

# Lecture 4

# Our Solar System

The Cassini

# Guiding Questions

1. Are all the other planets similar to Earth, or are they very different?
2. Do other planets have moons like Earth's Moon?
3. How do astronomers know what the other planets are made of?
4. Are all the planets made of basically the same material?
5. What is the difference between an asteroid and a comet?
6. What determines whether a planet or satellite can retain a certain gas in its atmosphere?
7. Why are craters common on the Moon but rare on the Earth?
8. Why do interplanetary spacecraft carry devices for measuring magnetic fields?

# **HOMEWORK SET 4**

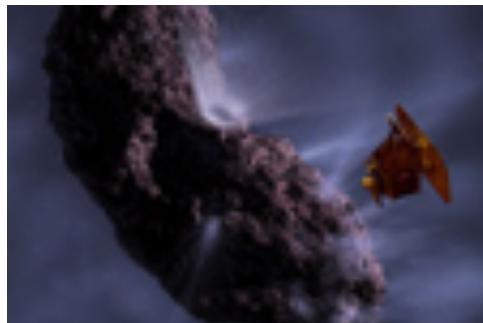
**Due September 28, Wednesday**

FGK10: Chap 7: Questions 25, 28, 29, 30, 33.



## Current, Future, and Past Solar System Missions

Planetary exploration missions are conducted by some of the most sophisticated robots ever built. Through them we extend our senses to the farthest reaches of the solar system and into remote and hostile environments, where the secrets of our origins and destiny lie hidden. The coming years of solar system exploration promise to be the most exciting and productive yet, as we explore entirely new worlds and probe in even greater detail the fascinating environments we have discovered.

