Chapter 5 The Solar System

5.1 A quick survey

- ✓ The Solar System is dominated by the central **Sun** - a star giving out light and heat, with mass about 300,000 times of the Earth!
- ✓ In 2006, the International Astronomical Union's (IAU，國際天文聯合會) general assembly held in Prague (布拉格) resolved that planets and other bodies in our Solar System be defined into three distinct categories, namely, *planet*, *dwarf planet* (矮行星) and *small Solar System bodies*.
  - ✧ **Planets:** Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and their satellites lie close to a common plane. Planets move in *nearly* circular orbits, except Mercury, around the Sun in counter-clockwise sense as seen from above (the north pole of the Earth). Besides, orbits of planets are *not* evenly spaced. The self-rotation of the planets also in counter-clockwise sense, except Venus (inclination of equator to orbit: 177.3^o) and Uranus (inclination: 97.86^o).
  - ✧ **Dwarf planet:** New category, with the first members being Ceres, Eris (formerly 2003 UB_{313}), and Pluto. Before being re-categorized as dwarf planets, Pluto was previously known as the ninth planet, and Ceres was an asteroid.[1]
  - ✧ **Small Solar System bodies:** refer to all other non-satellite objects orbiting the Sun. These currently include most *asteroids*(小行星), most *Trans-Neptunian Objects* (TNOs，海外天體), *comets* (彗星), and other small bodies.
- ✓ **Asteroid belt** (小行星帶) consists of asteroids with orbits lying mostly between Mars and Jupiter. Most are rocky debris as small as 0.1 km.
- ✓ **Meteor** (流星) refers to the sudden streak of light across the sky. Before its fiery plunge, the object in space is called a **meteoroid** (流星體), and any parts of it that survive the fiery passage to the Earth's surface are called **meteorites** (隕石).
- ✓ **Comets** are ″Dirty snowballs″ moving in highly elliptical orbits around the Sun. They become bright and develop tails when close to the Sun.
- ✓ **Solar wind:** High-energy charged particles blown off from the Sun.

[1] See https://www.iau.org/public/themes/pluto/ for details of the demotion of Pluto and the promotion of Ceres.

Fig.5-1: The relative sizes of the Sun, planets and first three dwarf planets. The Jovian planets are much larger than the terrestrial planets. (Note: the orbits are NOT in scale.)

Planets in the Solar System

Terrestrial planets

Terrestrial planets include Mercury, Venus, Earth and Mars, all lie in the *inner* Solar System. (Fig. 5-1) They have the following properties:

- ✓ Relatively *dense* (~3-5 g/cc), with cores of iron and nickel surrounded by a mantle of dense rocks.
- ✓ Relatively *small* in size and mass, having *weak* surface gravity, and hence very *thin* atmospheres.
- ✓ Only a *few* or no satellites, e.g., one for Earth, two for Mars.
- ✓ *No* ring system is observed. Surfaces of the planets are scarred with craters.

Jovian planets

Jovian planets include Jupiter, Saturn, Uranus and Neptune. All lie in the outer Solar System. (Fig. 5-1) All Jovian planets have the following properties:

- ✓ Gaseous-like, mainly made up of hydrogen and helium, low-density (~1 g/cc). No solid surfaces but thick liquid layers, possibly with small rocky core of the Earth′s size.
- ✓ *Large* in size and mass, having *strong* surface gravity, and hence *thick* atmospheres. Having strong atmospheric pressure and a lot of weather activities.
- ✓ *Many* satellites.
- ✓ *All* have **ring systems**.

5.2 Physical Processes

A. Tidal forces

- ✓ In the Earth-Moon system, tidal forces result in tides on Earth, slowing down of the Earth's self-rotation, and increase in the Moon-Earth distance. See Chapter 3 for details.
- ✓ **Tidal coupling:** The Moon′s orbital period equals its self-rotation period, hence it always keep the same face towards the Earth.
- ✓ Tidal coupling of spins and orbital motions are common in the Solar System. For example, two moons of Mars, Galilean moons of Jupiter, most moons of Saturn. In addition, Pluto and Charon even show *mutual synchronous rotation* - each keeps the same ″face″ towards the other.[2]
- ✓ **Tidal disintegration** of satellites: Since the tidal force (per unit mass) of a planet on a satellite is given by $F_{\text{tidal}} \sim \dfrac{2GMR_S}{r^3}$, where M, R_S and r are, respectively, the mass of the planet, the radius of the satellite and the distance between the planet and the satellite. The self-gravitational force of the satellite $F_{\text{self}} = \dfrac{Gm}{R_S^2}$, where m, is the mass of the satellite. If the satellite is close to the planet, i.e., r is small, such that $F_{\text{tidal}} > F_{\text{self}}$, the satellite may be torn into pieces! Ring systems of Saturn are created in this way.
- ✓ Mathematically, tidal disintegration may occur when $\dfrac{2GMR_S}{r^3} > \dfrac{Gm}{R_S^2}$; and therefore, $r^3 < 2\dfrac{M}{m}R_S^3$. In terms of the average densities of the planet and the satellite, namely $\bar{\rho}_P = M/(\frac{4}{3}\pi R_P^3)$ and $\bar{\rho}_S = m/(\frac{4}{3}\pi R_S^3)$. The satellite may be disintegrated if $\boxed{r < 2^{1/3}\left(\dfrac{\bar{\rho}_P}{\bar{\rho}_S}\right)^{1/3} R_P}$. A more careful analysis by Roche shows that oscillations are developed and may disintegrate the satellite at distances $r < r_c = 2.46\left(\dfrac{\bar{\rho}_P}{\bar{\rho}_S}\right)^{1/3} R_P$, where r_c is called **the Roche limit**, that is the maximum orbital radius inside which a satellite might be disintegrated. Of course, it is only an *upper limit*. The actual situation depends on the satellite′s internal *cohesive force*.

[2] The situation in the Pluto-Charon system is also called tidal locking.

B. Planetary atmospheres

Temperature of planet

- ✓ For simplicity, we shall assume the Sun and the planets as **blackbodies** (see ***Box 5.1***) which absorbs and emits EM radiations all ranges frequency. [3]

- ✓ As an example, let's estimate the surface temperature of the Earth. By the Stefan-Boltzmann law, the flux of solar radiation energy on Earth is $F_s = \dfrac{4\pi R_\odot^2 \times \sigma T_\odot^4}{4\pi r^2} = \sigma T_\odot^4 \left(\dfrac{R_\odot}{r}\right)^2$, where r and $R_\odot$ are, respectively, the Sun-Earth distance and the radius of the Sun, and $T_\odot$ is the effective surface temperature. Since $r = 1.5\times 10^{11}\,\mathrm{m}$, $R_\odot = 6.96\times 10^{8}\,\mathrm{m}$ and $T_\odot = 5{,}770\mathrm{K}$, so F_s = 1,360 W m^{-2}. This is called the *solar constant* for the Earth.

  At thermal equilibrium, the emission rate equals the absorption rate on Earth, we have $F_s \times \pi R_E^2 \times (1-\alpha) = \sigma T_E^4 \times 4\pi R_E^2$, and thus $\dfrac{1}{4} F_s (1-\alpha) = \sigma T_E^4$, where T_E is the effective surface temperature, and α (called **planetary albedo**)[4] is the fraction of the energy being reflected, so $1-\alpha$ is the fraction being absorbed by the Earth.

  Take $\alpha = 0.3$, T_E = 254 K = -19°C, which is lower than the average temperature on the Earth (~15°C)! Why?

- ✓ In order to explain the discrepancy, one needs to consider **the Greenhouse effect** in the atmospheres of terrestrial planets. The Earth′s atmosphere is transparent to visible light and radio wave, but opaque at other wavelengths due to the presence of CO_2, H_2O, etc. Having absorbed the infrared radiation emitted from the ground, the Earth's atmosphere acts as another heat source; therefore, the ground temperature of the Earth is higher than that in the case without the atmosphere

- ✓ By using a simple model that treats the Earth's atmosphere as a *single* layer of blackbody, the Earth's surface temperature is estimated to be about 30°C. The actual situation is even more complicated due to convection, latent heat of condensation, etc.

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[3] You may wonder why the Earth's atmosphere is almost opaque to any EM radiations, except visible light. Actually, high-energy radiations of $\lambda < 0.2\,\mu\mathrm{m}$ are being absorbed by photodissociation and ionization of N_2 and O_2 molecules. Ultraviolet radiations of $0.2\,\mu\mathrm{m} < \lambda < 0.3\,\mu\mathrm{m}$ are being absorbed by the ozone layer. Long-wavelength EM waves such as infrared match the vibrational and rotational energies of atmospheric molecules and so could not transport freely through the atmosphere.

[4] Approximated albedoes for planets are 0.11 (Mercury), 0.75 (Venus), 0.31 (Earth), 0.25 (Mars), 0.34 (Jupiter), 0.34 (Saturn), 0.30 (Uranus), 0.29 (Neptune).

