# SOLAR SYSTEM
# Formation, Evolution and Death

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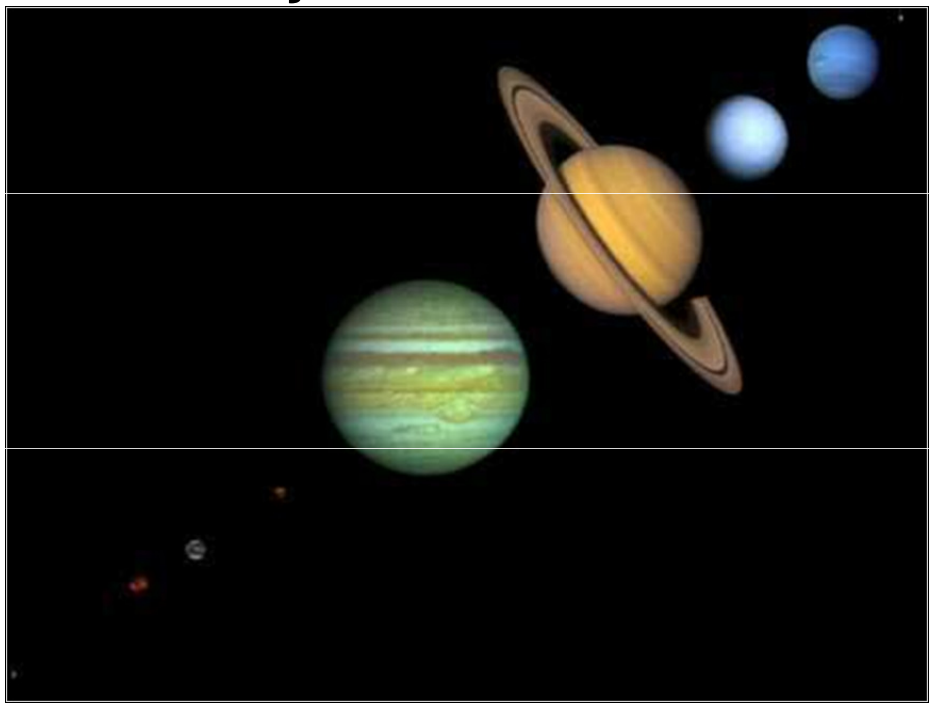
# DE2410: Learning Objectives

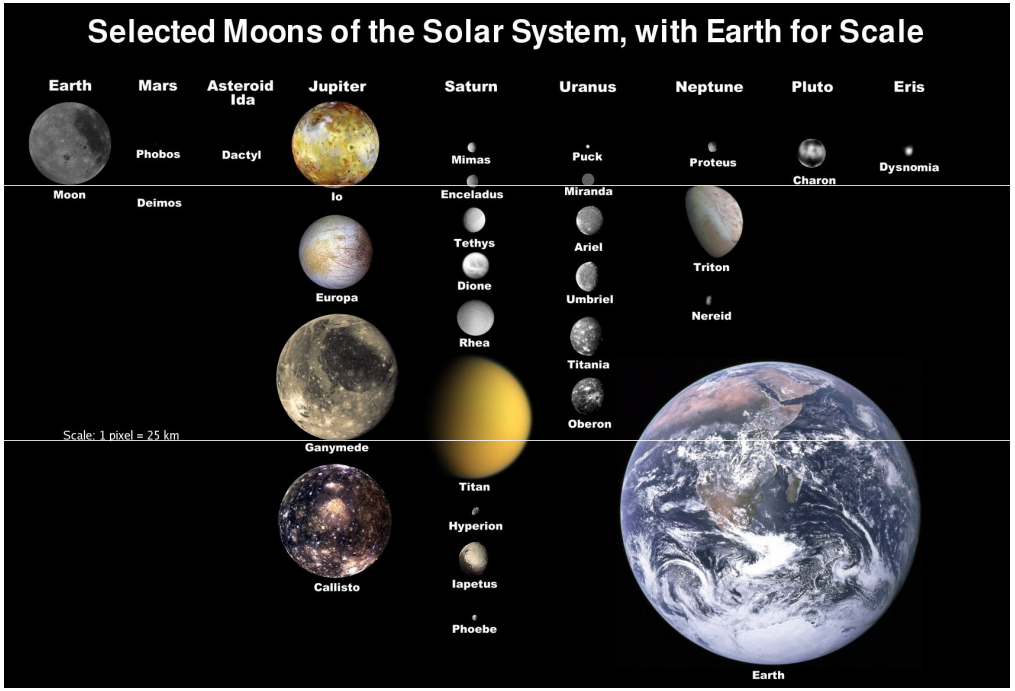
- To understand our planet, sun, and the solar system
- To understand the formation, and evolution of the solar system
- To understand the structure of the Universe
- To understand life on Earth, and search for extraterrestrial life
- Ultimately, to become a wise man, with correct understanding about where we live, and our place in the Universe.