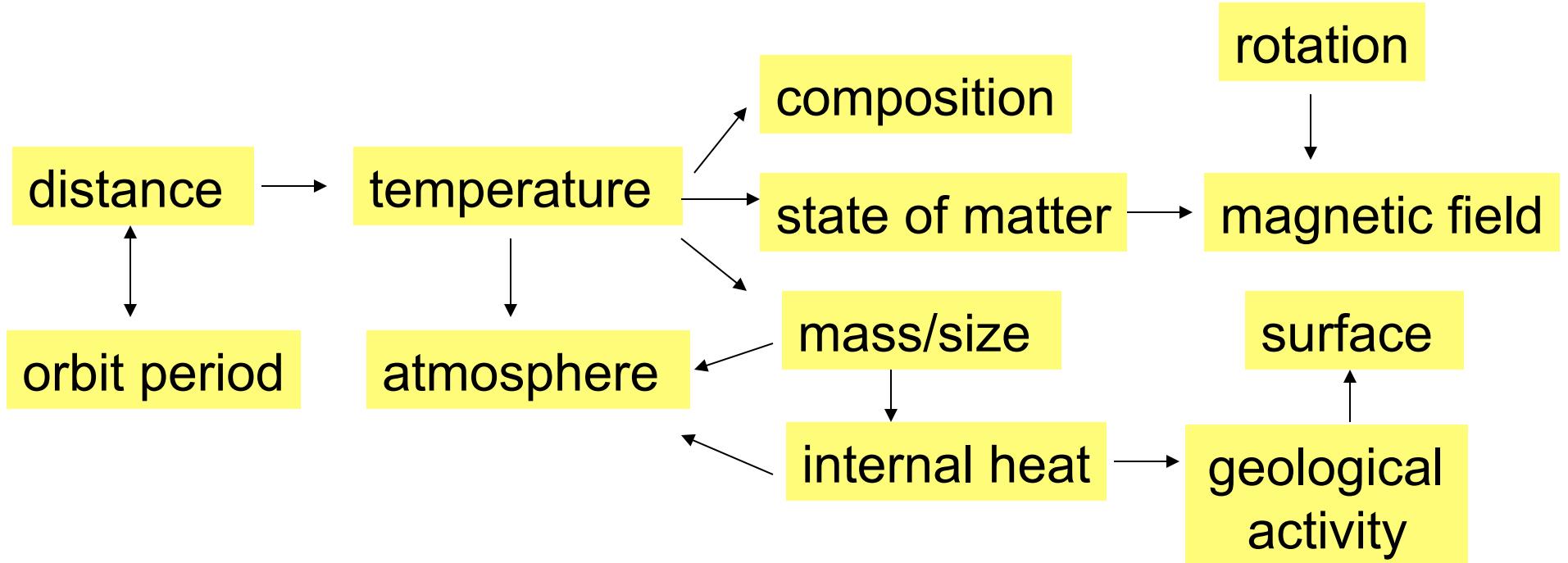


We will learn the **motion, structure, atmosphere, magnetic field** of the Sun, planets, and satellites, and how to observe them.

We will learn how to explain them -- **gravity, energy, and nature of light**.

We will learn why our planet, the Earth, hosts life.

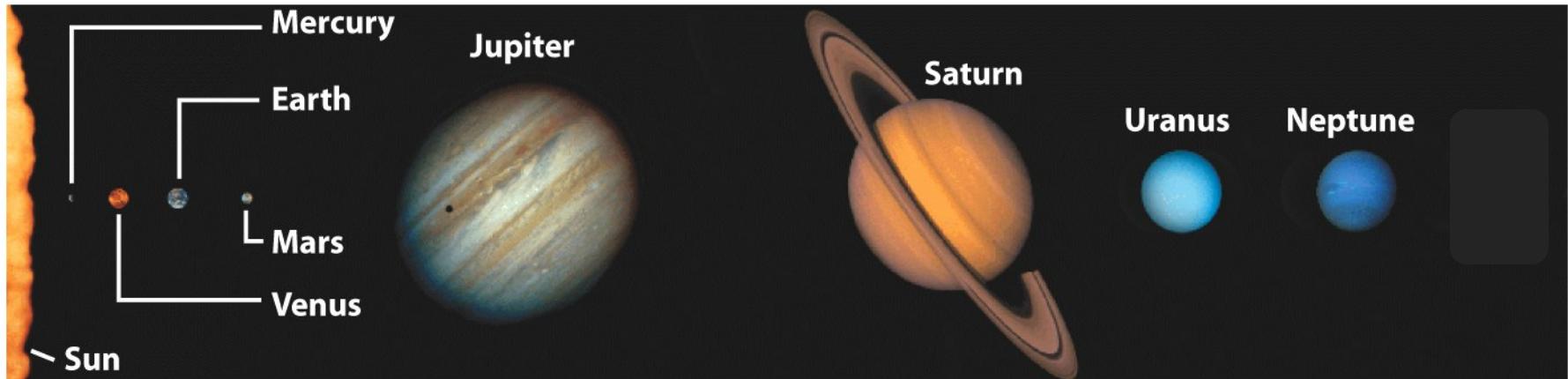
# Gravity and distance to the Sun are the keys to understanding the solar system