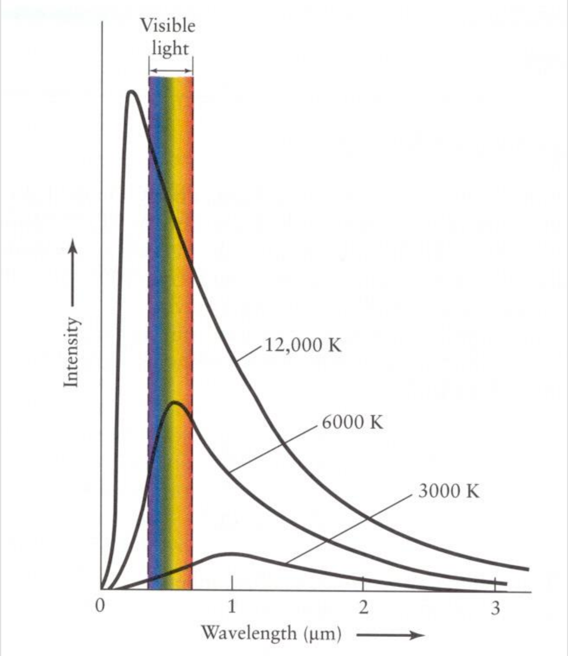
Box 5.1 Blackbody radiation

Blackbody is an ideal absorber and emitter, i.e., it absorbs and emits all ranges of electromagnetic radiations. Blackbody radiation is quite common. It is responsible for the light emitted by an incandescent light bulb. Electricity flowing through the filament of the light bulb heats it to high temperature, and it glows. Many objects in astronomy, including stars, emit radiation as if they were nearly perfect blackbodies.

The shape of the spectrum of a blackbody only depends on its temperature, as shown in the figure. As the temperature (T) of a blackbody increases, the wavelength of maximum emission ($\lambda_{\max}$) decreases. The mathematical formula to describe their relation is known as

the Wien's law: $\boxed{\lambda_{\max} = \dfrac{0.0029}{T}}$,

where $\lambda_{\max}$ is in metre and T is in degree Kelvin.



Spectrum of a blackbody at different temperature.

Blackbody radiation also satisfies

the Stefan-Boltzmann law: $\boxed{F = \sigma T^4}$,

where F is the energy flux (in J m^{-2} s^{-1}), T is the blackbody's temperature (in K), and the Stefan-Boltzmann constant $\sigma = 5.67\times10^{-8}$ W m^{-2}K^{-4}. Hence, the **luminosity** of the blackbody is $\boxed{L = 4\pi R^2 \sigma T^4}$, where L is the total radiation energy (in W) and R is the blackbody's radius (in m^2). For example, the radius of the Sun is about 7×10^8 m^2, so the Sun's luminosity is about $L_\odot = 3.9\times10^{26}$ W.

Compositions of planetary atmospheres

✓ Another interesting phenomenon of planetary atmospheres is the variation in the atmospheric compositions of planets and satellites. For instance, there is virtually no hydrogen in Earth's atmosphere, yet Jupiter's atmosphere consists mainly of hydrogen.

✓ The speeds of the atmospheric particles follow the Maxwell-Boltzmann distribution (see *Box 5.2*). The root mean square speed is given by $v_{\rm rms} = \sqrt{3kT/m}$.

✓ In order to escape, we require $v > v_{\rm esc} \equiv \sqrt{2GM/R}$, where $v_{\rm esc}$ is the escape velocity, M and R are, respectively, the mass and the radius of the planet.

- ✓ A certain type of gas will leave the atmosphere in a few days if $v_{rms} \geq v_{esc}$; it will be retained in the atmosphere for billions of years if $v_{esc} > 10v_{rms}$ (Fig. 5-2), or equivalently, $\boxed{T < \frac{GMm}{150kR}}$.

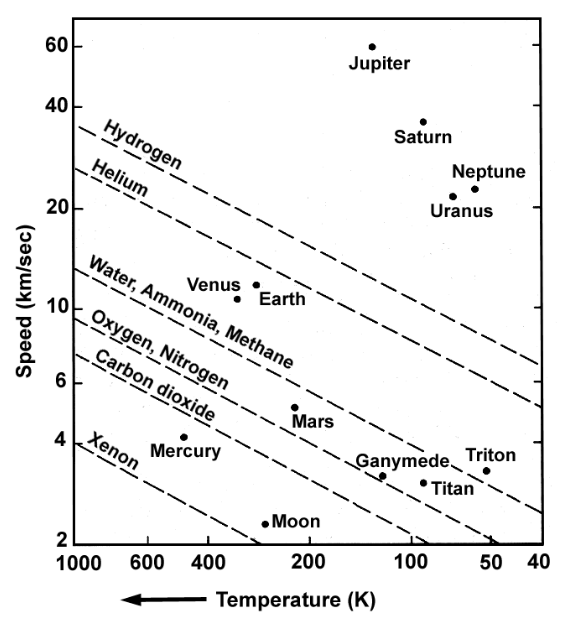
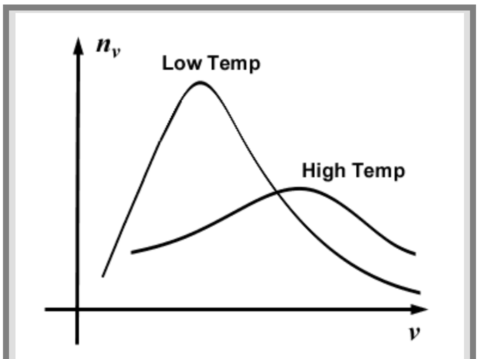


Fig. 5-2: The dashed lines represent 10 v_{rms} for various molecules. Each dot represents the escape velocity of a planet/satellite.

- ✓ As a result, Mercury and the Moon have almost no atmosphere; Venus, Earth and Mars can retain O_2 and N_2, but not H_2 and He. Jovian planets retain all gases. Since H and He are the most abundance elements, Jovian planets have thick atmospheres of H and He.
- ✓ Some other reasons of losing atmospheres: solar UV radiation breaks up molecules into lighter particles (photodissociation), which in turn escape; Solar wind collides with and dissociates molecules in upper atmosphere; Meteoroids heat up the atmosphere, and cause some energetic particles to escape.

Box 5.2 Maxwell-Boltzmann velocity distribution

Gas particles at a certain temperature do not have the same speeds. They instead distribute according to the Maxwell-Boltzmann distribution. The diagram shows schematic plots of the distribution at two temperatures. The number of gas particles within a range of v and v+dv is given by n_vdv. Therefore, *the total number of gas particles in the box is the area under the curve.*



Schematic plots of Maxwell-Boltzmann distribution of the speeds of particles. The shape of distribution depends on temperature.

According to the Maxwell-Boltzmann distribution, the root mean square speed of molecules is given by $\boxed{v_{rms} = \sqrt{\frac{3kT}{m}}}$, where $k = 1.38\times10^{-23}$ J K^{-1} is the Boltzmann constant. Hence the average kinetic energy of molecules is $\boxed{\frac{1}{2}mv_{rms}^2 = \frac{3kT}{2}}$.

5.3 Features of the planets

A. Mercury

- ✓ It is small, dense, with a relatively large iron core.
- ✓ Its heavily-cratered surface resembles the lunar surface. (Figs. 5-3, 5-4)

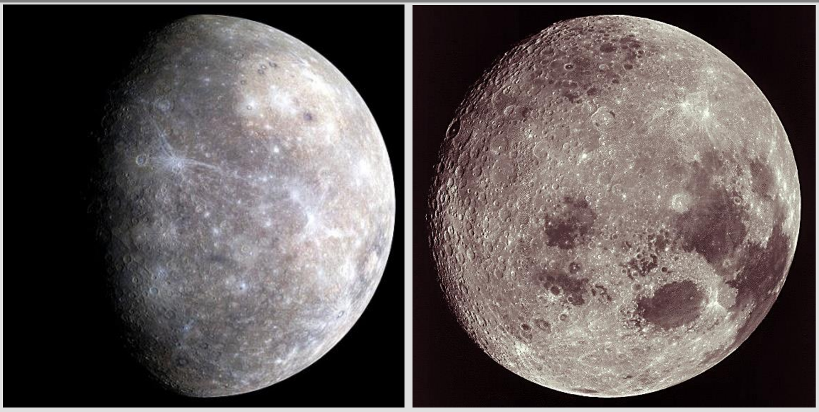


Fig. 5-3: Left: Image of Mercury taken by the Messenger spacecraft. Right: The Moon as seen from Earth.

