The Sun and the Solar System

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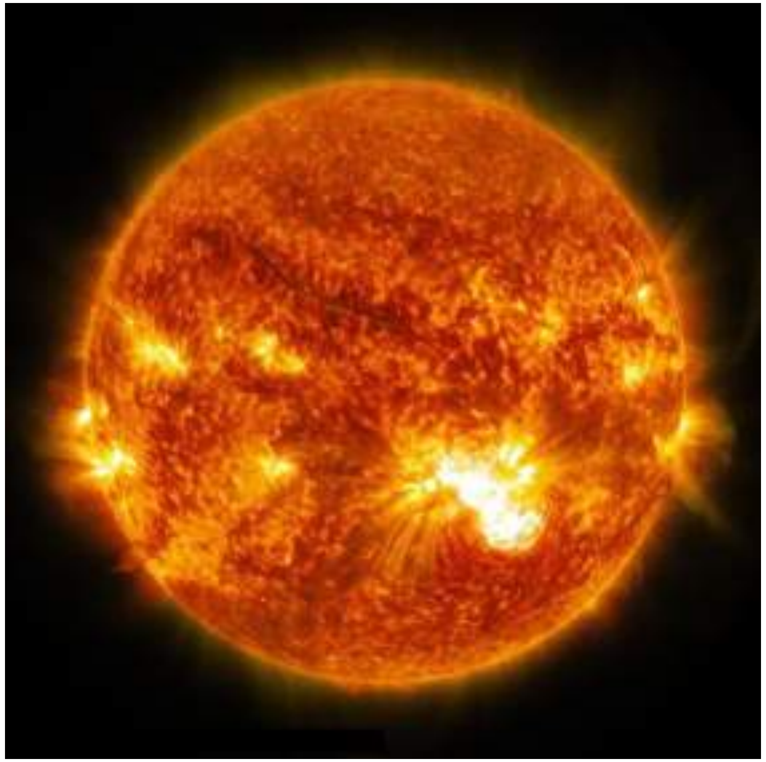
The Sun

- The Sun is a ***4.5 billion-year-old yellow dwarf*** star at the center of our solar system. It is a G2 V, yellow dwarf main- sequence star.

- It is about ***93 million miles (150 million kilometers)*** from Earth and the only star in our solar system. Amount of time it takes for light from the Sun to reach Earth is about eight minutes.

- The Sun is the largest object in our solar system. Its diameter is about ***865,000 miles (1.4 million kilometers).*** It is about 109 times wider than the Earth – about 1.3 million Earths could fit inside the Sun.



- The Earth and all other objects in our solar system orbit around the Sun due to gravity – the ***Sun contains over 98% of all mass in the solar system*** and so exerts a strong gravitational pull.

- The Sun is a dynamic star that is constantly changing and sending energy out into space. The science of studying the Sun and its influence throughout the solar system is called ***heliophysics***.

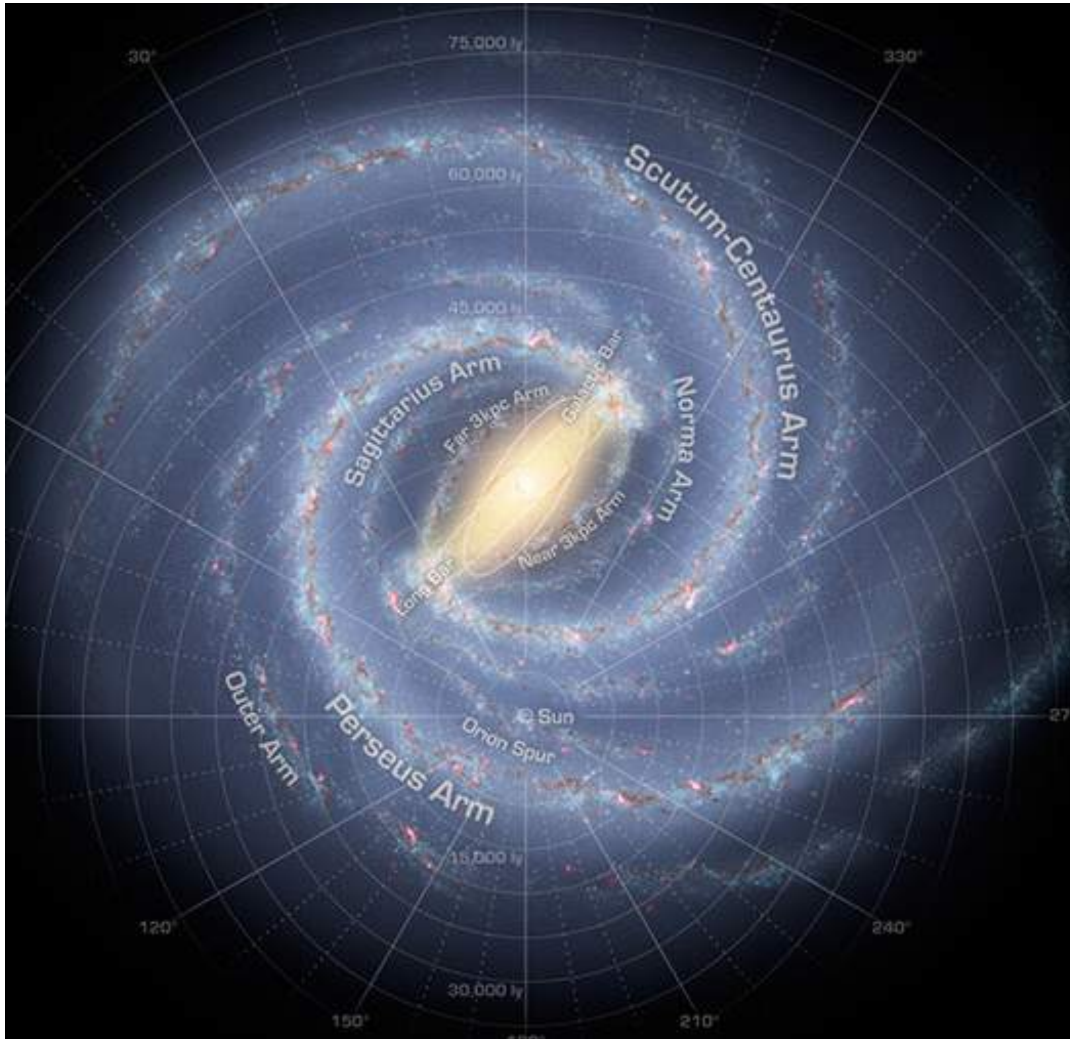
- Like other stars, the Sun is a dense ball of gas that creates energy through ***nuclear fusion reactions in the core***, creating helium atoms from hydrogen atoms.