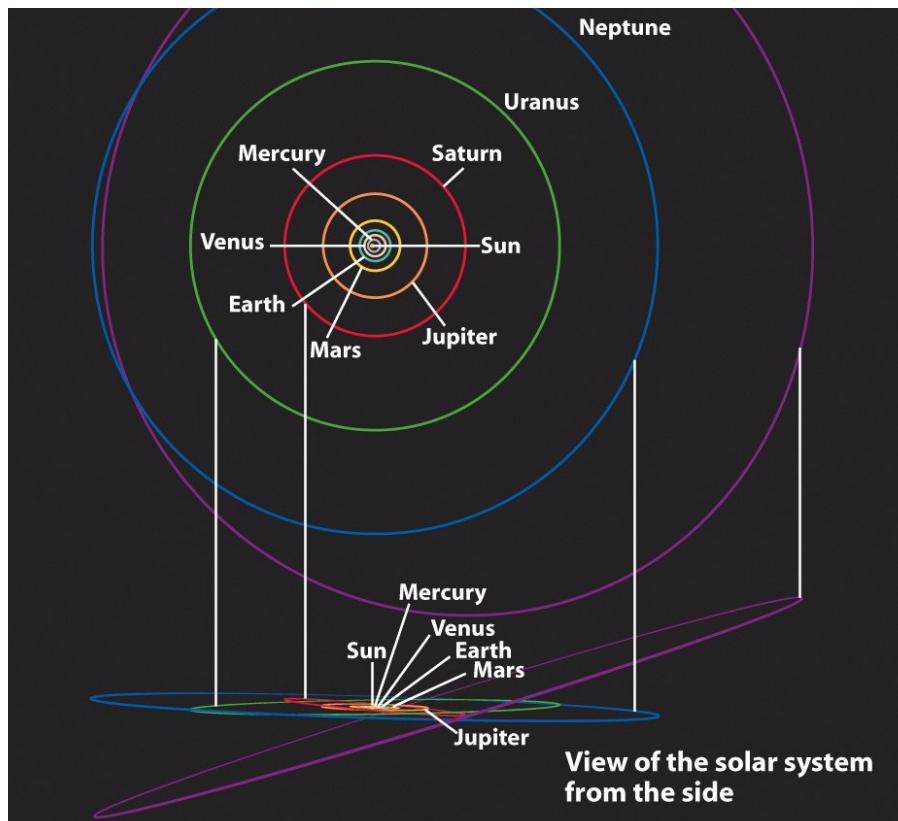
**Q: Where does GRAVITY spell out?**

Our knowledge of the Universe critically depends on how much we understand LIGHT.

## 4.1 planets



According to their orbits, **planets** fall into two classes: the inner planets (Mercury, Venus, Earth, and Mars) are Earthlike, and the outer planets (Jupiter, Saturn, Uranus, and Neptune) are Jupiter like.



# the terrestrial (inner) planets

	Mercury	Venus	Earth	Mars
Average distance from Sun ( $10^6$ km)	57.9	108.2	149.6	227.9
Average distance from Sun (AU)	0.387	0.723	1.000	1.524
Orbital period (years)	0.241	0.615	1.000	1.88
Orbital eccentricity	0.206	0.007	0.017	0.093
Inclination of orbit to the ecliptic	7.00°	3.39°	0.00°	1.85°
Equatorial diameter (km)	4880	12,104	12,756	6794
Equatorial diameter (Earth = 1)	0.383	0.949	1.000	0.533
Mass (kg)	$3.302 \times 10^{23}$	$4.868 \times 10^{24}$	$5.974 \times 10^{24}$	$6.418 \times 10^{23}$
Mass (Earth = 1)	0.0553	0.8150	1.0000	0.1074
Average density ( $\text{kg/m}^3$ )	5430	5243	5515	3934

The four inner planets are called terrestrial planets

- Relatively small: Earth is the largest
- Low mass: Earth is the heaviest
- High densities (4000 to 5500  $\text{kg/m}^3$ ) with iron cores
- Composed primarily of rocky materials with solid surface

# the Jovian (outer) planets

	Jupiter	Saturn	Uranus	Neptune	Pluto
Average distance from Sun ( $10^6$ km)	778.3	1429	2871	4498	5915
Average distance from Sun (AU)	5.203	9.554	19.194	30.066	39.537
Orbital period (years)	11.86	29.46	84.10	164.86	248.60
Orbital eccentricity	0.048	0.053	0.043	0.010	0.250
Inclination of orbit to the ecliptic	$1.30^\circ$	$2.48^\circ$	$0.77^\circ$	$1.77^\circ$	$17.15^\circ$
Equatorial diameter (km)	142,984	120,536	51,118	49,528	2300
Equatorial diameter (Earth = 1)	11.209	9.449	4.007	3.883	0.180
Mass (kg)	$1.899 \times 10^{27}$	$5.685 \times 10^{26}$	$8.682 \times 10^{25}$	$1.024 \times 10^{26}$	$1.3 \times 10^{22}$
Mass (Earth = 1)	317.8	95.16	14.53	17.15	0.0021
Average density ( $\text{kg/m}^3$ )	1326	687	1318	1638	2000