# Solar System: To Size Scale



# Major Natural Satellites



# Learning Objectives : This Lecture

- What constitutes the solar system
- Understanding the scale model of the solar system
- Origin of the Sun and planets
- Fate of the Sun and Planets



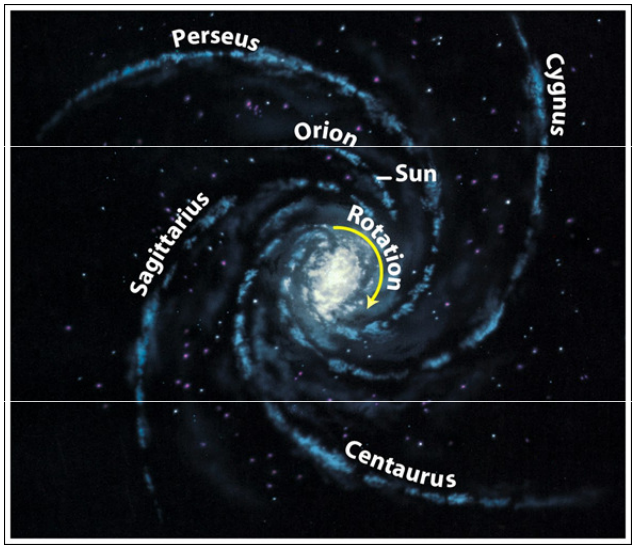
# Members of the Solar System

- Sun
- Eight planets
- More than 181 natural satellites (orbiting around planets)
- A large number of small bodies
  - Comets, asteroids
- Interplanetary medium
  - Kuiper belt and Oort cloud



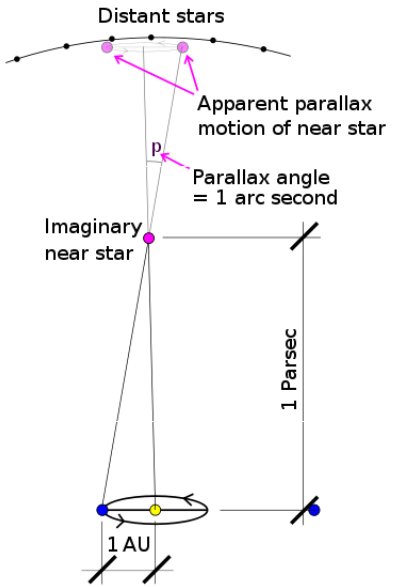
# Solar System Location

- The Solar System is in the Milky Way galaxy in its Orionis spiral arm, some 30,000 light years from the galactic centre. Its speed is about 220 km/s, thus, completes one revolution around the galactic centre in 220-250 million years. Since its formation, the Solar System has completed at least 18 such revolutions

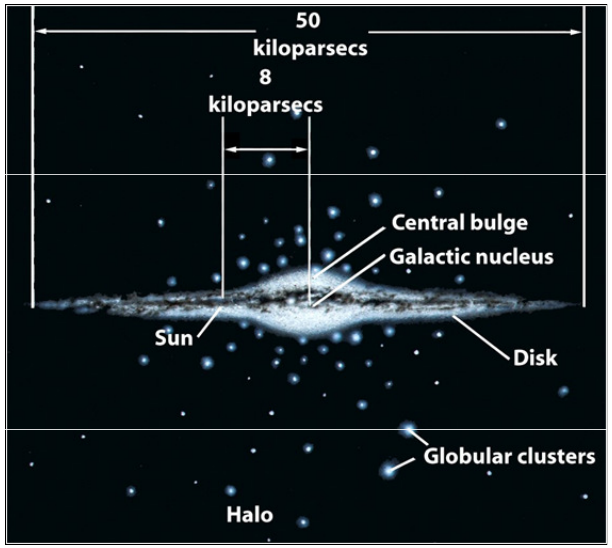





# Solar System Location




Earth's motion around Sun
1 AU 147.5 -152 x$10^6$ km



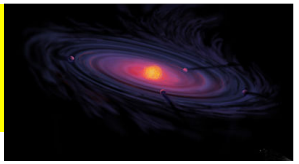

- 1 parsec = 3.262 light years
- 1 light year = 9.4605284 × $10^{12}$ km

# Solar System: 1/Billion Model

- What is the size of the Sun? 1.5m
- What is the size of the Earth? 1.4cm (a grape)
- How far is the Sun from the Earth? 160m
- How far is the Moon from the Earth? 40cm
- How big is the Jupiter? 15cm
- How far is Jupiter from the Sun 750m
- How far is the Saturn from the Sun 1500m
- How far are the Uranus/Neptune from the Sun 3km/4.8km
- How far is the nearest star from the Sun? 40km

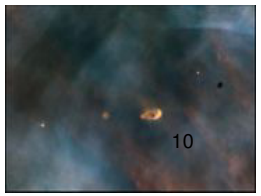


# Origin of the Solar System NEBULAE HYPOTHESIS



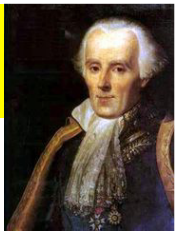
- Gravitational collapse of a small part of a giant molecular cloud
- Most of the collapsing mass collected in the centre, forming the Sun
- Rest of the mass flattened around into a protoplanetary disc
  - planets, moons, asteroids, and other small solar system bodies were formed

Hubble image of protoplanetary discs in the Orion nebula, a light-years-wide "stellar nursery"





# Nebulae Theory: A STRONG THEORY



P-S. Laplace

- Originated in the 18th century
  - Emanuel Swedenborg, Immanuel Kant, and Pierre-Simon Laplace
- Serious consideration in the space age in the 1950s
- 1980s: Acceptance with the observation of young stars being surrounded by cool discs of dust and gas
- 1990s: Strengthened by the discovery of extra-solar planets
- Theory has been refined based on the observations