- The Sun radiates different forms of energy, ***including ultraviolet, infrared, and light energy***, out into space. Light and heat energy from the Sun warm our planet and make life possible.

- The Sun is located in the Milky Way galaxy in a spiral arm called the ***Orion Spur*** that extends outward from the Sagittarius arm.

- The Sun orbits the center of the Milky Way, bringing with it the planets, asteroids, comets, and other objects in our solar system.

- The Sun rotates on its axis as it revolves around the galaxy. Its spin has a tilt of 7.25 degrees with respect to the plane of the planets’ orbits. Since the Sun is not solid, ***different parts rotate at different rates. At the equator, the Sun spins around once about every 25 Earth days, but at its poles, the Sun rotates once on its axis every 36 Earth days.***



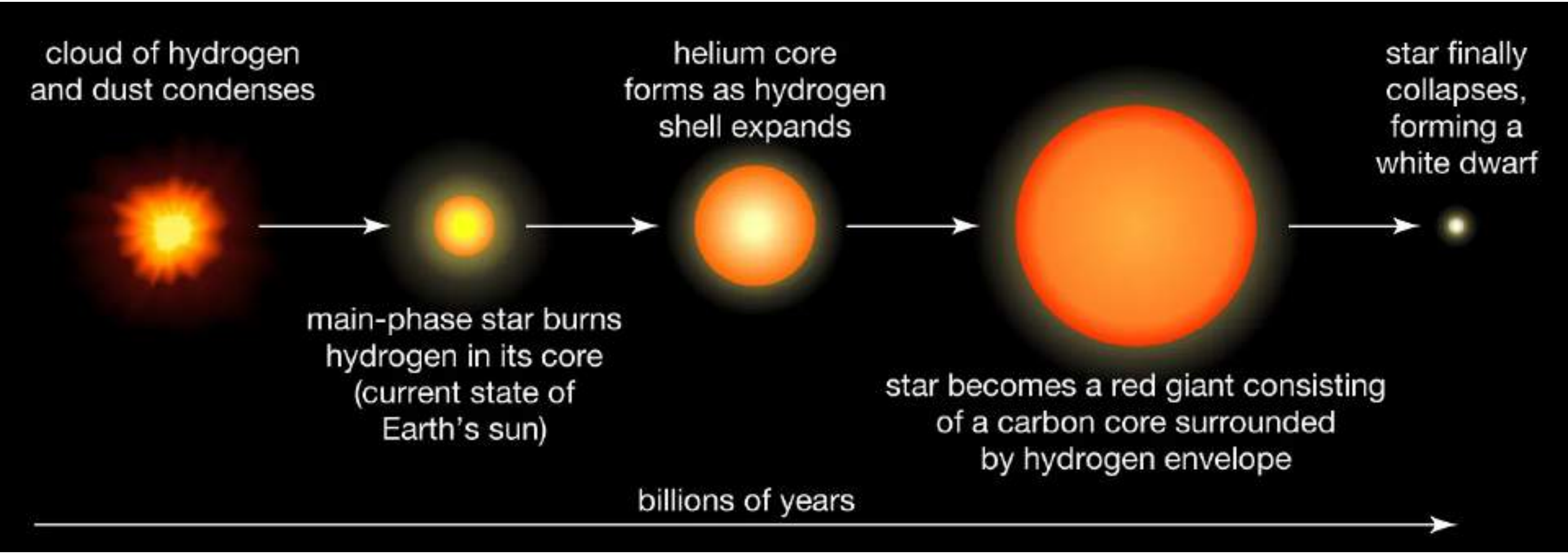
Formation of the sun

- The Sun formed about 4.6 billion years ago in a giant, spinning cloud of gas and dust called the solar nebula. As the nebula collapsed under its own gravity, it spun faster and flattened into a disk.

- Most of the nebula's material was pulled toward the center to form our Sun, which accounts for 99.8% of our solar system’s mass. Much of the remaining material formed the planets and other objects that now orbit the Sun.

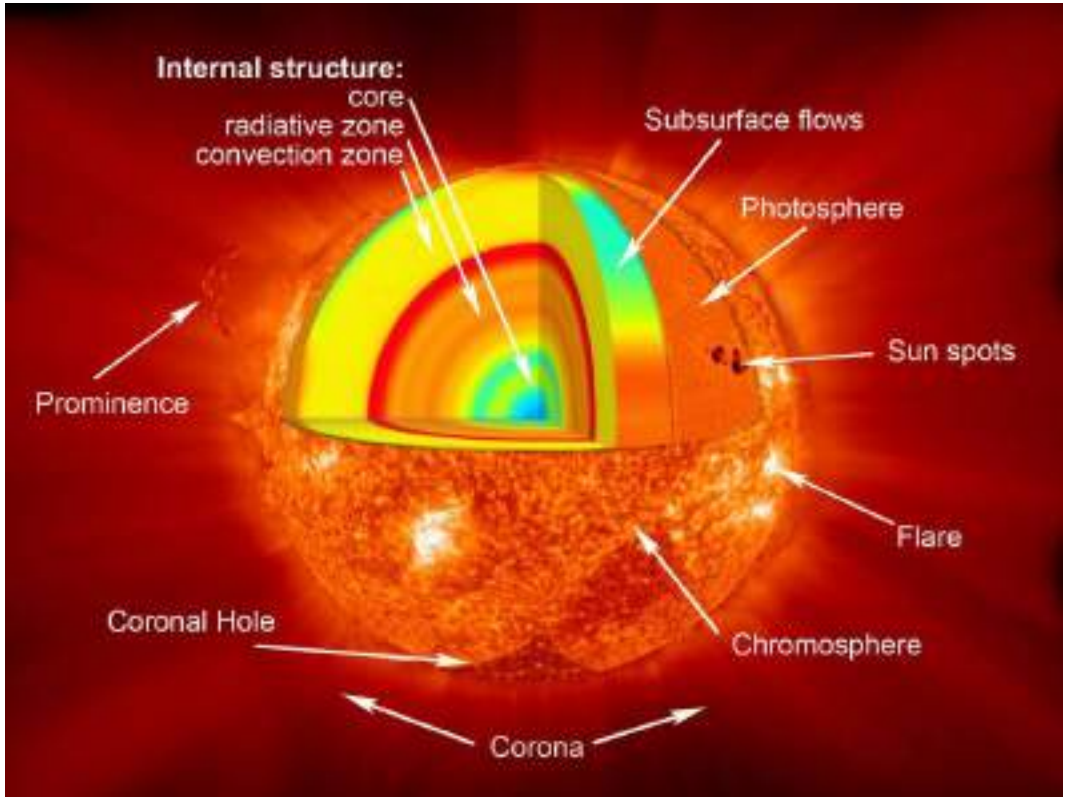
- Like all stars, our Sun will eventually run out of energy. When it starts to die, the Sun will expand into a red giant star, becoming so large that it will engulf Mercury and Venus, and possibly Earth as well. Scientists predict the Sun is a little less than halfway through its lifetime and will last another 5 billion years or so before it becomes a white dwarf.