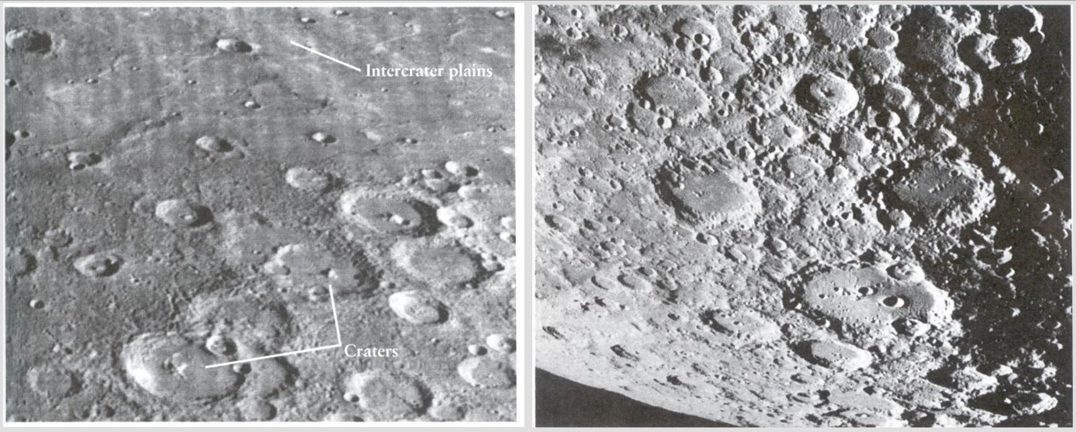


Fig. 5-4: Left: Mercury's craters and plains. Right: Lunar craters.

- ✓ Because the orbit of Mercury is rather elliptical, the tidal budges of Mercury by the Sun along the direction of the Sun at perihelion (at a position closest to the Sun). As a result, Mercury makes three complete rotations on its axis for every two complete orbit around the Sun. Mercury is locked into a **3-to-2 tidal coupling**. (Fig. 5-5) No other planet or satellite in the Solar System has this curious relationship.

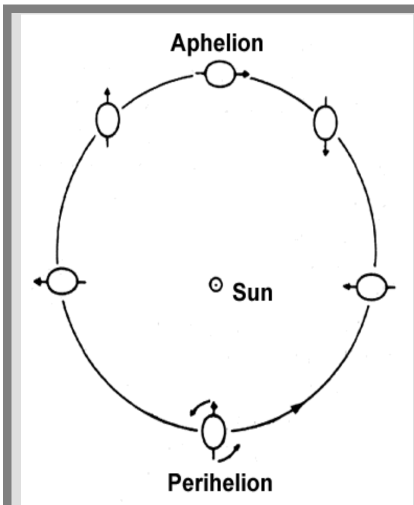


Fig. 5-5: The tidal bulges of Mercury align towards the Sun at perihelion.

- ✓ With high surface temperature and weak gravity (due to its small size), Mercury has almost no atmosphere. As a result, the temperature difference between day and night is huge (-173°C to 430°C).

- ✓ Many craters are retained on its surface for a long time (Fig. 5-4 left). Unlike the closely packed and overlapping lunar craters (Fig. 5-4 right), there are some low-lying **inter-crater plains** on Mercury's surface. These large, smooth areas are about 2 km lower than the cratered terrain.
- ✓ *Formation of inter-crater plains:* large meteoroids punctured a thin, newly formed crust, lava welled up from the molten interior to flood low-lying areas. Since Mercury is larger than the Moon, it cooled down more slowly, and its surface was refreshed by lava flooding more frequently.
- ✓ Observations show Mercury's plains are lower in iron content compared to the lunar maria (海, the large dark areas on the lunar surface, see Fig. 5-3). It may explain why Mercury's plains do not have the dark colour of the Moon's maria.

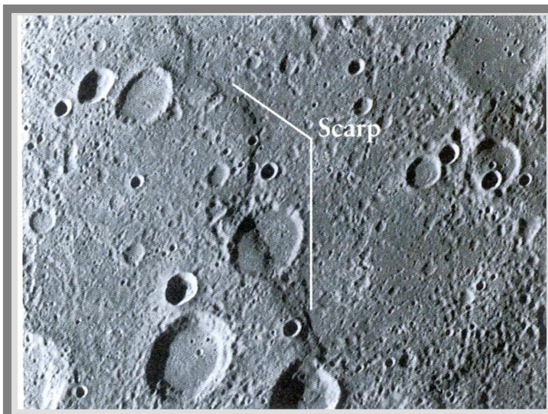


Fig. 5-6: A Scarp which passes through a crater; the crater was distorted vertically when the scarp formed.

- ✓ **Scarps** are long, meandering cliffs on Mercury. They are more than a kilometre high, and several hundred kilometres long. Such scarps are formed when Mercury's crust cooled and shrank. (Fig. 5-6)
- ✓ Mysterious magnetic field (~1% of the Earth's magnetic field strength) detected means Mercury has a liquid metallic (iron) conducting core. But the planet is so small that any molten core should have been cooled and solidified long ago. Why does a molten core exist?

B. Venus

- ✓ Venus spins in *clockwise* sense. The surface temperature is about 750 K.
- ✓ The surface is hidden below a dense and stable layer of clouds (Fig. 5-7). Thick atmosphere (~90 times the Earth′s) is composed *mostly* of CO_2 (96%), some N_2, traces of SO_2 and H_2O. Clouds contain sulphuric acid.
- ✓ The detailed altitude has been mapped by radar (Magellan and Pioneer spacecraft). Venus′ surface is covered mostly by rolling plains**,** with smaller areas of highlands and volcanic peaks. (Fig. 5-8) Widespread systems of faults are evidences of volcanic activities.

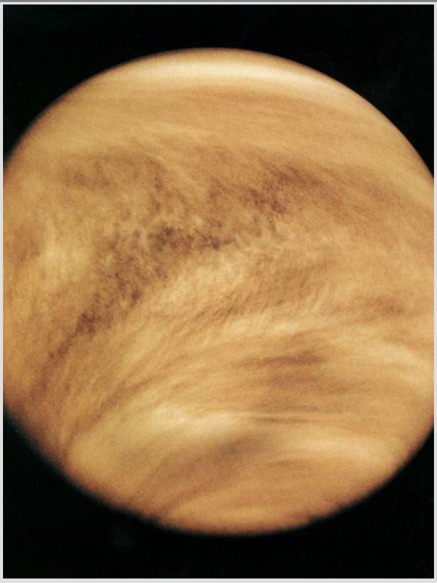


Fig. 5-7: Photograph of Venus taken by the Pioneer Venus orbiter. It shows thick clouds and complex weather patterns in the planet′s atmosphere, but no trace of the surface.

- ✓ Venus's magnetic field is much weaker than that of Earth's. This magnetic field comes from the interaction between the ionosphere and the solar wind, instead of the core.
- ✓ **Greenhouse effect in Venus:** When sunlight falls on Venus, the heated surface re-radiates mainly infrared. Most of this radiation is trapped in Venus's atmosphere, which is rich in CO_2 is thus opaque to infrared radiation.
- ✓ Venus has a very thick atmosphere of CO_2 and thus has a strong greenhouse effect. As a result, Venus's surface temperature is exceptionally high. Also, while the Earth has similar size and mass as Venus, the Earth's atmosphere is mainly nitrogen and oxygen. Also, there are oceans on the Earth, but not on Venus. These facts can be attributed to the **runaway greenhouse effect** on Venus (*Box 5.3*).

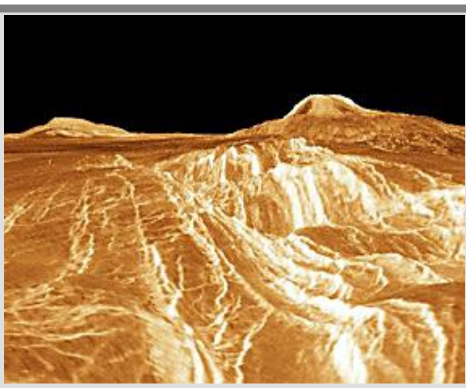
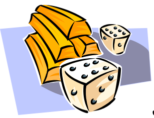
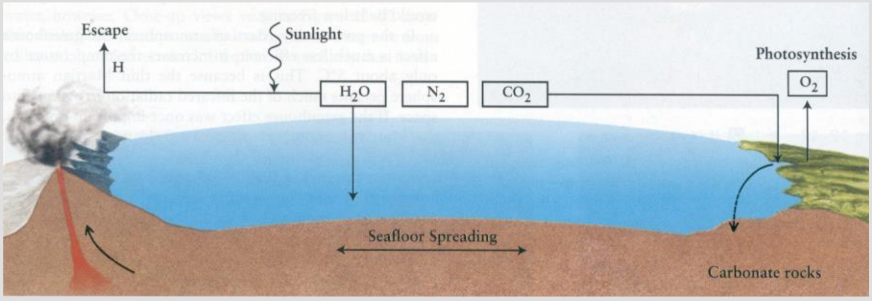


Fig. 5-8: Computer image based on radar data shows two volcanoes, and a rolling plain appears to be produced by lava flooding.



Box 5.3 Runaway greenhouse effect (*for reference only*)

Billions of years ago, volcanic outgassing of carbon dioxide, water vapour and nitrogen created a warm (by greenhouse effect), dense atmosphere for both Venus and the Earth. The primitive atmospheres of the Earth and Venus were probable similar.



The ancient atmospheres of the Earth.

On the Earth, carbon dioxide was removed from the atmosphere by rainfall and then stored in carbonate rocks. Tectonic activity causes volcanoes to release small amount of carbon dioxide from carbonate rocks. The whole process allows the Earth to keep a warm, thick atmosphere. Also, plants intake CO_2 and liberate oxygen molecules, ozone layer shields ultraviolet from the Sun. Greenhouse effect is under control.