# Nebulae Hypothesis: PROTOPLANETARY DISC

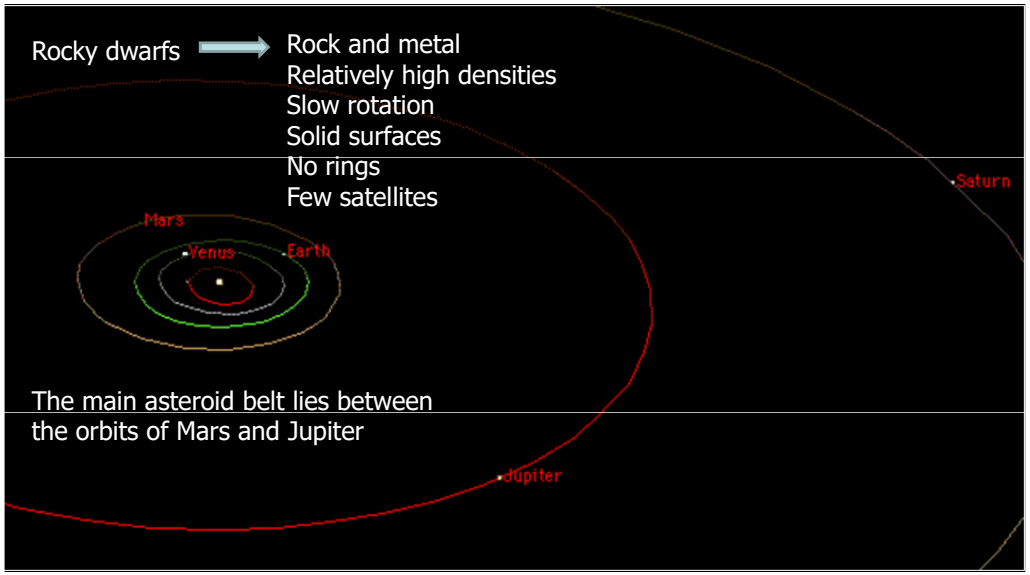
- Solar nebulae spun faster as it collapsed gravitationally
- As the nebulae collapsed, the molecules/particles began to collide with increasing frequency, converting their kinetic energy into heat.
- Gravity, gas pressure, magnetic fields, and rotation caused the contracting nebulae to flatten into a spinning protoplanetary disc with a diameter of 200 AU and form a hot, dense protostar (a star in which hydrogen fusion has not yet begun) at the centre.

# Nebulae Hypothesis: STABLE SUN and ACCRETION DISC

- Within 50 million years, the temperature and pressure at the core of the Sun became so great that its hydrogen began to fuse, creating an internal source of energy to counter the gravitational contraction
  - Sun became stable (hydrostatic equilibrium)
- Dust grains around the central Proto-Sun formed into clumps on 1-10km size by direct contact, which in turn collided to form larger bodies



# Inner Solar System: Rocky Dwarf






# Inner Solar System

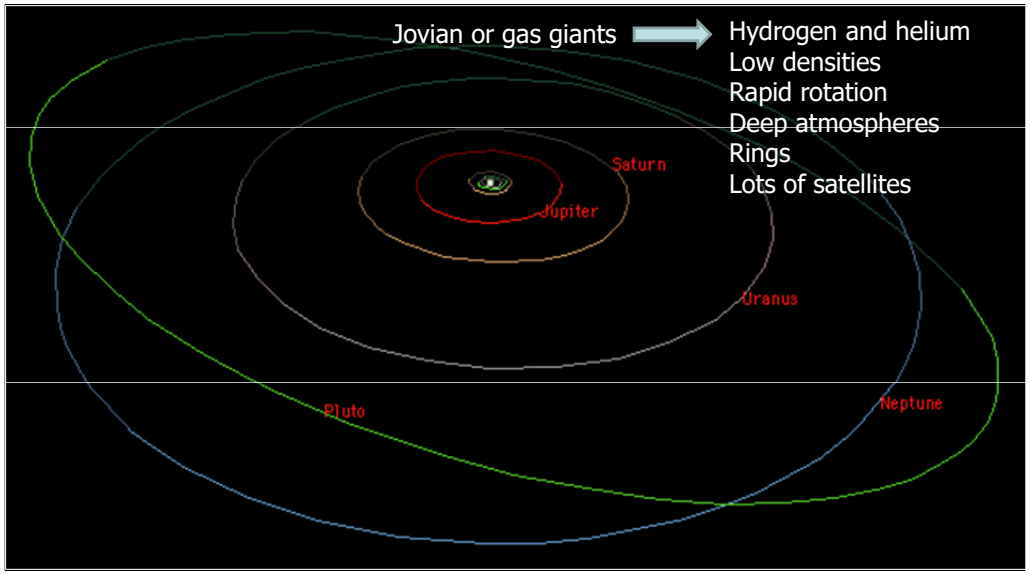
- Near the newborn Sun, temperature was so high that only the materials of high melting point could stay and form planets
  - Such as Fe, Ni, Al and rocky silicates
  - Inner solar system only comprise 0.6% of the nebulae mass
  - Thus small planetesimals were formed near the Sun
    - 50-100 Moon-Mars size bodies
- Solar wind (T-Tauri stage) of the new Sun swept away gasses to distant areas
- Within 100million years: inner solar system planetasimals collided and merged to form terrestrial planets
  - Mercury, Venus, Earth, and Mars