Evolution of a Sun-like star



Structure of the sun

- The interior regions include:
  - ***the core*** : It is the hottest part of the Sun. Nuclear reactions (where H is fused to form He) power the Sun’s heat and light. The temperature is about 15 million °C and its about 138,000 km thick. The density of the Sun’s core is about 150 gm/cc.
  - ***the radiative zone :*** extends outward from the outer edge of the core to base of the convection zone, characterized by the method of energy transport – radiation. Energy moves slowly outward, taking more than 170,000 years to radiate through this layer of the Sun.



- ***the convection zone*** : the outer-most layer of the solar interior extending from a depth of about 200,000 km to the visible surface where its motion is seen as granules and supergranules. Energy continues to move toward the surface through convection currents of the heated and cooled gas.

The solar atmosphere is made up of:

- **Photosphere** : It is the visible surface of the Sun.
- **Chromosphere** : It is an irregular layer above the photosphere where the temperature rises from 6000°C to about 20,000°C.
- **Transition Region** : It is a thin and very irregular layer of the Sun's atmosphere that separates the hot corona from the much cooler chromosphere.
- **Corona** : it is the Sun's outer atmosphere.

  Beyond the corona is the solar wind, which is actually an outward flow of coronal gas. The sun's magnetic fields rise through the convection zone and erupt through the photosphere into the chromosphere and corona. The eruptions lead to solar activity, which includes such phenomena as sunspots, flares, prominences, and coronal mass ejections.

Properties of Photosphere

- Photosphere is the innermost layer of the Sun that we can observe directly. It is the layer where most of the sun’s energy is emitted.
- The temperature of the photosphere ranges from 11,000 degrees Fahrenheit (6,125 degrees Celsius) at the bottom to 7,460 F (4,125 C) at the top. The photosphere is significantly cooler than temperatures at the sun's core.
- The sun's photosphere is about 300 miles (500 kilometers) thick, which is relatively thin when compared with the 435,000 miles (700,000 km) radius of the sun.
- The photosphere is marked by bright, bubbling granules of plasma and darker, cooler sunspots, which emerge when the sun's magnetic field breaks through the surface.
- The photosphere is also the source of solar flares: tongues of fire that extend hundreds of thousands of miles above the sun's surface. Solar flares produce bursts of X-Rays, UV radiation, electromagnetic radiation and radio waves.

Properties of Chromosphere

- The chromosphere is a layer in the Sun between about 250 miles (400 km) and 1300 miles (2100 km) above the solar surface (the photosphere).
- The chromosphere emits a reddish glow as super-heated hydrogen burns off. But the red rim can only be seen during a total solar eclipse. At other times, light from the chromosphere is usually too weak to be seen against the brighter photosphere.
- Physically, the chromosphere begins near the surface of the photosphere with a temperature near 4700 Celsius and a density of 10^{17} particles/cm^3, and at its highest level reaches a temperature near 25,000 Celsius and a lower density of 1010 particles/cm^3 (2×10^{-11} kg/m^3). But rather than being just a homogenous shell of plasma, it resembles the troposphere of our own planet Earth with complex storms and other phenomena roiling its volume from minute to minute. The reason for this is that the magnetic fields formed at or below the surface of the photosphere are not confined to the solar surface, but extend through-out the chromosphere.

FIG: Solar eclipse during 1999

- The chromosphere may play a role in conducting heat from the interior of the sun to its outermost layer, the corona.
- It is a complex zone of plasma and magnetic field, which transmits matter and energy between the photosphere and the corona.
- The NASA, IRIS solar observatory, launched in 2013 has instruments specifically designed to study the temperature, density and mass flows in the Chromosphere.

Properties of Corona

- The corona is the outermost layer of the Sun, starting at about 1300 miles (2100 km) above the solar surface (the photosphere). It appears as white streamers or plumes of ionized gas that flow outward into space.
- The temperature in the corona is 500,000 K (900,000 degrees F, 500,000 degrees C) or more, up to a few million K.
- The corona cannot be seen with the naked eye except during a total solar eclipse, or with the use of a coronagraph. The corona does not have an upper limit.

Solar System

- The planetary system of the solar system is located in an outer spiral arm of the Milky Way galaxy.
- Our solar system consists of our star, the Sun, and everything bound to it by gravity – the planets Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune; dwarf planets such as Pluto; dozens of moons; and millions of asteroids, comets, and meteoroids.
- Our solar system extends much farther than the eight planets that orbit the Sun. The solar system also includes the Kuiper Belt that lies past Neptune's orbit. This is a sparsely occupied ring of icy bodies, almost all smaller than the most popular Kuiper Belt Object – dwarf planet Pluto.