On Venus, a planet nearer to the Sun, solar heating vaporized water. Since water molecules are lighter than carbon dioxide molecules, it moved to top of atmosphere. Ultraviolet from Sun dissociated water. Hydrogen atoms escaped, and oxygen atoms formed oxide. Without water to dissolve CO_2 in the atmosphere, radiation from the Sun was trapped. As the surface temperature increased, more water evaporated and lost. This process is called **runaway greenhouse effect**. As a result, Venus has a thick atmosphere with mostly carbon dioxide.

C. Mars

Features of Mars

- ✓ Its surface temperature is about -140°C to 20°C. It is red because the soil contains minerals of iron (basically rust) (Fig. 5-9).

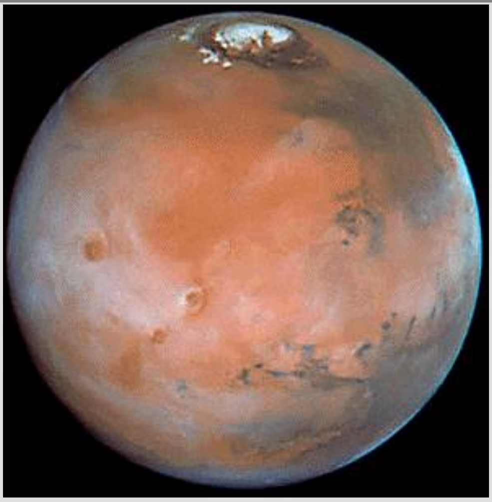


Fig. 5-9: A photograph of Mars. One of the polar caps is shown, and it shows shrink and grow seasonally.

- ✓ Mars is a cratered world with gigantic *volcanoes* and deep *canyons* (峽谷). Olympus Mons (奧林帕斯山) is nearly three times as tall as Mount Everest on Earth). Valles Marineris (水手號峽谷) extends from west to east for more than 4000 km! (Fig. 5-10)
- ✓ **Polar caps** shrink and grow seasonally, appearing as bright streaks against the darker surface.

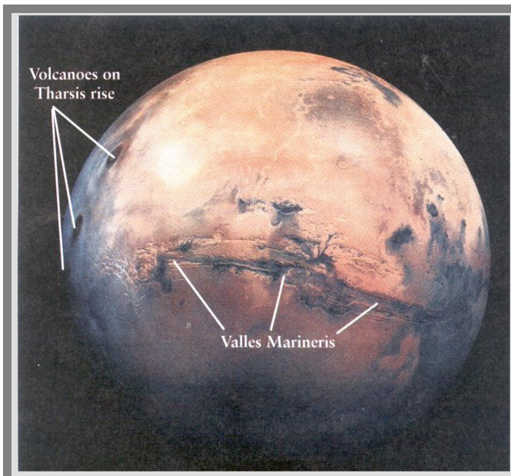


Fig. 5-10: Valles Marineris.

- ✓ It has no global-scale intrinsic magnetic field
- ✓ With smaller size, Mars′ surface gravity is about one-third compared to the Earth, hence the escape velocity is also smaller. Volatile gases have escaped away. In addition, dissociation of molecules by the Sun′s ultraviolet rays into lighter particles further enhances atmosphere losing. As a result, the Mars's atmosphere is dry and thin (~1/100 of the Earth′s), and is mainly carbon dioxide (~95%).

Water on Mars

- ✓ Many photographs and observations show channels, dried-up lakes and riverbeds in Mars. (Fig. 5-11) It is a strong evidence of the existence of liquid water before. Where is the water now?

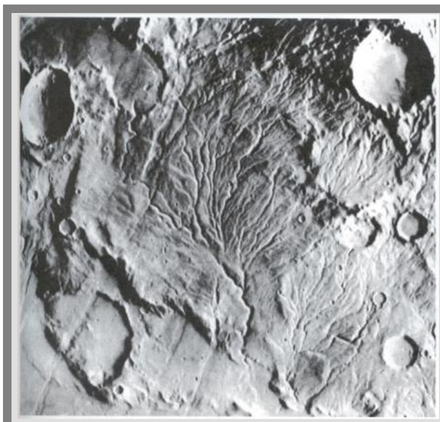


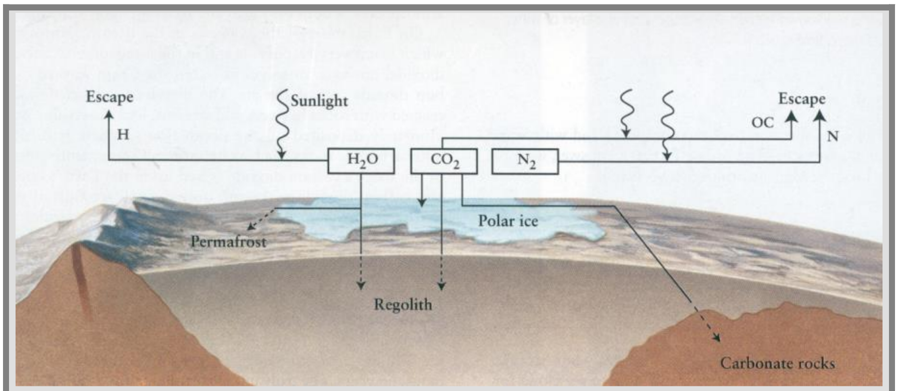
Fig. 5-11: Ancient river channels and riverbeds on Mars.

- ✓ Finally, in 2015, NASA confirmed the existence of *seasonal liquid water*.
- ✓ *Polar caps are reservoirs of frozen water*. During spring, the north polar cap receded rapidly, strongly suggesting that a thin layer of carbon dioxide was evaporating in the sunlight. However, the rate of recession during summer slowed abruptly, suggesting that a thicker layer of water ice had been exposed. The portion of the caps survive in summer is called **residual polar caps**.
- ✓ In addition, evidences show frozen water is also stored under the surface of Mars.

Why is there only a thin layer of atmosphere in Mars? What does it cause Mars and the Earth evolved so differently? See ***Box 5.4*** for the details.

Box 5.4 Mars and the Earth evolved differently (*for reference only*)

The discovery of riverbeds and channels was totally unexpected! In order to keep water on Mars in the liquid state, during the past, the Mars's atmosphere must have been both thicker and warmer than it is today.



The ancient atmospheres of Mars.

Like the Earth and Venus, billions of years ago volcanic outgassing of carbon dioxide, water vapour and nitrogen created a warm (by greenhouse effect), dense. But the Earth and Mars evolved differently. As discussed in ***Box 5.3***, carbon dioxide in carbonate rocks was liberated again, and rejoins the atmosphere by *plate tectonics*. Tectonic activity causes volcanoes to release carbon dioxide from carbonate rocks. The Earth keeps a warm, thick atmosphere.

However, plate tectonics did not occur on Mars; therefore, carbonate rocks could not be recycled. Ultimately, rainfall removed both water vapour and most of the carbon dioxide from the Mars's atmosphere. With only a thin carbon dioxide atmosphere remaining, surface temperature began to decline. As a result, most carbon dioxide stored as carbonate rocks, water frozen in the polar caps. Moreover, the atmospheric molecules were broken down into atoms by sunlight and escaped away. It results in further atmosphere loss in Mars.

D. Jupiter

- ✓ The largest planet in the Solar System, its mass equals 3/4 of the total mass of all other planets. Its surface temperature ~ -110^{o}C.
- ✓ A huge atmosphere exists. The atmosphere consists mainly of 80% of hydrogen, 19% of helium. There is complex weather activity, multicoloured clouds and strips (Fig. 5-12).
- ✓ Spin rapidly at equator with period 9h50m, and at poles with 9h55m. The **differential rotation** implies Jupiter cannot be solid throughout its volume. It is thus impossible for a spacecraft to land on Jupiter! In addition, rapid rotation explains the flattening of the gaseous planet (probably a more appropriate name is liquid planet).

Fig. 5-12: Jupiter is completely covered by multicoloured clouds arranged in lacy belts swirled by wind motions.

Jupiter's atmosphere

- ✓ **Great Red Spot**: The winds to the north and south of the Great Red Spot blow in opposite directions. The shearing leads to counter-clockwise winds within the *Great Red Spot* (Fig. 5-13), which is in fact a great cyclone that has lasted for at least 300 years! Why aren't cyclones on the Earth so persistent? Weather patterns on the Earth tend to change character and eventually dissipate when cyclones move between plains and mountains or between land and sea. There is no solid surface or ocean underneath Jupiter's clouds, so no such changes can occur.

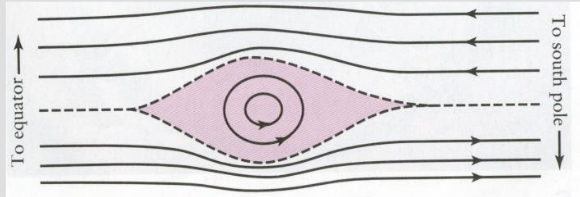


Fig. 5-13: Circulation around the Great Red Spot.

- ✓ Light-coloured **zones** are warm regions of *rising gas* heated from Jupiter's interior; Dark-coloured **belts** are cool regions of *sinking gas* (Fig. 5-14).