# Frost Line and Outer Solar System

- Beyond a distance from the Sun, temperature was low enough for gasses to condense and form planets
- Gasses were the most abundant (99% of mass), thus, bigger planets were formed far away from the Sun
  - Jupiter, Saturn, Uranus, Neptune
- Jupiter (5AU) was just outside the frost-line, and accumulated huge amount of mass
- Saturn was formed later, thus, accumulated less amount of gasses than Jupiter

# Outer Solar System: Gas Giants






# Uranus and Neptune

- Uranus, and Neptune are too big and too quick to be accreted at their distances from the Sun, thus, believed to have formed closer (between Jupiter and Saturn) and later moved outward
- After 500 million years almost all gas had been swept into interstellar space. Planet formation ceased



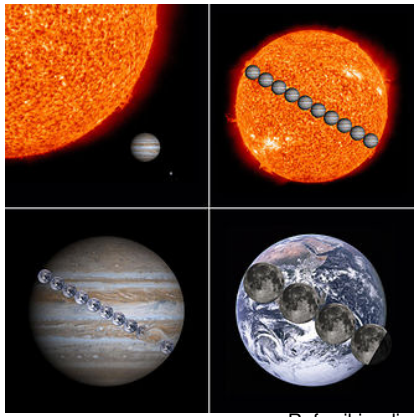
# Asteroid Belt

- With the formation of Jupiter and Saturn (5 million years), their gravity caused orbital resonance of nearby planetisimals that disturbed planet formation in the vicinity
  - Planetisimals in 2-4 AU couldn't accrete into planets
- Planetary embryos and small planetesimals of the asteroid belt might have been thrown out by Jupiter. And, some may have fallen on the Earth, bringing water here. Otherwise, water is too volatile to have been present at Earth's formation.



# Jupiter

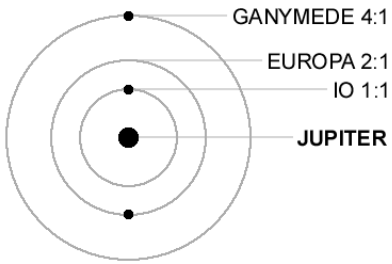
- Jupiter's diameter is one order of magnitude smaller (×0.10045) than the Sun, and one order of magnitude larger (×10.9733) than the Earth.
- The Great Red Spot has roughly the same size as the circumference of the Earth.
- The atmospheric proportions of hydrogen and helium are close to the theoretical composition of the primordial solar nebula



Ref: wikipedia

Jupiter is the only planet that has a center of mass with the Sun that lies outside the volume of the Sun. Jupiter's rotation is the fastest of all the Solar System's planets, completing a rotation on its axis in slightly less than ten hours; this creates an equatorial bulge easily seen through an Earth-based amateur telescope.

# Orbital Resonance



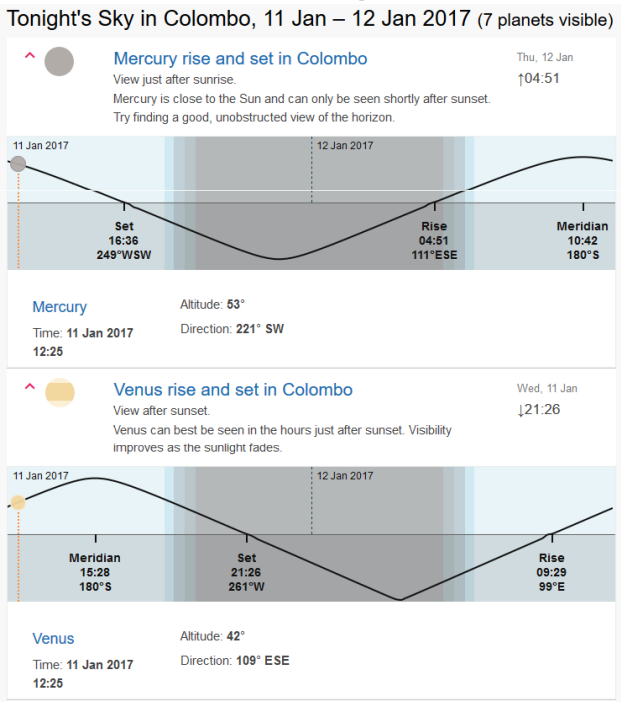

Galilean Moons

- Jupiter and Saturn underwent orbital changes and eventually reached 2:5 orbital resonance
- The Four Galileon moons of Jupiter has reached orbital resonance.
- Jupiter and Saturn caused Neptune to move outward, and also ejected planetisimals towards far reaches of the solar system



# Observing Planets

https://www.timeanddate.com/astronomy/night/sri-lanka/colombo



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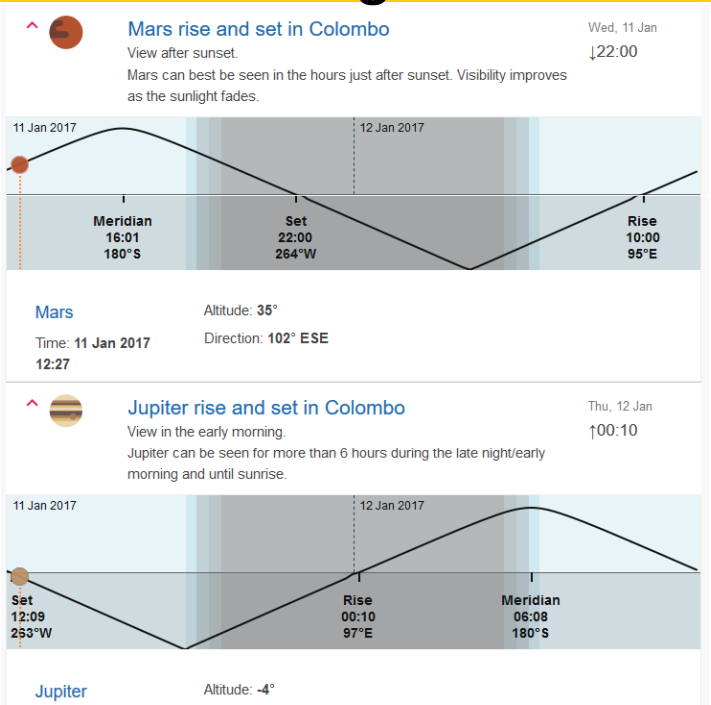