The four gas giant outer planets are called Jovian planets

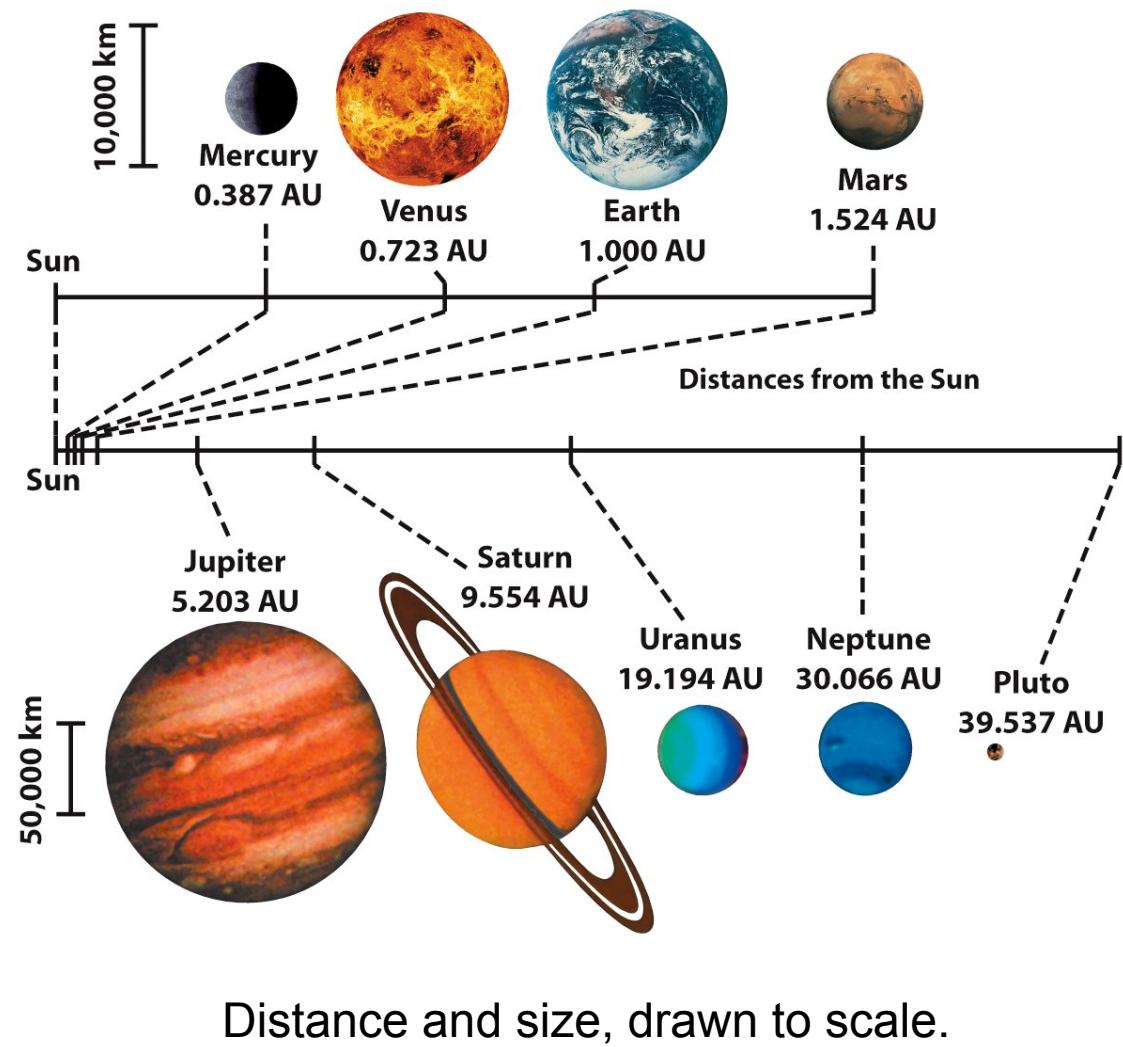
- Large diameters (4 to 11 times Earth's size)
- High mass (14 to 318 times Earth's mass)
- Low average densities (700 to 1700  $\text{kg/m}^3$ )
- Composed primarily of hydrogen and helium without a solid surface