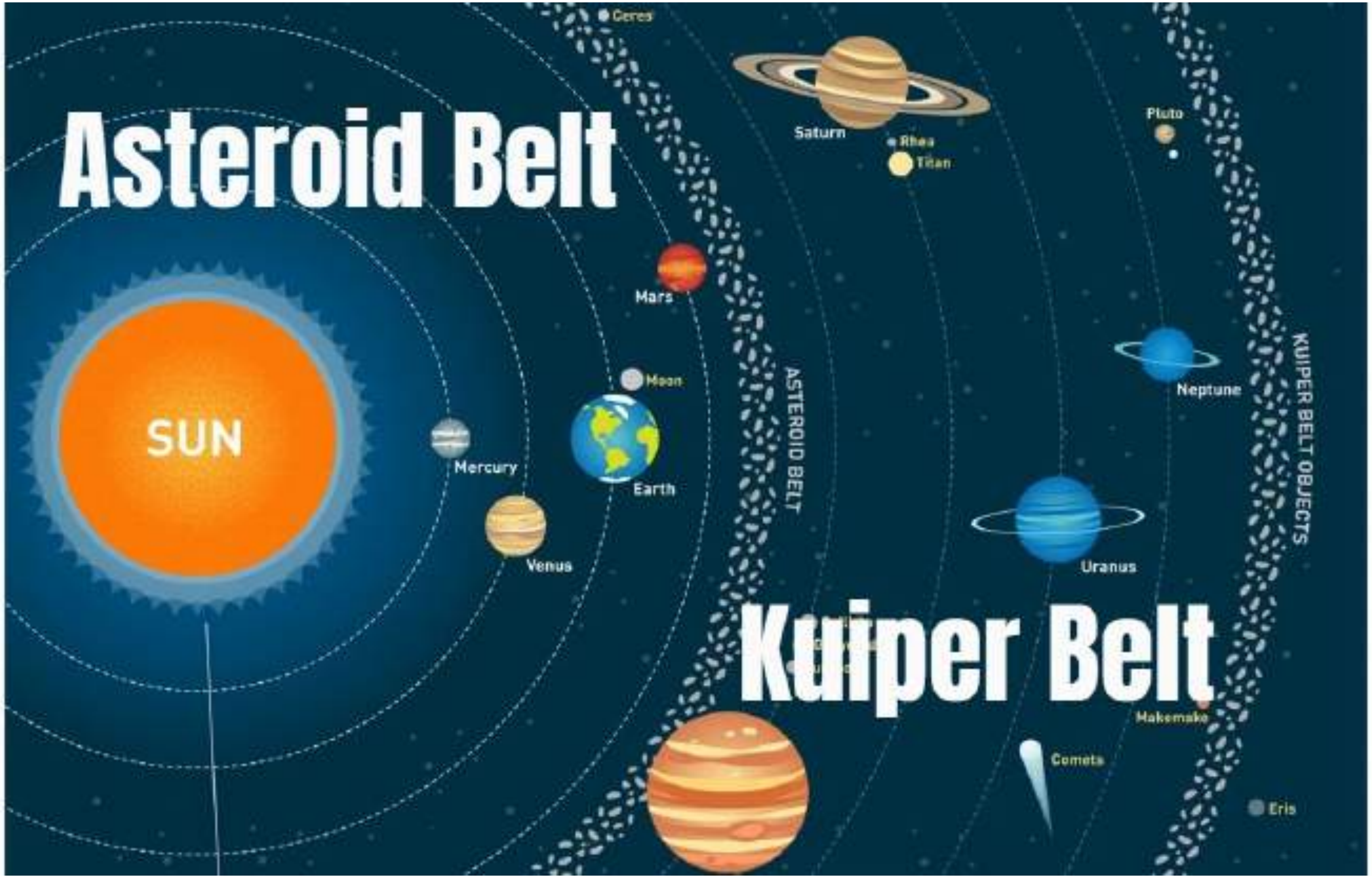


Figure: Sun and the solar system

- Beyond the fringes of the Kuiper Belt is the **Oort Cloud**. This giant spherical shell surrounds our solar system. It has never been directly observed, but its existence is predicted based on mathematical models and observations of comets that likely originate there.

- The **Oort Cloud** is made of icy pieces of space debris - some bigger than mountains – orbiting our Sun as far as 1.6 light-years away. This shell of material is thick, extending from 5,000 astronomical units to 100,000 astronomical units. One astronomical unit (or AU) is the distance from the Sun to Earth, or about 93 million miles (150 million kilometers). The Oort Cloud is the boundary of the Sun's gravitational influence, where orbiting objects can turn around and return closer to our Sun.

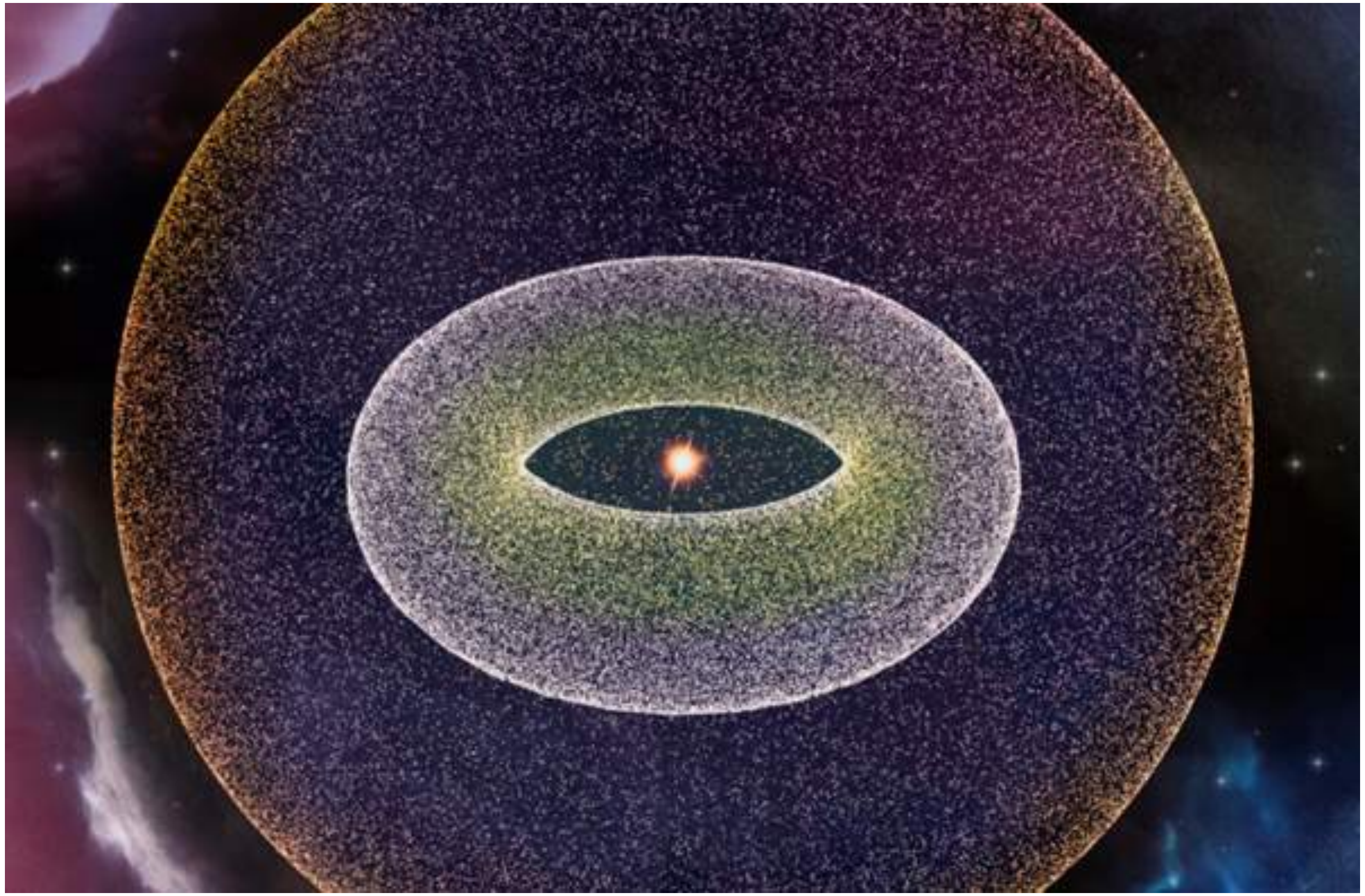


Figure: Oort Cloud

- The Sun's heliosphere doesn't extend quite as far. The heliosphere is the bubble created by the solar wind – a stream of electrically charged gas blowing outward from the Sun in all directions. The boundary where the solar wind is abruptly slowed by pressure from interstellar gases is called the termination shock. This edge occurs between 80-100 astronomical units.