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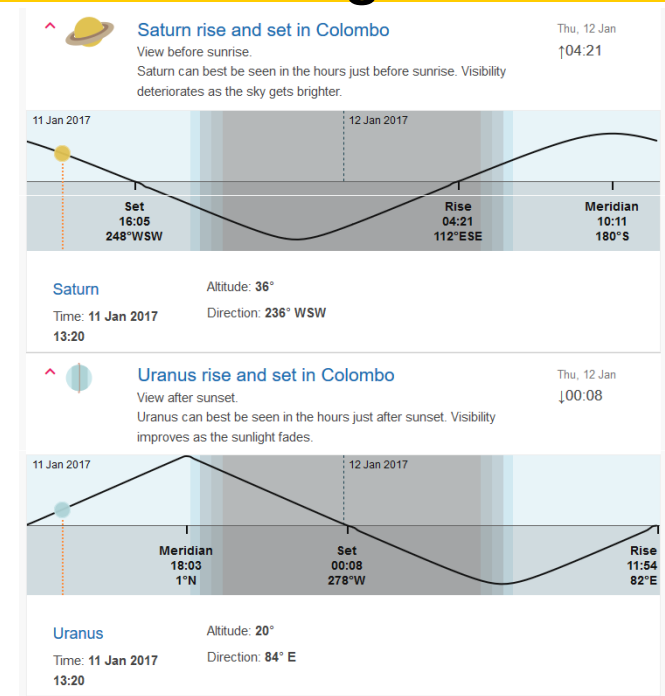
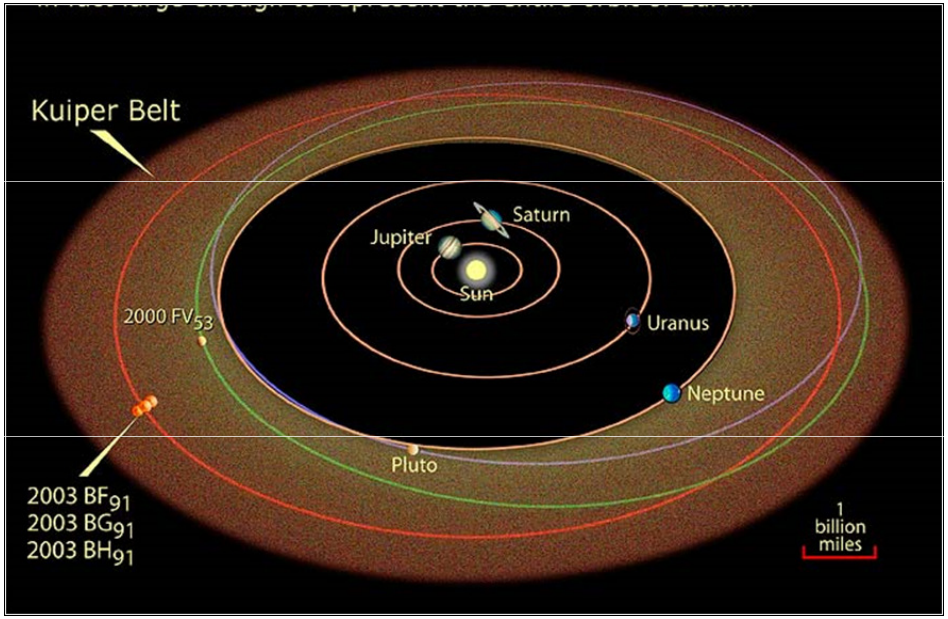
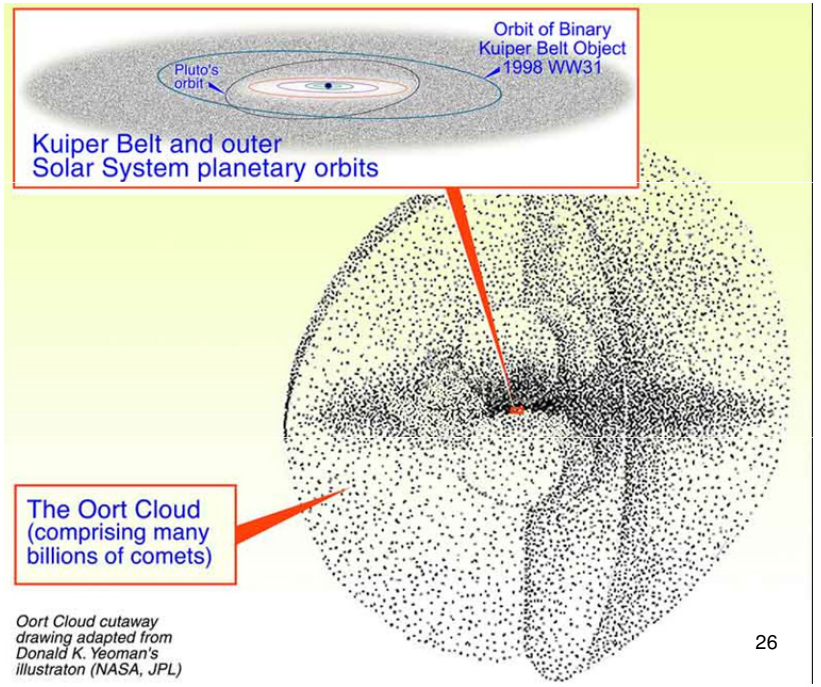