**Jupiter is the largest and the most massive!**

# Pluto – special case: no longer a planet!

## Pluto is a special case

- Smaller than any of the terrestrial planets
- Intermediate average density of about 1900 kg/m<sup>3</sup>
- Its density suggests it is composed of a mixture of ice and rock



## 4.2 satellites, asteroids, and comets

The Seven Giant Satellites							
	Moon	Io	Europa	Ganymede	Callisto	Titan	Triton
Parent planet	Earth	Jupiter	Jupiter	Jupiter	Jupiter	Saturn	Neptune
Diameter (km)	3476	3642	3130	5268	4806	5150	2706
Mass (kg)	$7.35 \times 10^{22}$	$8.93 \times 10^{22}$	$4.80 \times 10^{22}$	$1.48 \times 10^{23}$	$1.08 \times 10^{23}$	$1.34 \times 10^{23}$	$2.15 \times 10^{22}$
Average density (kg/m <sup>3</sup> )	3340	3530	2970	1940	1850	1880	2050
Substantial atmosphere?	No	No	No	No	No	Yes	No



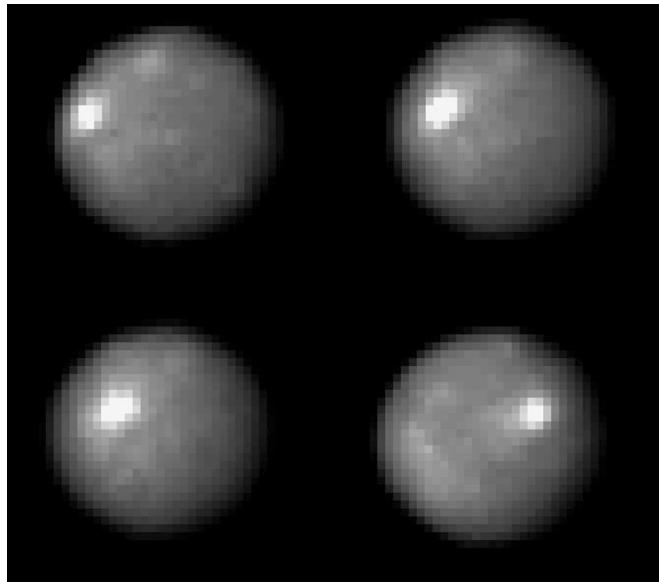
Moon      Io      Europa      Ganymede      Callisto      Titan      Triton

(JPL/NASA) R I V U X G

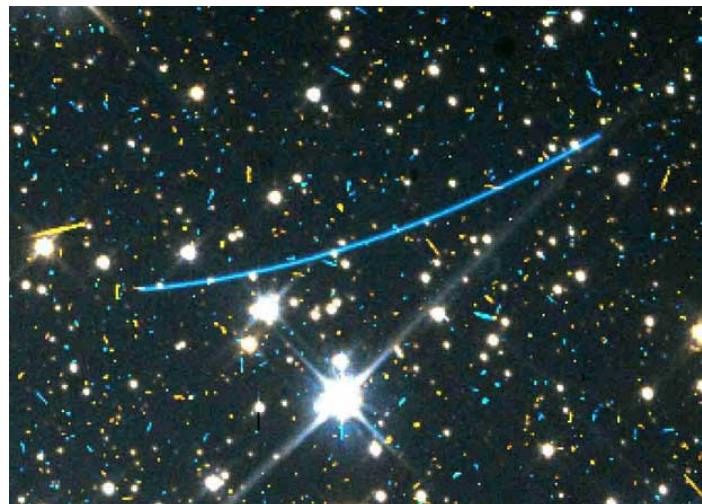
Earth's diameter is 12,800 kilometer, twice that of Titan.

- All the planets except Mercury and Venus have satellites.
- More than 130 satellites are known. Jupiter has more than 60.
- Seven large satellites are almost as big as the terrestrial planets.
- Ganymede and Titan are the largest; Titan has an atmosphere.