- Two NASA spacecraft launched in 1977 have crossed the termination shock: Voyager 1 in 2004 and Voyager 2 in 2007. Voyager 1 went interstellar in 2012 and Voyager 2 joined it in 2018. But it will be many thousands of years before the two Voyagers exit the Oort Cloud.

Theory of formation of the solar system : Nebular hypothesis

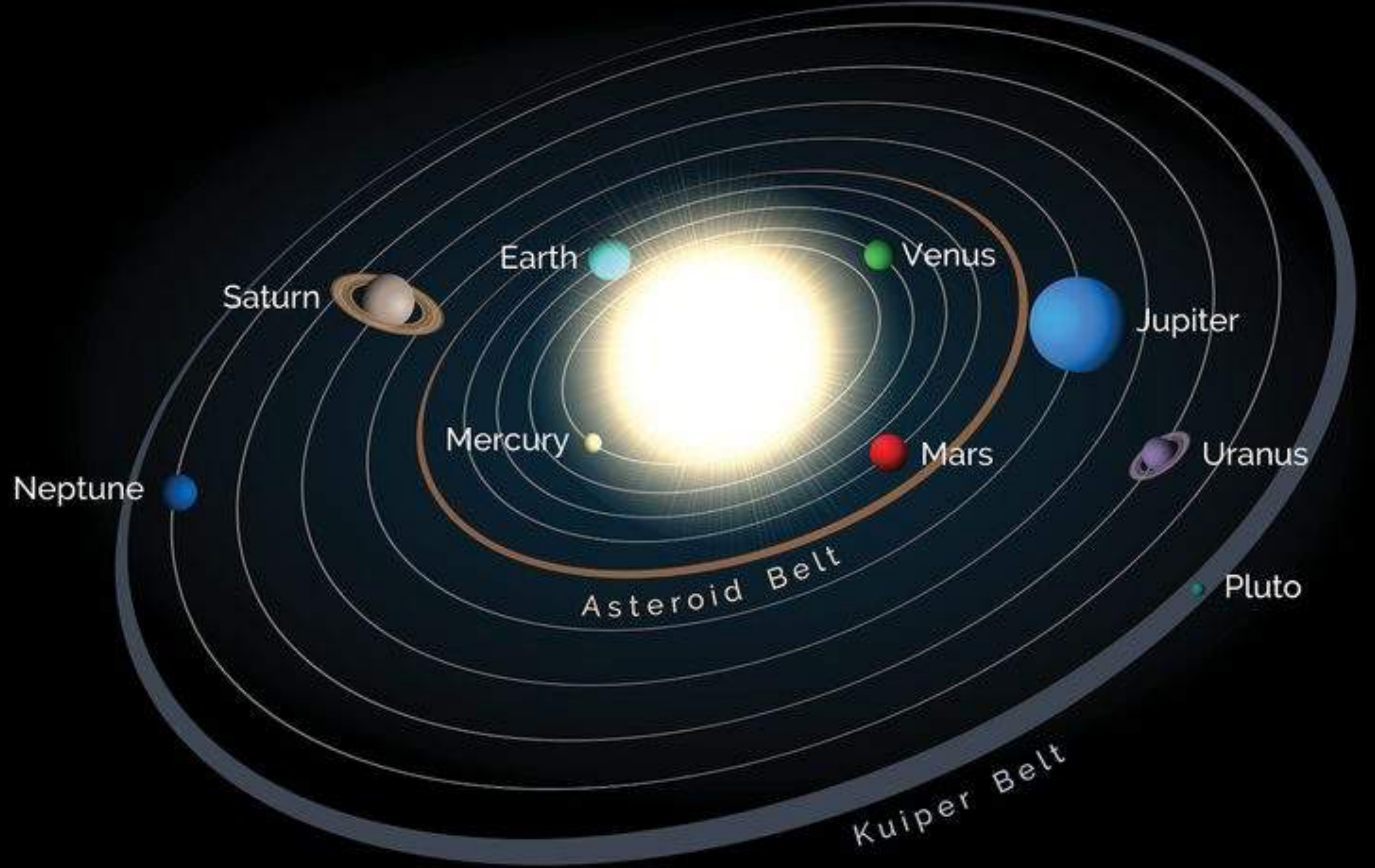
- This theory was proposed by German Philosopher “Immanuel Kent” and revised by Mathematician “Laplace”.
- Our solar system formed about 4.5 billion years ago from a dense cloud of interstellar gas and dust. The cloud collapsed, possibly due to the shockwave of a nearby exploding star, called a supernova. When this dust cloud collapsed, it formed a solar nebula – a spinning, swirling disk of material.
- The nebula resulted from an uneven distribution of gases throughout the universe. As the gravitational pull began to condense the gas toward the centre, the speed of the speed of the rotation increased, this resulted the cloud to flatten creating an accretion disk.
- At the center, gravity pulled more and more material in. Eventually, the pressure in the core was so great that hydrogen atoms began to combine and form helium, releasing a tremendous amount of energy. With that, our Sun was born, and it eventually amassed more than 99% of the available matter.

- Matter farther out in the disk was also clumping together. These clumps smashed into one another, forming larger and larger objects. Some of them grew big enough for their gravity to shape them into spheres, becoming planets, dwarf planets, and large moons. In other cases, planets did not form: the asteroid belt is made of bits and pieces of the early solar system that could never quite come together into a planet. Other smaller leftover pieces became asteroids, comets, meteoroids, and small, irregular moons.

Structure of the Solar System

- The order and arrangement of the planets and other bodies in our solar system is due to the way the solar system formed. Nearest to the Sun, only rocky material could withstand the heat when the solar system was young. For this reason, the first four planets – Mercury, Venus, Earth, and Mars – are terrestrial planets. They are all small with solid, rocky surfaces.
- Meanwhile, materials we are used to seeing as ice, liquid, or gas settled in the outer regions of the young solar system. Gravity pulled these materials together, and that is where we find gas giants Jupiter and Saturn, and the ice giants Uranus and Neptune.

