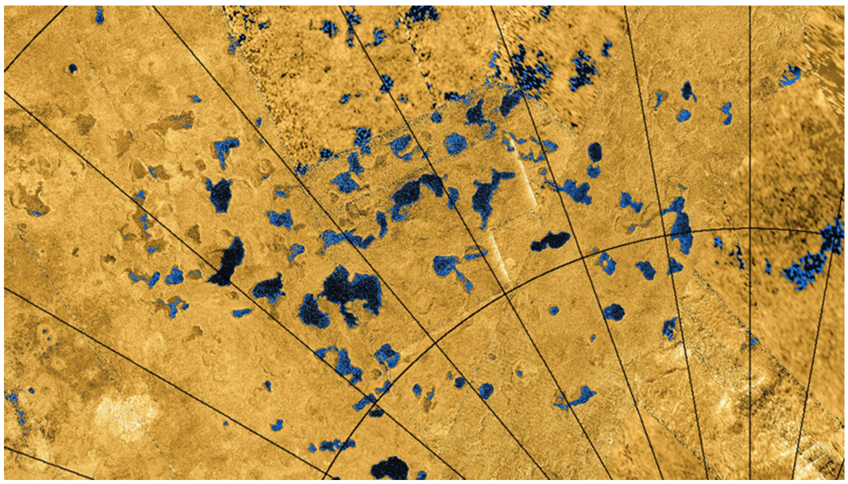


Figure 30: An artist's rendering of methane lakes on Titan (Source: NASA)

Titan has a unique hydrocarbon cycle similar to that of the hydrologic cycle on Earth. The hydrocarbon cycle does, however, have lower erosion than water, and is less prevalent. Many of these lakes may also be salty with similar chemicals to lakes. There may also be underground hydrocarbon aquifers.

11.5 Mountains

Titan also has mountain-esque features, but instead created via cryovolcanic eruptions of water and ammonia. There may also be upwelling events as well.

12 Uranus

Figure 31: An image of Uranus (Source: Wikipedia)

Uranus is the closer of the two gas giants, and has a unique orbital tilt.

12.1 Orbital Parameters

Uranus has a much higher axial tilt than any of the other planets. This leads to poles getting 42 years of sunlight and darkness on and off. This also means the polar regions are warmer. The explanation for this is an ancient protoplanet that collided with Uranus and forced it off axis.

12.2 Rings

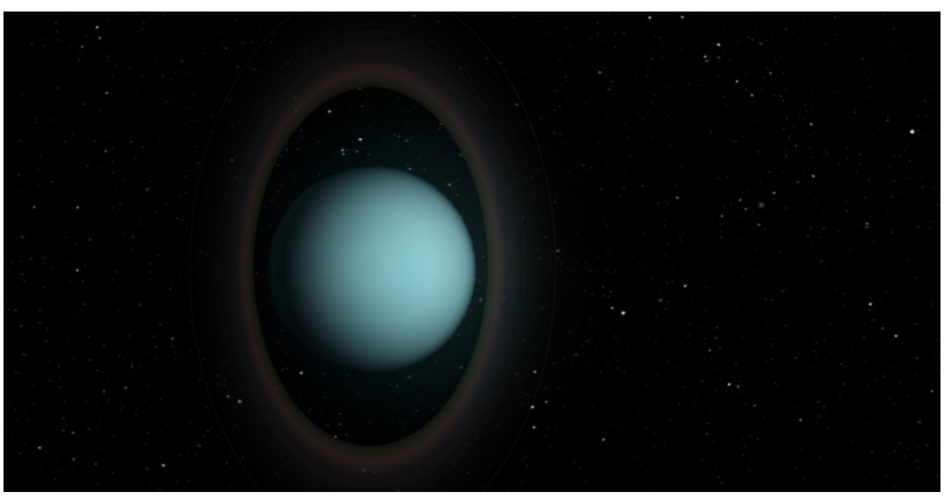


Figure 32: An image of the Uranian rings (Source: NRAO)

Uranus' rings have dark particles, and are likely young. Uranus's rings were detected when they occulted a distant star.

12.3 Tilt Origin

The tilt of Uranus' origin is unknown. One of the leading theories is that a single impact or a series of impacts by one or more large protoplanets that caused it to tilt off-orbit. Other theories have suggested that the gravitational influence of a protoplanet or an ancient moon could have caused the tilt.