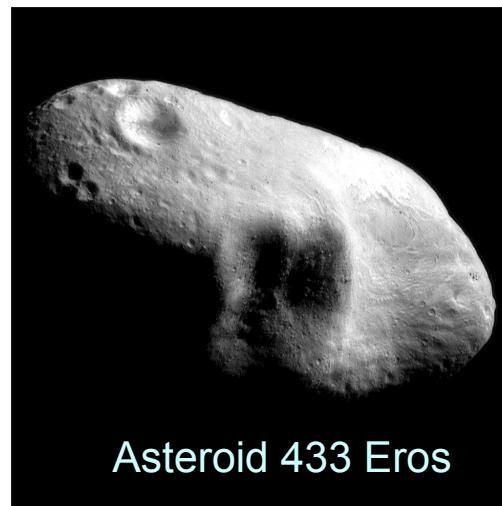
**Asteroids** are small **rocky** objects, orbiting the Sun at distances of 2 to 3.5 AU in 'the **asteroid belt**', between Mars and Jupiter.



Hubble Space Telescope observed rotation of the mini planet Ceres, the largest asteroid (diameter = 900 km) in the asteroid belt. Water may exist beneath its surface.

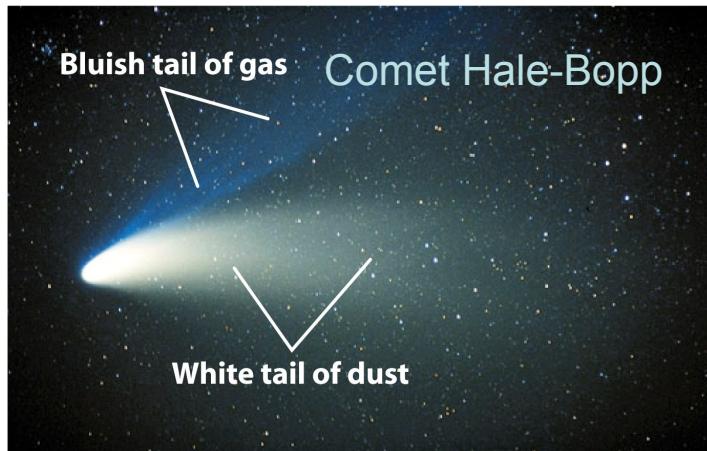


Asteroids in the distance by HST.  
(R. Evans, & K. Stapelfeldt JPL)