SOLAR SYSTEM



Physical properties of the Planets

Composition

The **average density** gives a rough idea of the composition of a planet.

$$\rho = \frac{M}{V} = \frac{M}{\frac{4}{3}\pi R^3}$$

ρ = density, *M* = mass of the object , *V* = volume of the object = $\frac{4}{3}\pi R^3$ (for spheres)

R = radius of the spherical object

- Average density of water: ρ_{water} = 1000 kg/m^3
- Average density of metal: ρ_{metal} = 13,000 kg/m^3
- Average density of rock: ρ_{rock} = 3000 kg/m^3

- The **terrestrial planets** (ρ = 4000-5500 kg/m^3) are made of **rocky materials** and have dense **iron cores**.
- The **Jovian planets** (ρ = 700-1700 kg/m^3) are composed primarily of light elements such as **hydrogen and helium.**

Newton/Kepler's law determines the planet mass

Newton's Law of Universal Gravitation accounts for Kepler's laws and explains the motions of a binary system.

$$F_G = G\frac{mM}{r^2}$$

F = gravitational force between two objects (in newtons)

m = mass of the planet (in kilograms)

M = mass of the Sun (in kilograms)

r = distance between planet and Sun (in meters)

$G = 6.67\times10^{-11}\ Nm^2/kg^2$, universal constant of gravitation

Newton's form of Kepler's third law (determination of distance of the planet from the sun)

- The gravitational (pull or attractive) force keeps the planets orbiting the Sun.
- $F = m\omega^2 r = \frac{4\pi^2 mr}{P^2} = F_G$
- Newton demonstrated that Kepler's
- third law follows logically the law of gravity,
- and can be re-written as:

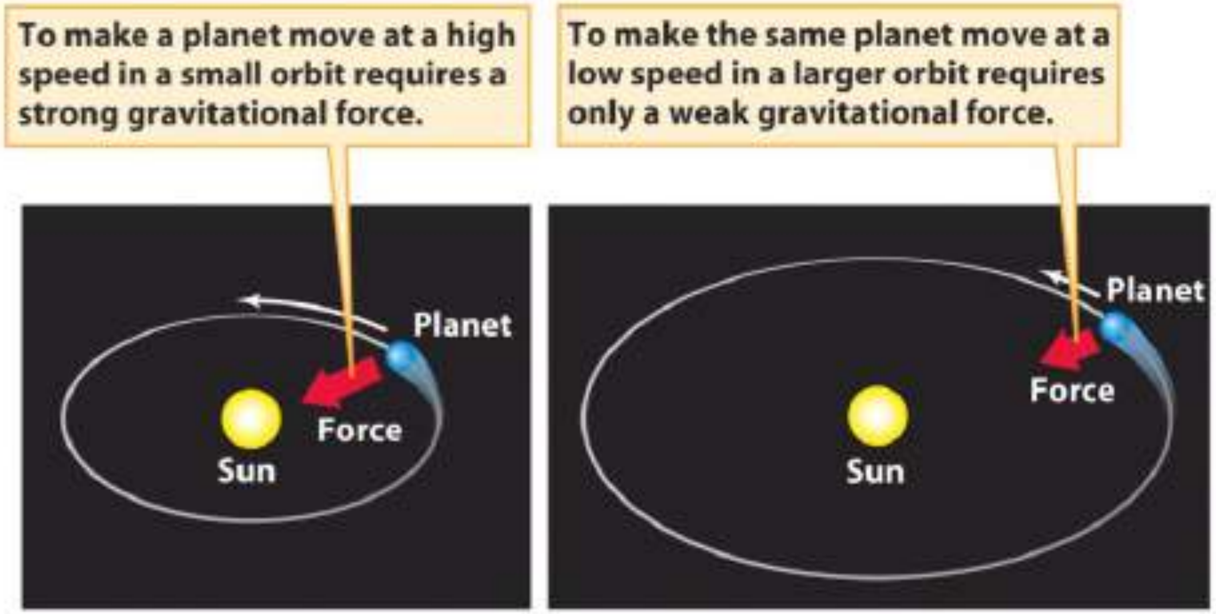
$$a^3 = \left[\frac{GM}{4\pi^2}\right]P^2$$

- P = sidereal period, in seconds

  a = semimajor axis, in meters

  M = mass of the Sun, in kg

  G = universal constant of gravitation $= 6.67 \times 10^{-11}\ Nm^2/kg^2$



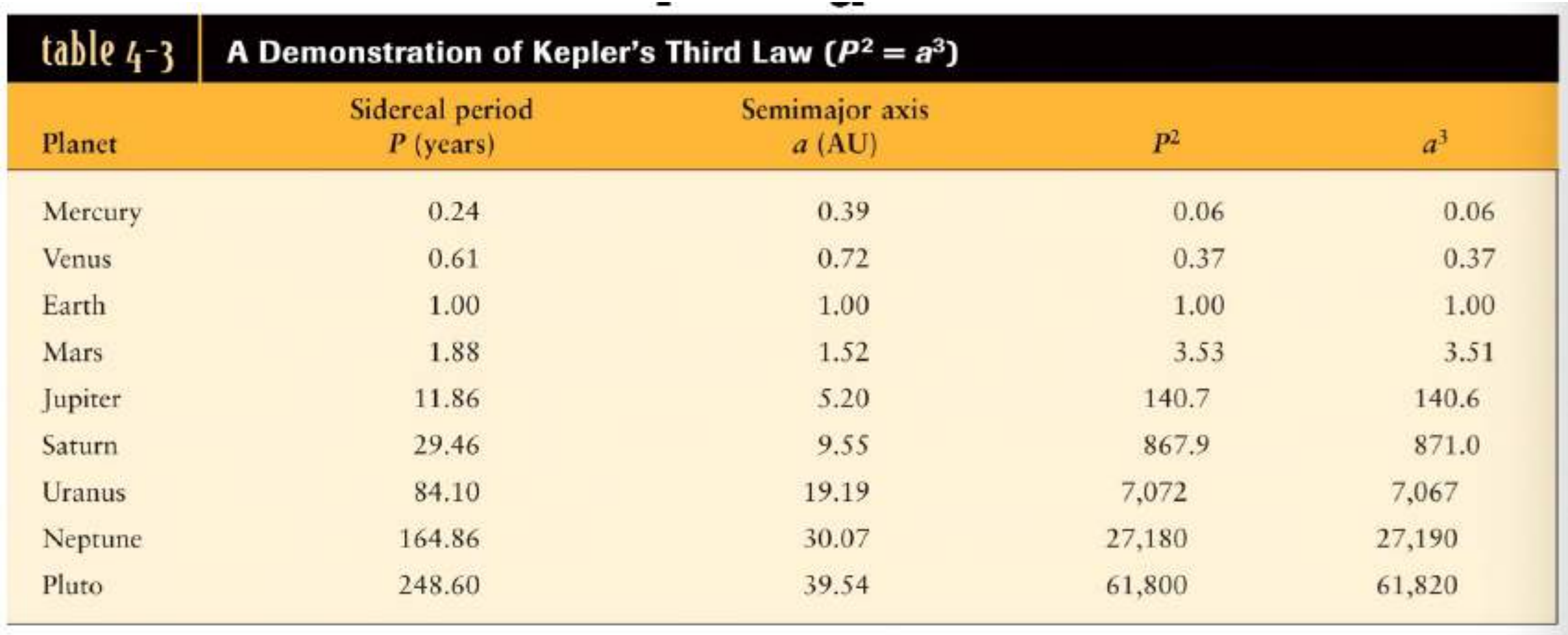


table 4-3 A Demonstration of Kepler's Third Law ($P^2 = a^3$)