12.4 Atmosphere

Uranus' atmosphere is fairly uniform, except for a brighter polar region due to dense methane clouds caused by higher temperatures there (this is the pole that is facing the sun). There are some seasonal variations in Uranus' cloud coverage due to distance from the sun, but these are extremely minimal compared to all other planets, even Venus.

13 Neptune

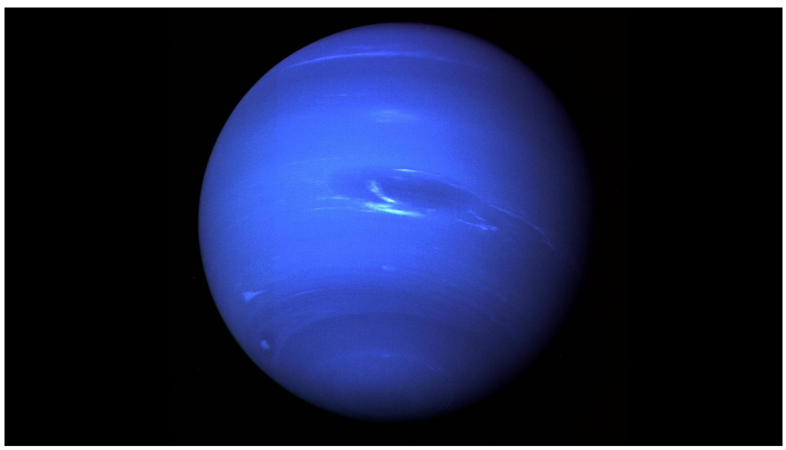


Figure 33: An image of Neptune (Source: Space.com)

Neptune is the farthest of the ice giants, famed for its storms.

13.1 Composition

Uranus and Neptune have similar compositions of hydrogen and helium atmospheres, but with a large percentage of ice than the gas giants. Ice here includes water, ammonia, and methane ices. The inner core region is both rock and ice. Neptune has a more stratified atmosphere that Uranus.

13.2 Orbital Parameters

Neptune has an incredibly long orbit that approaches that of Uranus and which the orbit of Pluto crosses. Neptune is inclined enough to cause seasons, although they are very long. Neptune also has significant effects on the Kuiper belt through resonances.

13.3 Storms

The most famous storm on Neptune is the Great Dark Spot, a storm similar to the Great Red Spot that disappeared. Neptune's storms are thought to occur from dark, lower clouds as methane cyclones. These storms are poorly understood, but thought to occur near the break in Neptune's atmospheric composition.

14 Pluto and Charon

Figure 34: An image of Pluto (Source: University of Arizona)

Pluto and Charon are two dwarf planets in the Kuiper Belt, a ring of smaller rocky bodies past the orbit of Neptune.

14.1 What is a Planet?

According to the IAU or International Astronomical Union, a planet meets all three of the following criteria, while a dwarf planet meets the first two:

- orbits the sun
- enough self-gravity to achieve a round shape in hydrostatic equilibrium and overcome rigid forces
- has cleared its neighborhood of debris

14.2 Tidal Locking

Pluto and Charon are tidally locked, meaning they have the same face facing each other all the time.

14.3 Geology

Pluto is covered in nitrogen ice plains. It has a large heart-shaped glacier, which has polygonal convection ice cells making glacier flow clear. It may have an ocean below the surface from radioactive element decay.

15 Asteroids

Asteroids are a type of rocky body scattered in several locations throughout the solar system.