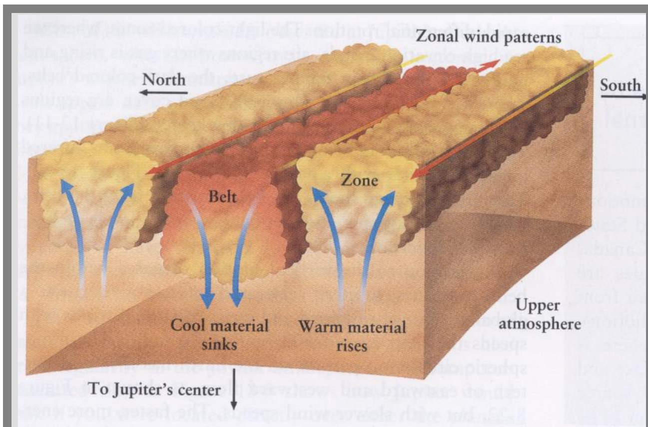


Fig. 5-14: The Belt-Zone structure.

- ✓ Because of rapid differential rotation shapes these regions of rising and sinking gas into bands parallel to the planet's equator. (Fig. 5-14) The colours in the clouds come from photochemical reactions of atmospheric particles (mostly ammonium compounds) caused by sunlight.

Jupiter's interior

- ✓ The internal pressure is extremely high. The hydrogen deep inside Jupiter is compressed into **liquid metallic hydrogen**, in which electrons are free to move easily from atom to atom. On Earth, the metallic state can be created under tremendous pressure in lab.
- ✓ Since rapid rotation of liquid metallic hydrogen produces a strong magnetic field, so the strength of Jupiter's magnetic field is about 100 times of that of the Earth. Hence it can trap and accelerate charged particles, which come from solar wind and the volcanic activity of Io (a satellite of Jupiter). As a result, electrons gyrate rapidly in magnetic fields; and therefore, intense radio waves are emitted.
- ✓ Fig 5-15 shows the internal structure of Jupiter. It has a rocky core; surrounded by liquid metallic hydrogen and a thick atmosphere.

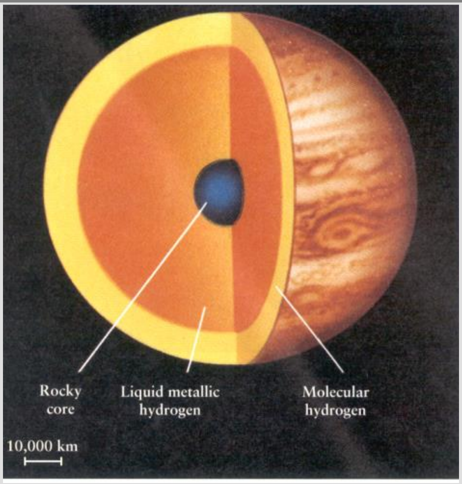


Fig. 5-15: The internal structure of Jupiter.

Jupiter's satellites

- ✓ Jupiter has more than 50 satellites,[5] and the four largest ones were discovered by Galileo, from the nearest one: **Io**, **Europa**, **Ganymede** and **Callisto**. Two major effects from Jupiter on the satellites:
  - ✧ *Tidal heating*: changing tides cause friction within a moon (Fig. 5-16)

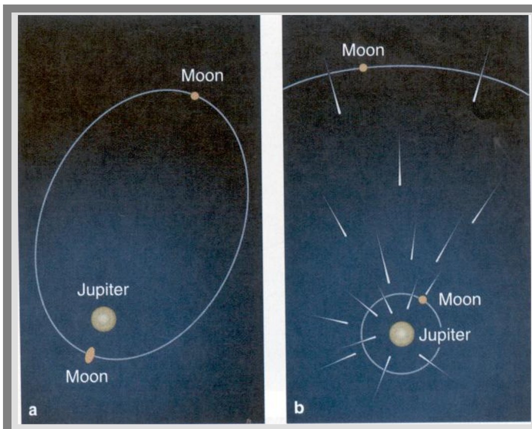


Fig. 5-16: Tidal heating and Focusing of meteoroids.

[5] See NASA's "Planetary Fact Sheets" (http://nssdc.gsfc.nasa.gov/planetary/planetfact.html) and "Solar System Exploration" (https://solarsystem.nasa.gov/planets/) for the most updated information of the Solar System.

- ✧ *Focusing of meteoroids*: The focusing of meteoroids exposes satellites in small orbits to more impacts than satellites in larger orbits receive (Fig. 5-16).

✓ **Io**: It is the most volcanically active body in the Solar System. Volcanoes in Io spew out gas and solid debris rich in colourful sulphur compounds. The surface renewed, hence no craters are found in the surface. A molten metallic core exits to generate magnetic field. With similar size as the Moon, the core should have cooled down since formation, so how does the magnetic field still exit, and why is it so volcanically active? It is believed that *tidal heating* is responsible for keeping Io hot. In addition, Jupiter's magnetic field interacts with Io to produce a powerful electric current that flow through a curving path called **Io flux tube,** i.e., it is a conducting channel of ionized gas between Io and Jupiter.

✓ **Europa:** Its crust is rather *new* (not many craters). Stress fractures the mantle and produces a network of cracks. The tidal heating kept the molten metallic core hot, creating a weak magnetic field.

✓ **Ganymede**: the surface is relatively old and is heavily cratered, crossed with grooved terrain. Because of its elliptical orbit, the tidal heating kept a molten metallic hot, creating a magnetic field (~10% of Earth's).

✓ **Callisto:** no magnetic field, hence no molten metal core. It has a *heavily* cratered, and a layer of frozen water roughly 10 km thick below its crust.

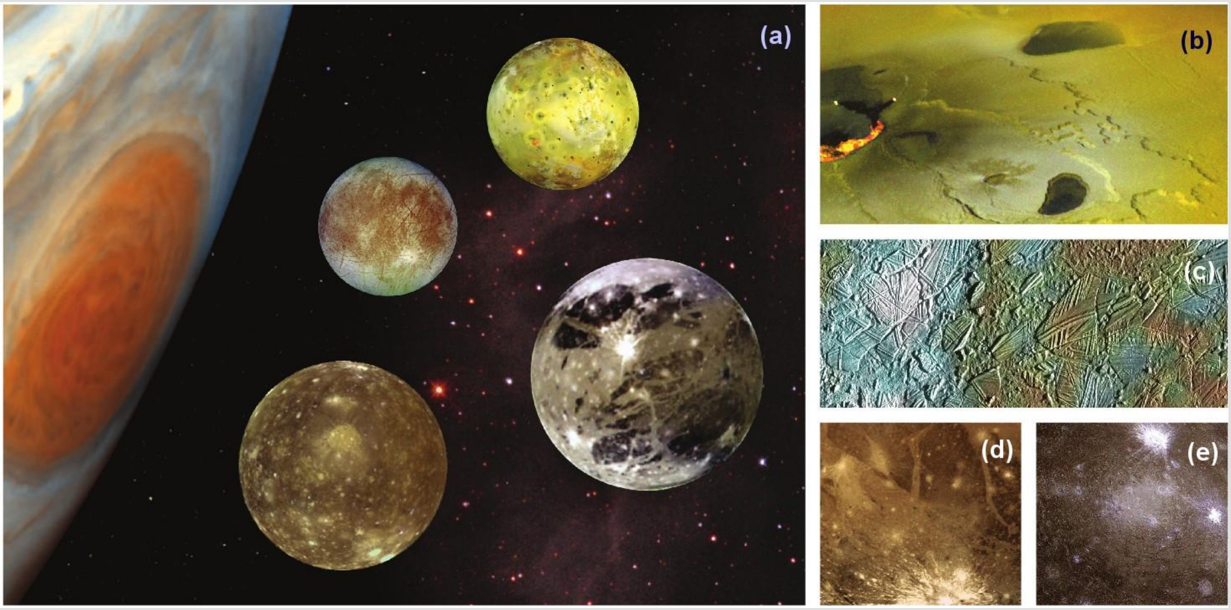


Fig. 5-17: (a) A comparison of Jupiter's Galilean moons. The yellow one (upper right) is Io. The other three in the counter-clockwise direction are Europa, Ganymede, and Callisto. Jupiter is not shown in scale. (b) Io's surface with volcanoes and newly erupted hot lava. (c) False-color image of Europa with the broken icy crust. (d) Impact crater on Ganymede. (e) Impact crater on Callisto. (Image credit: NASA)

E. Saturn

- ✓ The second largest planet with more than 50 satellites. The surface temperature of Saturn is about -180°C. The average density lower than water (0.7 g/cc).
- ✓ Atmospheric condition is similar to Jupiter, but the belts and zones seem less distinct. It has fewer but stronger winds.

Fig. 5-18 Hubble Space Telescope image of Saturn, on which there was a storm.