# Kuiper Belt






# Oort Cloud




*Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustraton (NASA, JPL)*



# Verification of Nebulae Theory: Extra Solar Planets

- First confirmation: Orbiting pulsars PSR B1257+12 (1992) and PSR B1620-26 (1993)
  - millisecond pulsar, a kind of neutron star, and was found to have anomalies in the pulsation period, which led to investigations as to the cause of the irregular pulses

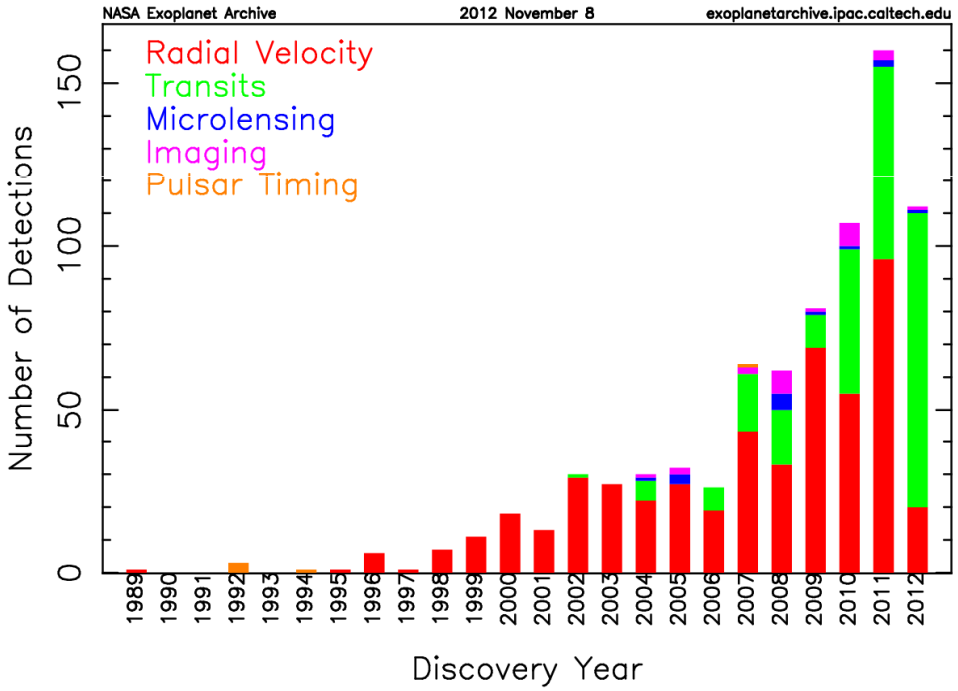
| Companion (in order from star) | Mass | Semimajor axis (AU) | Orbital period (days) | Eccentricity | Inclination | Radius |
|---|---|---|---|---|---|---|
| A (b) | 0.020 ± 0.002 $M_{\oplus}$ | 0.19 | 25.262 ± 0.003 | 0.0 | ~50° | — |
| B (c) | 4.3 ± 0.2 $M_{\oplus}$ | 0.36 | 66.5419 ± 0.0001 | 0.0186 ± 0.0002 | 53° | — |
| C (d) | 3.9 ± 0.2 $M_{\oplus}$ | 0.46 | 98.2114 ± 0.0002 | 0.0252 ± 0.0002 | 47° | — |



# Verification of Nebulae Theory: Extra Solar Planets

- The first extra-solar planet orbiting a normal star 51 Pegasi was discovered in 1995
- At present, there are **281** planets listed
  - **277** orbiting normal stars
    - **63** in multiple planet systems
    - **214** in single planet systems
  - **4** orbiting pulsars

# Extra-Solar Planet Discoveries



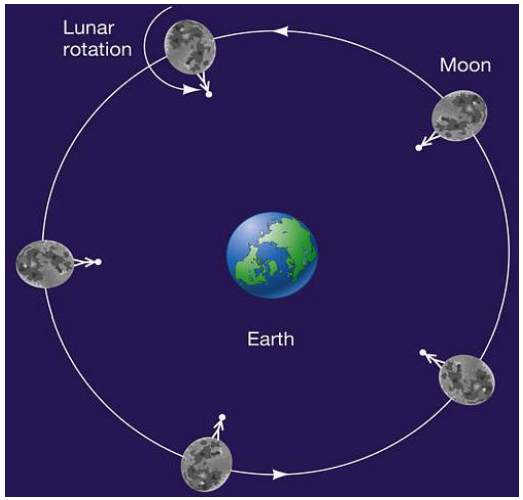

# Destiny of the Planets

- Planets' orbits are chaotic over longer timescales
  - In all cases this means that the position of a planet along its orbit ultimately becomes impossible to predict with any certainty
- After next few billion years
  - Mars's eccentricity may grow to around 0.2, such that it lies on an Earth-crossing orbit, leading to a potential collision with the Earth.
  - Mercury's eccentricity may grow even further, and a close encounter with Venus could theoretically eject it from the Solar System altogether



# Earth-Moon Dynamics

- Why do we always see the same side of the Moon?