15.1 Types of Asteroids

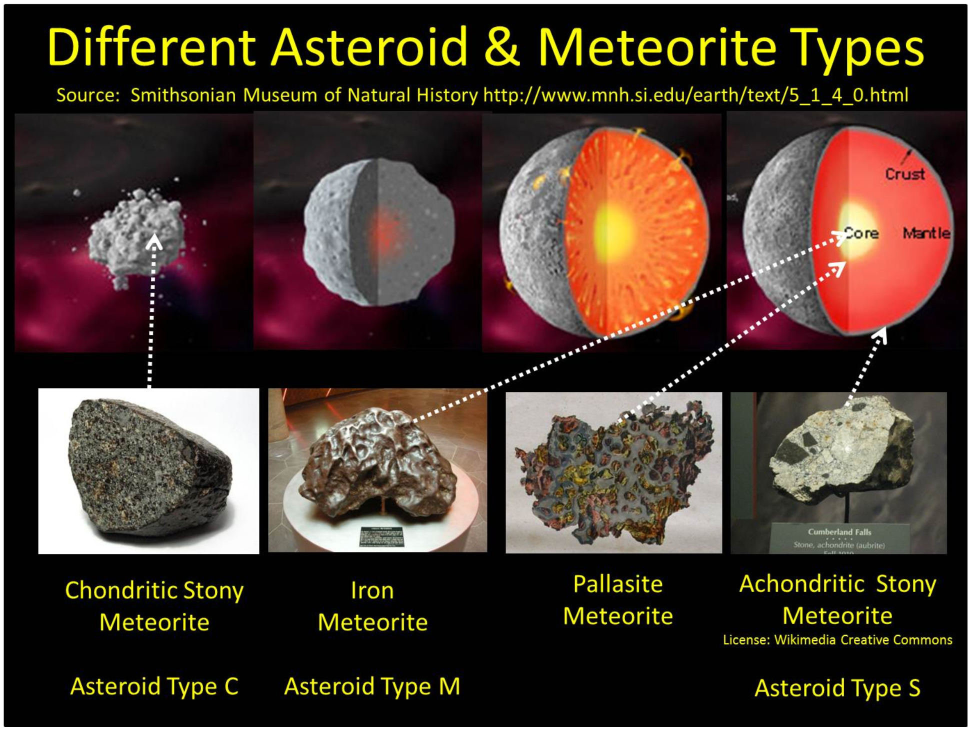


Figure 35: A diagram classifying the types of asteroid (Source: Smithsonian)

Asteroids are classified into three types. C-type, or chondrites, are the most common and made of silicates and clay. They are dark and ancient. S-type or stony asteroids are made of metals and silicates, while M-type of metallic asteroids are just made of metals.

15.2 Locations

Asteroids are found in the asteroid belt, but there are also Trojan asteroids at the L4 and L5 Lagrange points, where the gravity of Earth and the Sun balance out stably. Various other asteroid groups exist.

15.3 Importance

Asteroids are important because of the possibility of large impacts on Earth, as well as because of their ability to retain and reveal the geologic composition of the early solar system and other planets.

16 Comets

Comets are a bright phenomenon that come streaking in and out of the inner solar system.

16.1 Structure

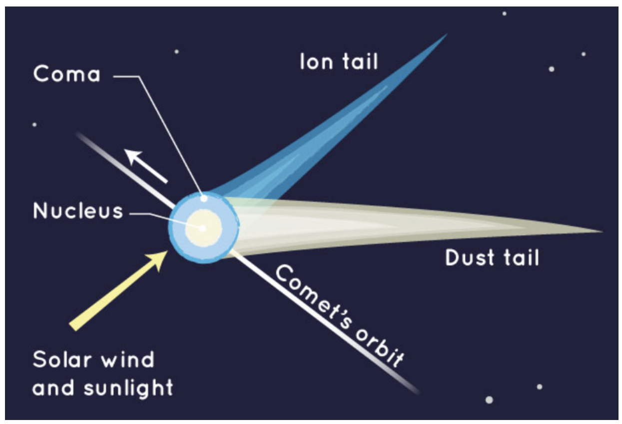


Figure 36: A diagram labelling the parts of a comet superimposed on an image (Source: NASA)

Comets are modeled by the dirt snowball model, which describes them as a central ball of ice and rocky material, with a coma of gas as dust around them, and a dust tail and an ion tail. As they approach the sun, the ice sublimates to form the coma and tails, and reduces the comet's mass. Some facts about the ion and dust tails:

- The ion tail is approximately straight and often consists of linear streamers. Their spectra show emission lines of ionized molecules (nitrogen, carbon monoxide, etc.).
- The dust tail is broader and gently curved. It is rich in dust particles that reflect light, making it visible from afar.
- Ion tails are much more influenced by solar wind and thus point directly away from the Sun. Dust tails are much more influenced by the comet's orbit and curve, thus "lagging" behind due to fewer interactions.

16.2 Long vs. Short Period

Comets are classified into long and short period depending on their origin. Short period comets come from closer by, in the Kuiper Belt or further in and could be seen multiple times in human history. On the other hand, long period comets come from the Oort Cloud or outside of the solar system and are have not been seen multiple times in human history.

16.3 Importance

Comets are important because they are thought to have contributed key water to a young Earth, allowing for the planet to have developed the way it has. Isotopic compositions between water ices from comets match those found in Earth largely.