Saturn's rings

- ✓ As you may have seen before, there is a large, bright ring system of Saturn (Figs. 5-18, 5-19). Three rings (**A**, **B** and **C**) can be easily resolved as observed on the Earth.
- ✓ Some photographs by Voyager 2 spacecraft show that the rings may be as thin as 10m only! In fact, the rings are made of billions of *small icy* particles! Therefore in spite of their appearance, the rings do not have solid surfaces.
- ✓ Particles in the rings orbits around Saturn. The particles further away have longer orbital periods, according to Kepler's laws.
- ✓ Most rings lie within the **Roche limit** of the planet (Fig. 5-20).
- ✓ Why are there many rings? Or equivalently, there exists many gaps - regions devoid of particles, e.g., **Cassini's division**, in the ring. (Fig. 5-20) In fact,

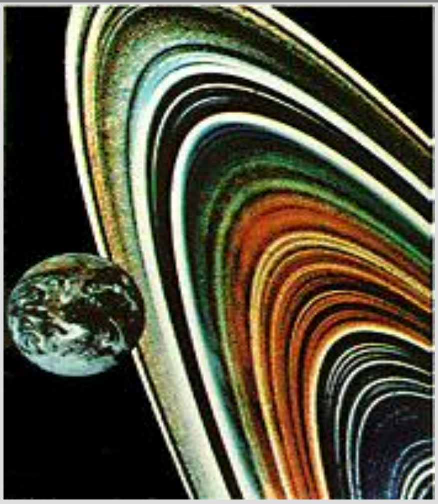


Fig. 7-19 Saturn's rings are actually made up of tens of thousands of ringlets. The Earth is included for scale.

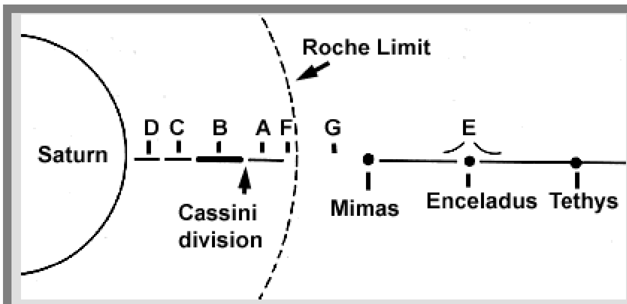


Fig. 5-20: Most of the rings of Saturn lie inside the Roche limit.

the structure of the rings is influenced by the gravitational force of the *satellites*. **Resonance** (see Section 5.5) between orbital motions of moons and particles in rings produces gaps.

Saturn's satellites

- ✓ The **F** ring is narrow and irregularly twisted (Fig. 5-21). Observation shows two small satellites, called **shepherd satellites**, orbiting, one inside and one outside the F ring (Fig. 5-22). The distortions appear to be caused by gravitational interactions between particles in the ring and the satellites. They also carve the gaps and keep the edges of the ring.
- ✓ **Titan** is the largest satellite, and others are much smaller. It has an atmosphere of nitrogen and methane.
- ✓ NASA's Cassini spacecraft has found evidence of material orbiting Rhea, Saturn's second largest moon. This would mark the first discovery of rings around a satellite.[6]

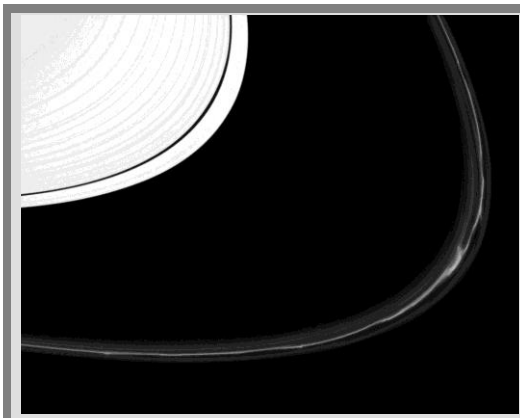


Fig. 5-21: F ring shows twists and kinks. (Image credit: NASA)

Fig. 5-22: Two of Saturn's shepherd satellites (Pandora on the left, and Prometheus) near to the F ring. (Image credit: NASA)

[6] See http://www.nasa.gov/mission_pages/cassini/media/rhea20080306.html for details.

F. Uranus

✓ Discovered in 1781 by William Herschel. An atmosphere of mostly H, 15% helium (He) and a few % of methane (CH_4), NH_3 and H_2O. Methane makes the planet looks blue. Atmospheric circulation is *much* less distinct than that on Jupiter (Fig. 5-23).

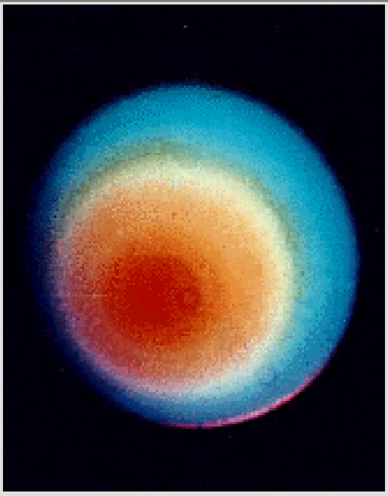


Fig. 5-23: A computer-enhanced image of Uranus reveals traces of belt-zone circulation.

✓ Self-rotation axis almost lies on its orbital plane. For an observer on the planet, the Sun would not set for half of the orbital period, and would not rise for the other half of the period! (Fig. 5-24)

✓ It has a dark, narrow, widely spaced ring system perpendicular to its orbital plane. They were discovered by observing an **occultation** - passage of the planet in front of a star.

✓ It has 5 large satellites and 9 very small ones, and all are rocky worlds. For example, **Miranda** is the smallest of the 5 large moons, system of grooves and huge cliffs were found on its surface. It may be originated by a major impact.

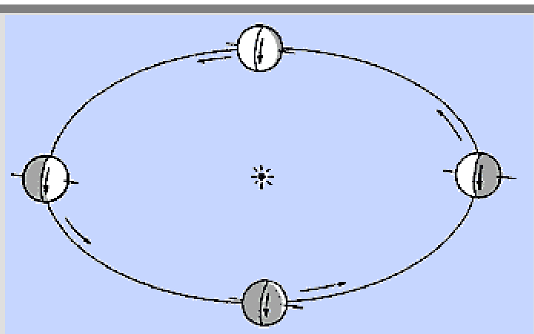


Fig. 5-24: Uranus rotates on an axis that is tipped 97.9° from the perpendicular to its orbit.

G. Neptune

✓ In 1846, the existence of an outer planet was predicted due to the difference in the observed and calculated orbital motion of Uranus. Neptune was found near to the predicted position.

✓ Similar to Uranus in size, mass, and atmospheric condition.

✓ Cyclone patterns have been discovered, e.g. **Great Dark Spot**. White clouds of frozen methane stand in high altitude.

✓ It has small dark rings and 8 moons. Only 2 large ones are visible from Earth. **Triton** is the only large satellite orbiting in clockwise sense, surface covered with frozen N_2, CH. **Nereid** has a long-period, highly elliptical orbit.

5.4 Dwarf planets

This is a new category of classification of celestial bodies in the Solar System which is proposed by the International Astronomical Union's (IAU) in 2006. The first members are Ceres, Eris and Pluto. As of early 2014, officially there are five dwarf planets. More members are expected to be announced in the future.

A. Ceres (穀神星)

Ceres (穀神星) is the largest asteroid in the asteroid belt (Section 5.6), has a diameter of only about 1/3 that of the Moon.

B. Eris (formerly 2003 UB_{313})[7]

It was discovered by Michael Brown and his colleagues in 2005 from images taken on 21/10/2003. Its diameter is 2400 km and surface is coated with methane. It is the largest Kuiper belt object (Section 5.7) currently known, the second Pluto. Eris has an elongated orbit. (Fig. 5-25)

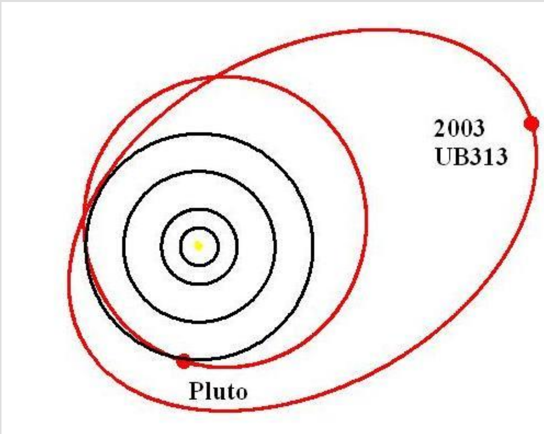


Fig. 5-25: The orbit of 2003 UB313 and Pluto.

C. Pluto

From its discovery by Clyde Tombaugh in 1930 until 2006, Pluto was considered the ninth and smallest planet of the Solar System (Fig. 5-26); however, it was "demoted" from the category of planets in 2006. Pluto orbits around the Sun elliptically, overlapping with Neptunian orbit (Fig. 5-25); the orbital plane tipped at 17.2° to the common plane of planets, and spins is in clockwise sense with the inclination of equator to orbit 118°.