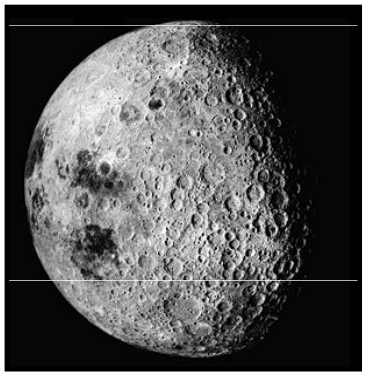





# Earth-Moon Dynamics

- 1:1 lock at present: Moon always shows one side towards Earth

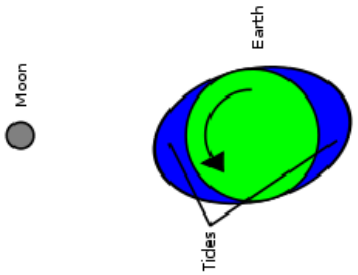
Near Side (visible)

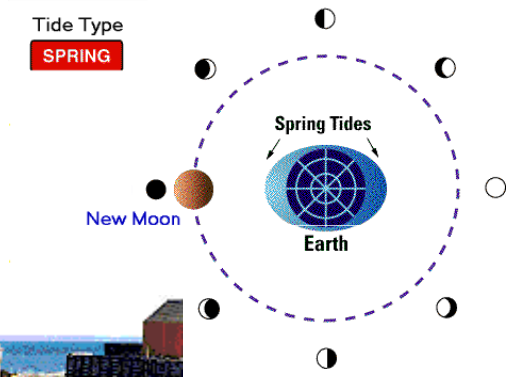


Far Side (not visible)

# Moon and Tides

- Moon revolves (27days) around the Earth slower than the Earth's rotation (24hrs) causing gravitational bulge on Earth's seas to lead ahead of the Moon
  - Momentum transfers from Earth to Moon
  - Slows down the spin of the Earth
  - Speeds up the Moon, causing it to spiral out and recede from us
  - After 50B years, both the Earth and Moon will show one side to each other






# Planet-Moon Dynamics

Neptune and Triton
*Seen by Voyager2*

- When a moon is revolving around a planet faster than the planet's rotation, the tidal bulge lags behind the moon in its orbit
  - Momentum transfers from the moon to planet
  - Planet speeds up its rotation
  - Moon slows down and spiral in to the planet, reach the Roche limit, tears apart and fall, or form a ring system
    - Phobos of Mars (within 30 to 50 million years)
    - Triton of Neptune (in 3.6 billion years)
    - Metis and Adrastea of Jupiter
    - at least 16 small satellites of Uranus and Neptune.



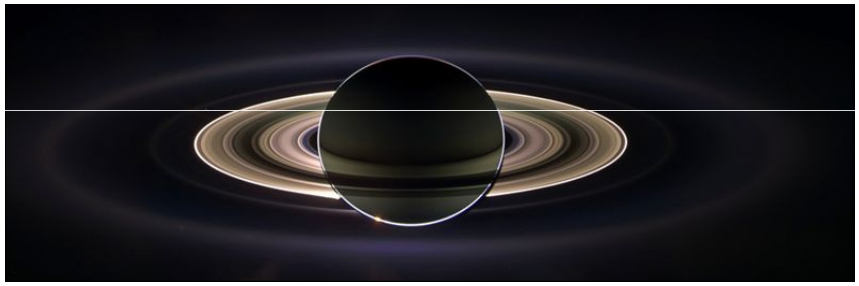
# Planet-Moon Dynamics: Tidal-lock

- Tidal bulge stays directly under the moon, there is no transfer of angular momentum, and the orbital period will not change
- Pluto and Charon are an example of this type of configuration



# Saturn's Rings

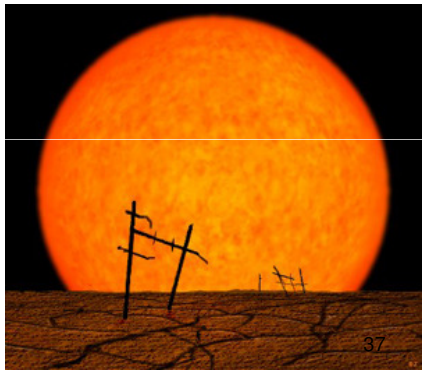
- Gravitational interactions with Saturn's moons were expected to gradually sweep the rings' outer edge toward the planet
- However, data from the *Cassini* mission led scientists to revise that early view. Observations revealed 10 km-wide icy clumps of material that repeatedly break apart and reform, keeping the rings fresh



Backlit Saturn shows two new faint rings and Earth
(Cassini mission, 2007)

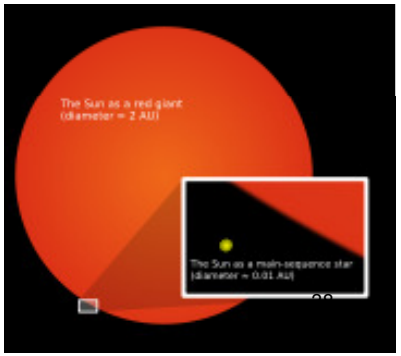
# Fate of the Solar System

- changes in the Solar System will come from changes in the Sun itself as it ages
- As the Sun burns its hydrogen fuel, it gets hotter, and burns the remaining fuel even faster. As a result, the Sun is growing brighter at a rate of 10% every 1.1 billion years