Planet	Sidereal period P (years)	Semimajor axis a (AU)	P^2	a^3
Mercury	0.24	0.39	0.06	0.06
Venus	0.61	0.72	0.37	0.37
Earth	1.00	1.00	1.00	1.00
Mars	1.88	1.52	3.53	3.51
Jupiter	11.86	5.20	140.7	140.6
Saturn	29.46	9.55	867.9	871.0
Uranus	84.10	19.19	7,072	7,067
Neptune	164.86	30.07	27,180	27,190
Pluto	248.60	39.54	61,800	61,820

The further away from the sun, the longer it takes to finish one orbit. Kepler's law also applies to asteroids and comets, all solar system objects that **orbit the Sun**.

Atmosphere of the Planet

Whether gases can stay in a planet's atmosphere depends on the combination of the following three factors:

1. **Planet's mass and size**: gravity can retaining as particles.
2. **Gas composition** : light gases run faster than heavy gases.
3. **Temperature:** gases at higher temperature run faster.

When an object has a high enough speed, it can escape from the planet's gravity (think about how we launch a rocket). The escape speed is:

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

M= mass of the planet (kg)
R= radius of the planet
G= gravitational constant

The average speed of a gas at a temperature is given as:

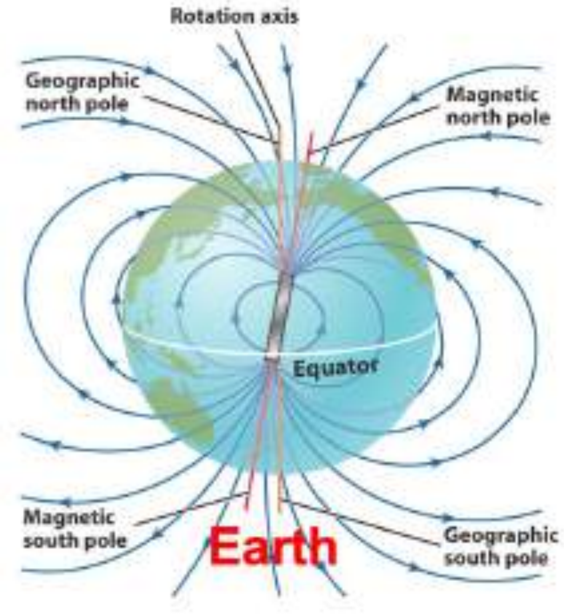
$$v_{th} = \left(\frac{3kT}{m}\right)^{1/2}$$

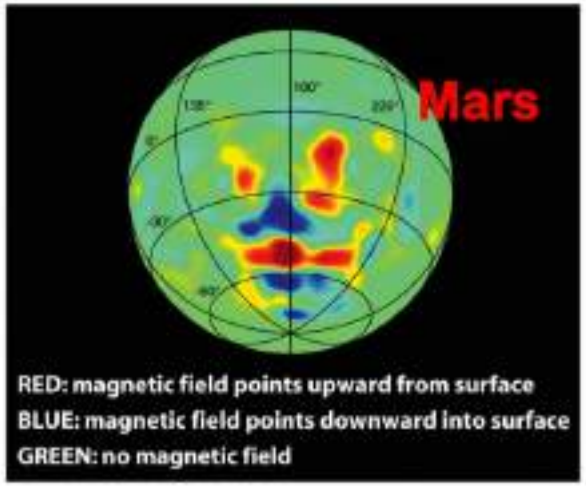
m = gas mass(kg)
T = temperature (K=kelvins)
v_{th} = speed (m/sec);\
k = Boltzmann constant

- If $6\,v_{th} > v_{esc}$, the particles (atoms or molecules) escape.
- If $6\,v_{th} < v_{esc}$, the particles (atoms or molecules) stay
- Higher temperature, less likely to retain a gas.
- Gas particles with smaller mass (m), less likely to be retained.
- Planet of larger mass (M), more likely to retain a gas.
- **Terrestrial planets**: high temperature, weak gravity, so low mass gases escape and **massive gases stay**.
- **Jovian planets**: low temperature, strong gravity, can **retain** even very light **gases**, e.g., hydrogen and helium.

Magnetic Fields

- A planet with a magnetic field indicates a **fluid interior in motion**
- Planetary magnetic fields are produced by the motion of electrically conducting liquids inside the planet.
- This mechanism is called a **dynamo.**
- If a planet has no magnetic field, that is evidence that there is little such liquid material in the planet’s interior or that the liquid is not in a state of motion.
- The magnetic fields of **terrestrial planets** are produced by metals such as iron in the liquid state.
- Mercury and Earth have global magnetic field.
- Mars has magnetized regions.





- Magnetic field is not found in Venus, may be due to its slow rotation.
- The stronger fields of the **Jovian planets** are generated by liquid metallic hydrogen (Jupiter & Saturn) or by water with ionized molecules dissolved in it (Uranus and Neptune).
- Jupiter, Saturn, Uranus and Neptune all have global magnetic field.
- Jupiter has the strongest magnetic field among all planets.

Asteroids: Asteroid Belt

- **Asteroids** are small **rocky** objects, orbiting the Sun at distances of 2 to 3.5 AU in `the **asteroid belt**’, between Mars and Jupiter. They are the remnants left over from the early formation of our solar system about 4.6 billion years ago.
- Their shapes are not known, but variations in brightness suggest that they are irregular.
- Their size ranges from meters to hundreds of meters in diameter.
- Asteroids have been classified in two ways:

According to their orbits: The orbits of asteroids provide a way to estimate the rate of impact on the various planets. For example : the perihelia (the point in the orbit closest to the Sun) of Amor asteroids lie inside the orbit of Mars but outside the orbit of Earth. Clearly, the objects of this class can impact Mars but not Earth.

According to their optical properties such as **albedo** and **spectral reflectivity** which provide some indication of composition.

Composition *of* Asteroids

The three broad composition classes of asteroids are C-, S-, and M-types.