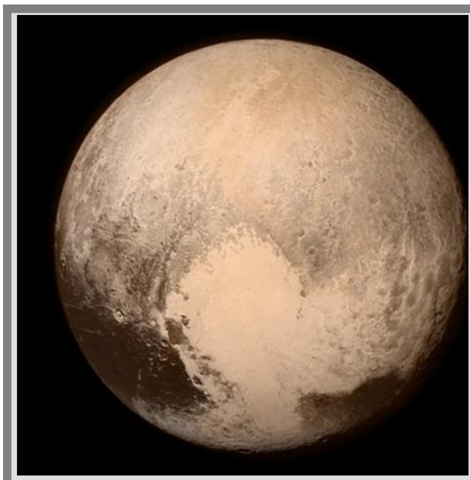


Fig. 5-26: Pluto, taken by the spacecraft The New Horizons (Image: NASA/APL/SwRI)

A relatively large-size, low-density satellite, **Charon** (查倫), is tidally locked to Pluto. Charon contains less rock than ice. Pluto and the satellite have often been considered a binary planet because they are more nearly equal in size than any other planet/moon combination in the solar system, and because the two bodies orbit a point not within the surface of either.

[7] See http://www.iau.org/public_press/news/detail/iau0605/ for details of Eris and its renaming.

5.5 Asteroids

- Asteroids are small rocky debris that revolves around the Sun. Most orbits lie in the **asteroid belt** between Mars and Jupiter, whose gravitational forces affects their orbits significantly. Fig. 5-27 shows the asteroid Graspa.

Fig. 5-27: The asteroid Graspa.

- Only two dozens or so are more than 200 km, most as small as ~0.1 km, irregular in shape.
- **Kirkwood′s gaps** are regions in the belt almost devoid of asteroids. They lie at orbital distances in *resonance* with Jupiter. Resonance occurs when the orbital period of an asteroid is equal to a rational fraction of that of Jupiter, e.g., 1/4, 2/7, 1/3, 2/5, etc. (Fig. 5-28) Imagine that the period of an asteroid is twice of that of Jupiter, it will find Jupiter in opposition in alternate periods, so the cumulative perturbation changes its orbits until it is no longer in resonance.

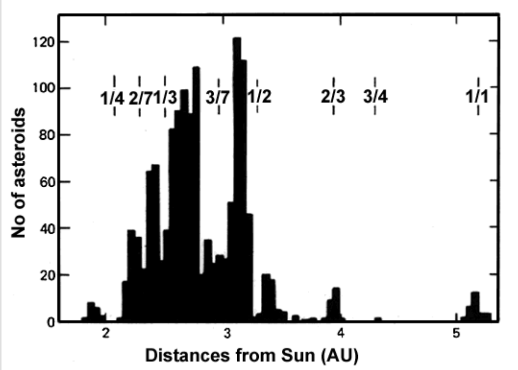


Fig. 5-28: Kirkwood′s gaps

- The combined gravitational forces of planet and the Sun work together to hold asteroids at locations called the **Lagrangian points**. The asteroids trapped at Jupiter's Lagrangian points are called **Trojan asteroids** (~ 700 altogether). (Fig. 5-29)

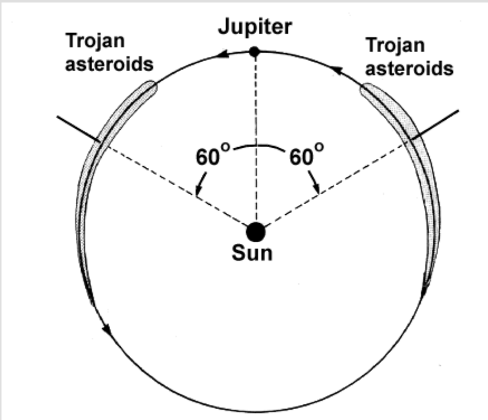


Fig. 5-29: Trojan asteroids.

- Collision with the Earth is possible! For example, in 2013, a 17m-diameter asteroid hit the Earth, releasing an amount of energy equivalent to about 30 times the Hiroshima atomic bomb. Another even bigger asteroid (30m) past the Earth at about 1/13 of the distance to the Moon.
- A theory of extinction of dinosaurs: It is believed that there was an asteroid hitting the Earth 65 million years ago. Afterwards, dust from fire triggered by the explosion

shrouded our planet for years, extinguishing Sun′s ray. Consequently, plants died and food chain disrupted. Dinosaurs died finally. The suspected impact scar has been found in Central America. Iridium anomaly in sediments of the same age all over the world.

5.6 Comets

- ✓ Many of them are far beyond Pluto (perhaps as far as 50,000 AU), and moving in *highly elliptical* orbits around the Sun.
- ✓ Most are ″long-period comets″ (period > 200 years) comets with the longest period may take ~10^5-10^6 years to complete an orbit. A few ″short-period comets″ return for another encounter within a human life span, e.g., Halley′s comet has a period of ~76 years. It is expected to reappear in 2061.
- ✓ When a comet is approaching the Sun, its orbits could change significantly midway due to burn-off of materials by the Sun. They could be broken up into pieces by other planets, or even collide with planets or the Sun. For example, collisions of the comet Shoemaker-Levy with Jupiter happened in July 1994.

Structure of a Comet

- ✓ **Nucleus:** The solid body of a comet is about a few kilometres. It has a rocky core covered with a mixture of ice and dust. Only nucleus exists when a comet is far from the Sun.
- ✓ When a comet is approaching the Sun, solar heat begins to vaporize the comet’s ice, librating gases and dust particles. The liberated gases begin to glow, producing a luminous ball called **coma**, typically ~ 1 million km in diameter. The solar wind and sunlight blow these luminous gases and dust particles, outward into a long, flowing **tail**. The tail can be longer than 100 million kilometres in length! (Fig. 5-30)

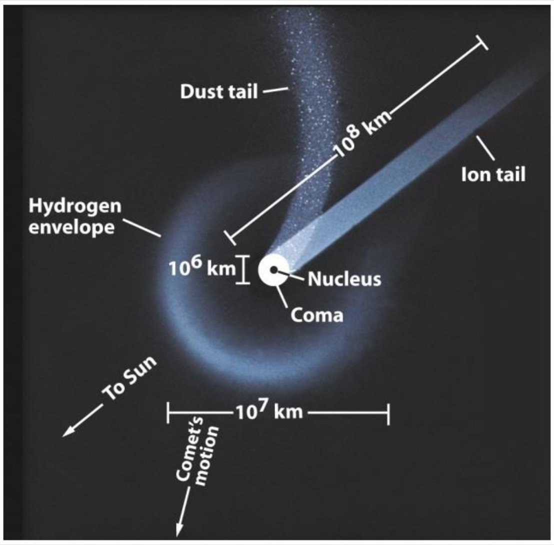


Fig. 5-30: The structure of a comet.

- ✓ A part of a comet that is not visible to the human eye is the **hydrogen envelope**. Solar ultraviolet radiation from Sun breaks up water molecules into hydrogen atom. The atoms will then absorb and re-emit ultraviolet photons. These can be detected above the Earth's atmosphere, since the Earth's atmosphere is opaque to ultraviolet light.
- ✓ **Tail** is vaporized matters directed away from the Sun (Figs. 5-30, 5-31). Typically, a comet has two tails:
  - ✧ **Ion tail** (type I tail) is straight, and it is made up of ions pushed away from the Sun by *solar wind*. The distinct blue colour of the ion tail is caused by emission from methane.
  - ✧ **Dust tail** (type II tail) is smooth, featureless and curved. Light exerts a pressure on an object that absorbs or reflects it. This pressure is called **radiation pressure**. Since dust particles are of ~1 μm only, one estimates that the dust particles are so *small* that the radiation pressure is larger than the gravitational attraction by the Sun. Derivation is found in *Box 5.5*.

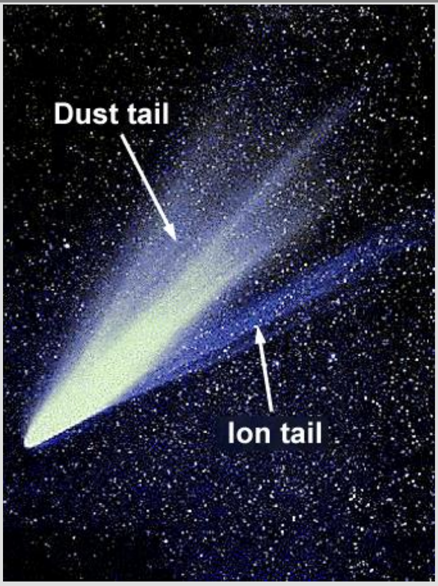


Fig. 5-31: Comet West in 1976.

- ✓ The **Oort cloud** is a vast and distant reservoir of inactive comets. Up to a trillion comets orbit the Sun from about 30,000 AU to 1 ly, but only a few are disturbed and enter the Solar System. The comet from the Oort cloud is a long-period comet.

5.7 Kuiper Belt

- ✓ After 5 years of searching, the first trans-Neptunian objects (not included Pluto) was detected in 1992 by David Jewitt and Jane Luu.[8] The region outside Neptune's orbit at 30 AU, and up to about 100 AU, is now called Kuiper Belt.
- ✓ Small icy objects in Kuiper Belt are possibly the source of many short-period comets. Pluto, Charon, Triton, etc. could be just large Kuiper Belt Objects (KBO).