# Fate of the Solar System

- Around 5.4 billion years from now, all of the hydrogen in the core of the Sun will have fused into helium. The core will loose its counter action against gravitational collapse and begins to contract
- This heats up the shell around the core until hydrogen starts burning there. This will cause the outer layers of the star to expand greatly, bringing the Sun to the red giant stage




Sun: as at present and when it is a red giant

# Fate of the Solar System

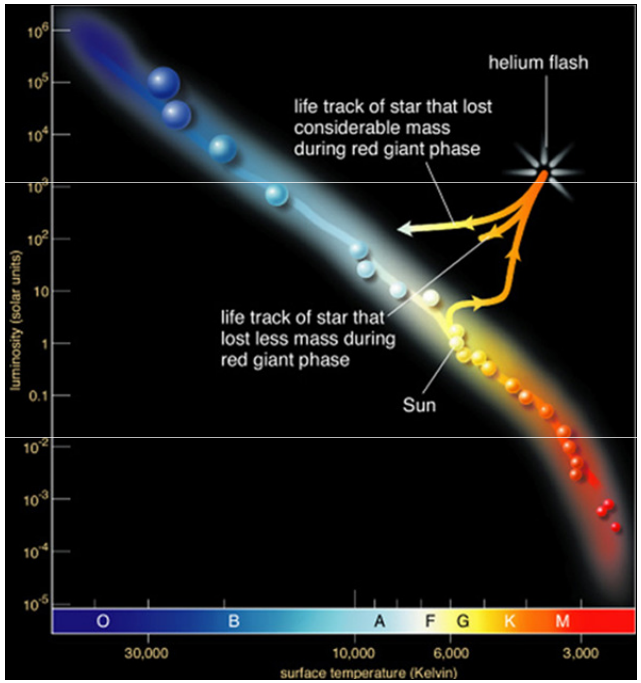
- 7.5 billion years, the Sun will expand to a radius of 1.2 AU—250 times its current size
- Sun's surface will be much cooler, about 2600 K than now and its luminosity much higher—up to 2700 times current solar luminosity
- Sun will have a strong stellar wind which will carry away around 33% of its mass
- As the Sun expands, it will most likely swallow the planets Mercury and Venus. Earth's fate is less clear, but a 2008 study suggests that Earth will likely be swallowed up as a result of tidal interactions with the Sun's weakly bound outer envelope



# Fate of the Solar System

- Hydrogen burning in the shell around the solar core will increase the mass of the core until it reaches about 45% of the present solar mass, at which point the density and temperature will become so high that the fusion of helium into carbon will begin, leading to a helium flash; the Sun will shrink from 250 ⇒ 11 times its present radius. Consequently, its luminosity will decrease from 2700 ⇒ 54 times its current level, and its surface temperature will increase to about 2600 K ⇒ 4770 K
- The Sun will keep burning helium in its core in a stable fashion much like it burns hydrogen today. The helium-fusing stage will last only 100 million years

# He flash





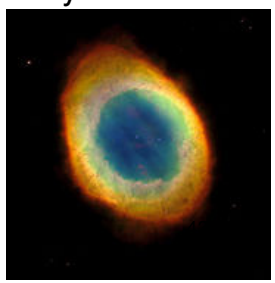

# Fate of the Solar System: Second Expansion

- As the core depletes with He, the Sun will burn the reserves of hydrogen and helium in its outer layers and will expand for a second time.
- Here the luminosity of the Sun will increase again, reaching about 2100 times of the present luminosity, and it will cool to about 3500 K. This phase will last about 30 million years



# Fate of the Solar System: Planetary Nebulae

- Over the course of a further 100,000 years, the Sun's remaining outer layers will fall away, ejecting a vast stream of matter into space and forming a halo known (misleadingly) as a planetary nebula
- The ejected material will contain the helium and carbon produced by the Sun's nuclear reactions, continuing the enrichment of the interstellar medium with heavy elements for future generations of stars



The Ring nebula, a planetary nebula similar to what the Sun will become

# Fate of the Solar System: White Dwarf

- Sun's loss of mass could send the orbits of the surviving planets into chaos, causing some to collide, others to be ejected from the Solar System, and still others to be torn apart by tidal interactions
- Afterwards, all that will remain of the Sun is a white dwarf, an extraordinarily dense object, 54% its original mass but only the size of the Earth
- Initially, this white dwarf may be 100 times as luminous as the Sun is now. It will consist entirely of degenerate carbon and oxygen, but will never reach temperatures hot enough to fuse these elements. Thus the white dwarf Sun will gradually cool, growing dimmer and dimmer

# Fate of the Solar System: Black Dwarf

- As the Sun dies, its gravitational pull on the orbiting bodies such as planets, comets and asteroids will weaken due to its mass loss. All remaining planets' orbits will expand; if Earth still exists, its orbit will lie at about 1.85 AU. And, all the remaining planets will become dark

- Carbon and oxygen in the Sun's core will freeze, with over 90% of its remaining mass assuming a crystalline structure

- Eventually, after billions more years, the Sun will finally cease to shine altogether, becoming a **black dwarf**