- The **C-type (chondrite)** asteroids are most common. They probably consist of clay and silicate rocks, and are dark in appearance. They are among the most ancient objects in the solar system.
- The **S-types (stony)** are made up of silicate materials and nickel-iron.
- The **M-types** are **metallic (nickel-iron).** The asteroids' compositional differences are related to how far from the Sun they formed. Some experienced high temperatures after they formed and partly melted, with iron sinking to the center and forcing basaltic (volcanic) lava to the surface.

Asteroid Belt

- The majority of known asteroids orbit within the asteroid belt between Mars and Jupiter, generally with not very elongated orbits. The belt is estimated to contain between 1.1 and 1.9 million asteroids larger than 1 kilometer (0.6 miles) in diameter, and millions of smaller ones. Early in the history of the solar system, the gravity of newly formed Jupiter brought an end to the formation of planetary bodies in this region and caused the small bodies to collide with one another, fragmenting them into the asteroids we observe today.
- This image depicts the two areas where most of the asteroids in the Solar System are found: the asteroid belt between Mars and Jupiter, and the trojans, two groups of asteroids moving ahead of and following Jupiter in its orbit around the Sun.

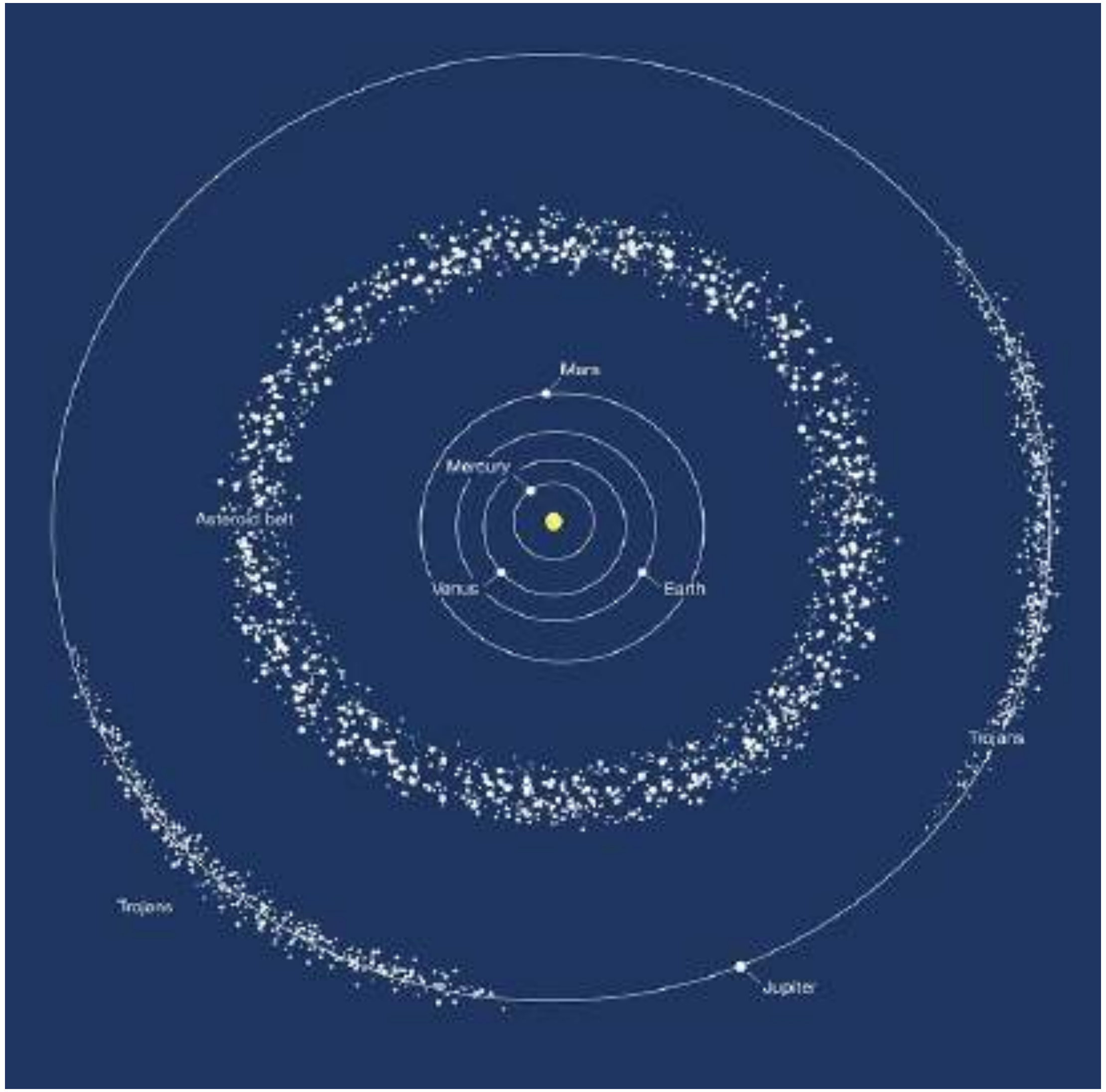


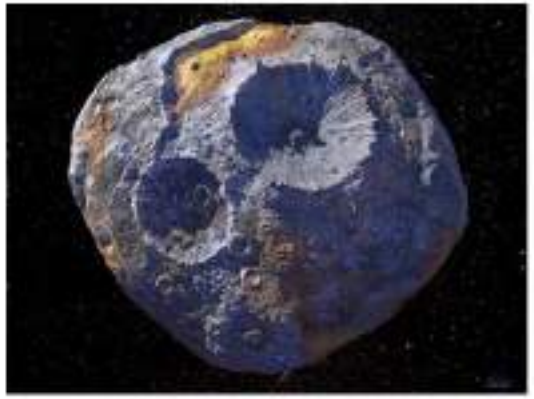
Figure: Asteroid Belt

101955 Bennu

433 Eros

4 Vesta

243 Ida



Asteroid Psyche

Didymos & Dimorphos

Meteoroids, Meteors and *Meteorite*

- **Meteoroids** are objects in space that range in size from dust grains to small asteroids. Think of them as “space rocks.”
- Sometimes one asteroid can smash into another which can cause small pieces of the asteroid to break off. Those pieces are called meteoroids whose sizes are smaller than the typical size of the asteroids.
- Meteoroids can also come from comets. When a meteoroid comes close enough to Earth and enters Earth’s atmosphere, it vaporizes and turns into a **meteor**- a streak of light in the sky also known as **shooting star** although they are not actually stars.
- When a meteoroid survives a trip through the atmosphere and hits the ground, it’s called a **meteorite**.


Iron Meteorite


Looking down on a shooting star


Perseid Meteor 2016


Impact on Asteroid Pallas

Thank you!