[8] The Shaw Prize in Astronomy 2012 was awarded to Prof. Jewitt and Prof. Luu: http://www.shawprize.org/en/shaw.php?tmp=3&threeid=208&fourid=329 .

✓ Eris (the largest KBO ever found) was first photographed by Michael Brown with the 48-inch Samuel Oschin Telescope on October 31, 2003; Quaoar (夸奧瓦) has a size of about half Pluto, and was discovered in 2002.[9]

Box 5.5 Solar radiation pressure on a dust particle

(*for reference only*)

In the figure, the solar radiation energy falling on a particle per unit time is given by $\dfrac{dE}{dt}=\dfrac{4\pi R_{\odot}^2\sigma T_{\odot}^4}{4\pi r^2}\times\pi R^2=\pi R^2\left(\dfrac{R_{\odot}}{r}\right)^2\sigma T_{\odot}^4$. Note that $\Delta p=\Delta E/c$; hence, the **radiation force** on the particle is then

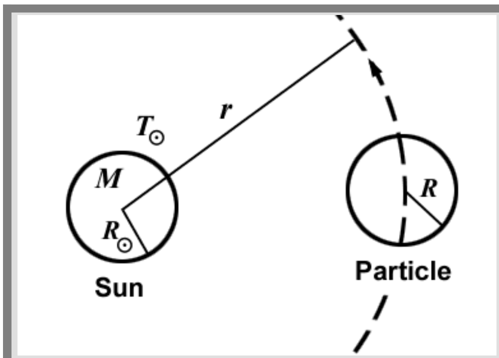
$$F_R=\frac{\Delta p}{\Delta t}=\frac{1}{c}\frac{\Delta E}{\Delta t}=\pi R^2\left(\frac{R_{\odot}}{r}\right)^2\frac{\sigma T_{\odot}^4}{c}.$$

On the other hand, the **gravitational force** on the particle is given by

$F_G=\dfrac{GMm}{r^2}=\dfrac{GM}{r^2}\times\dfrac{4}{3}\pi R^3\bar{\rho}$, where $\bar{\rho}$ is the average density of the particle. Therefore

$$\frac{F_R}{F_G}=\frac{3\sigma R_{\odot}^2 T_{\odot}^4}{4GMc\bar{\rho}R}\propto\frac{1}{R}.$$

Radiation pressure is therefore significant for small particles. Note that the ratio is independent of the distance r between the particle and the Sun.



Radiation pressure on a dust particle.

Taking $T_{\odot}=5{,}770\,\mathrm{K}$, $R_{\odot}=6.96\times10^{7}$ m, $M=1.99\times10^{30}$ kg, $\bar{\rho}\sim 3.5\,\mathrm{g/cc}$ for silicate, $F_R=F_G$ when $R\sim 0.2\,\mu\mathrm{m}$. For particles of $R>>2\,\mu\mathrm{m}$, the radiation pressure can be neglected.

[9] For further information about Quaoar, see http://hubblesite.org/newscenter/archive/2002/17/.

5.8 Meteoroids

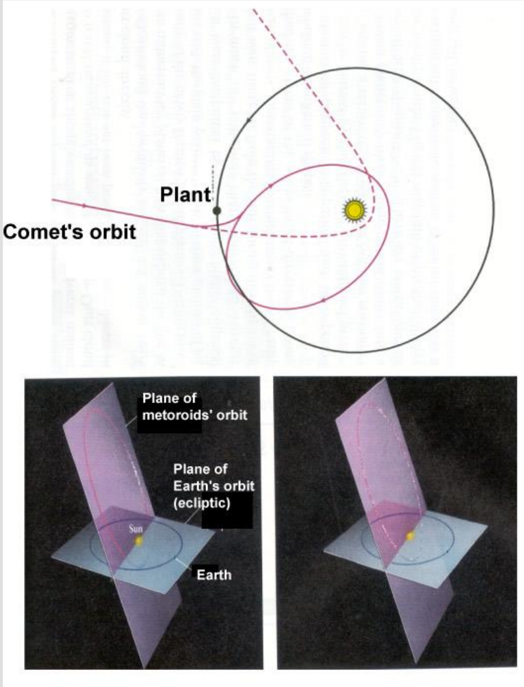


Fig. 5-32: The giant tidal forces by planets tear the comet's nucleus into fragments, and deflect the trajectories of these fragments (up), forming a meteoritic swarm (down).

- ✓ **Meteor** (流星) refers to the sudden streak of light across the sky. Before its fiery plunge, the object in space is called a **meteoroid** (流星體), and any parts of it that survive the fiery passage to the Earth's surface are called **meteorites** (隕石). A very large meteorite may cause a crater on the Earth.
- ✓ Radioactive dating shows that meteorites are about 4.6 billion years old, which is about the same as the age for the entire Solar System.
- ✓ When a comet enters into the Solar System, the giant tidal forces may tear the comet's nucleus into fragments. The planets' gravity may also deflect the trajectories of these fragments, forming a **meteoritic swarm**. (Fig. 5-32) If the Earth's orbit happens to pass through the swarm, a **meteor shower** is seen as the small fragments strike the Earth's atmosphere. It seems that meteors diverge from a point called radiant. (Fig. 5-33)

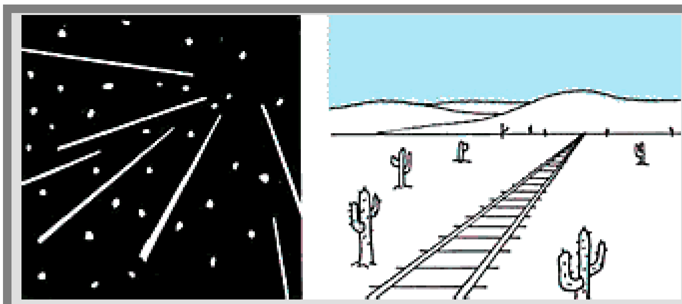


Fig. 5-33: The radiant of a meteor shower.

- ✓ Most meteoroids are destroyed in the atmosphere, but any parts that reach the ground are called **meteorites.** (Fig. 5-34) Meteorites are relatively high density, may come from asteroids but *not* from comets. Types of meteorites:
  - ✧ **Iron meteorites** - rich in *iron* and *nickel*, account for about 4% of the

Fig. 5-34: The meteorite crater in Arizona was formed 50,000 years ago by the impact of an iron meteorite. The crater is 1.2 km in diameter.

materials that falls on the Earth. Before human began extracting iron from ores around 2000 B.C., the only source of the metal was from iron meteorites!

✧ **Chondrites** - stony, dark gray granular rocks containing *chrondrules*, round bits of glassy rock < 5 mm, make up 80% of the falls. On the other hand, **Achondrites** is stony meteorites without chrondrules.

5.9 Formation theory (Solar nebula hypothesis)

✓ The **solar nebula** was a spinning cloud of gas and dust (Fig. 5-35).

✓ The **centrifugal force** due to spinning flattened the cloud to form a disk. Some materials away from centre, forming planets. It explains why most planets′ orbits lie on the same plane, orbiting the Sun and self-rotating in the same direction.

✓ **Differential condensation**: Near the centre, the temperature was higher, only *metal* and *metal oxides* condensed there, the condensed seeds were dense and small. On the other hand, farther out in the disk, the temperature was lower, only *silicates, rocky* materials condensed.

✓ Seeds of condensation called **planetesimals** (~cm - ~km) grew to planets. Apart from continuous condensation of particles, static electricity and cohesive forces also led to accretion of particles. As a result, rather *small, dense* planets were formed near the centre (Terrestrial planets). They have weak gravity, holding thin atmospheres, capturing a few satellites. On the other hand, *large, low density* planets were formed farther out (Jovian planets). They have strong gravity, holding thick atmospheres, capturing many satellites and rings.

✓ The central cluster formed the Sun. When it became hot and luminous, radiation pressure and solar wind pushed away the remaining gas and dust. This may stop the planets building process. Remnant of nebula became the Oort cloud and the Kuiper belt finally.

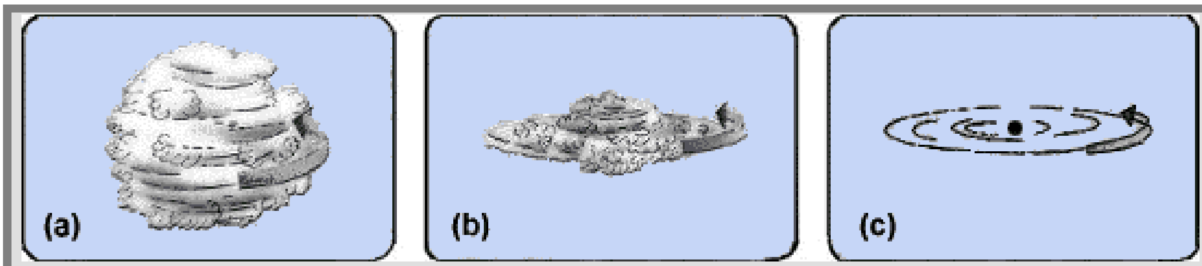


Fig. 5-35: (a) Because the solar nebula was rotating, (b) it contracted into a disk, and (c) the planets with orbits lying in nearly the same plane.