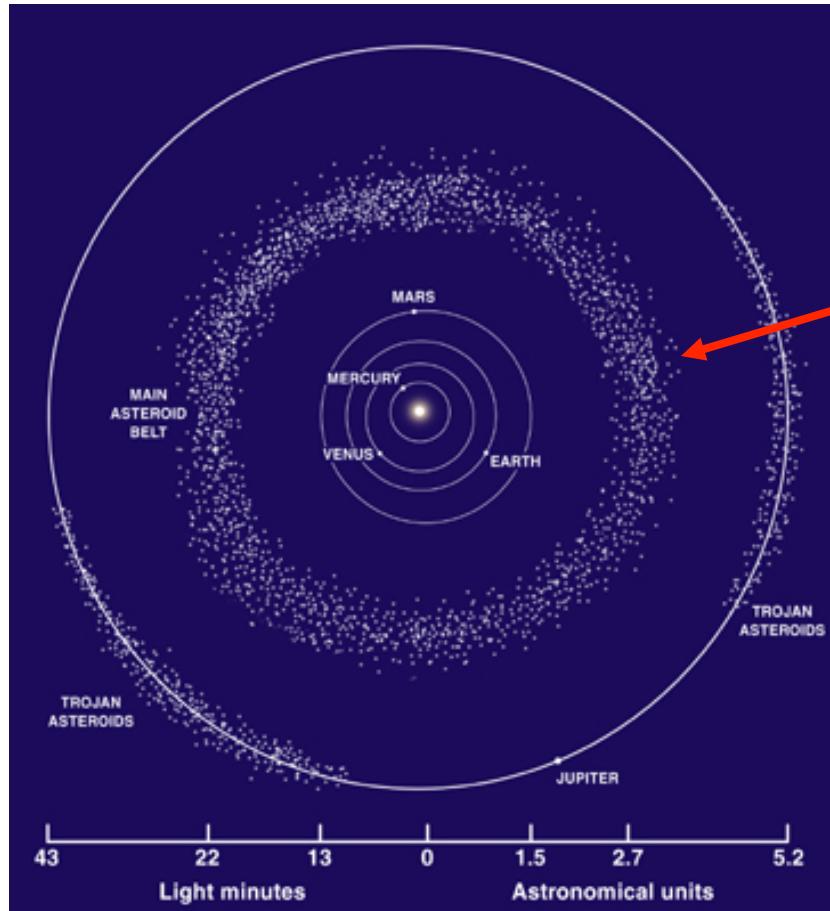


Asteroid 433 Eros

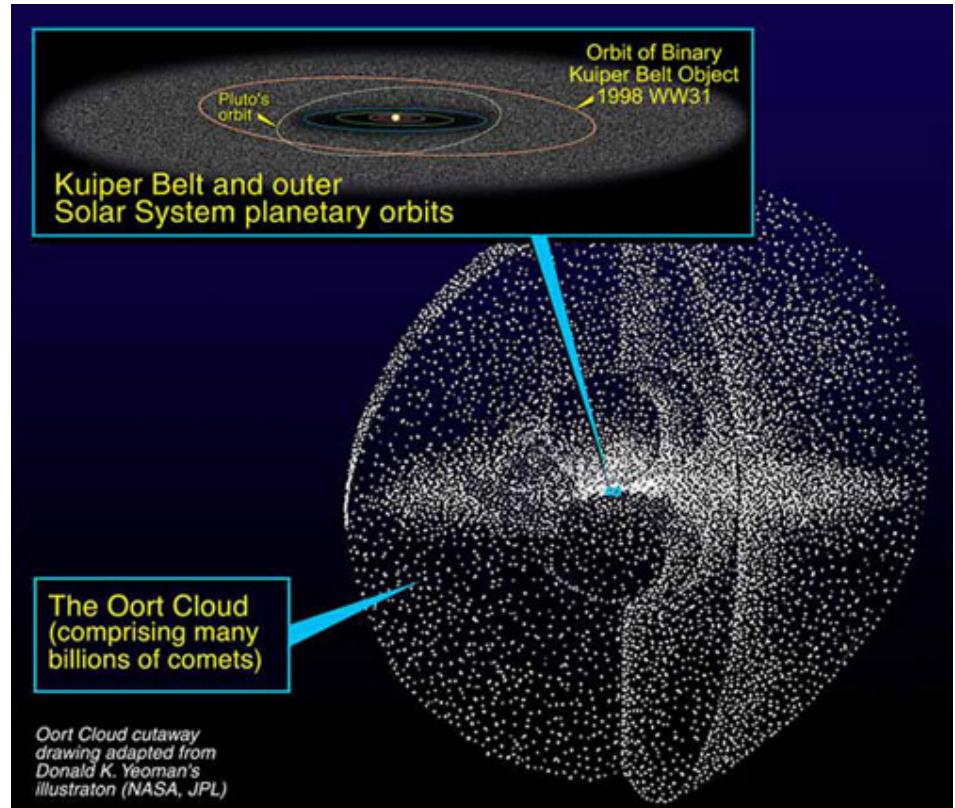
- Comets and other **Kuiper belt** objects are made of **dirty ice**.
- The **Kuiper belt** extends far beyond the orbit of Pluto.
- Pluto is the largest member of the Kuiper belt.



- Both asteroids and comets are remnants left over from the formation of the planets.
- They all orbit around the Sun, following Kepler's laws.
- Like the two categories of planets, asteroids are more "terrestrial", comets are "Jovian".



asteroid belts



Kuiper belt and  
Oort cloud

Q: What's the difference between planets, satellites, asteroids, and comets?

1. Satellites orbit around planets, planets orbit the Sun.
2. Asteroids and comets also orbit the Sun, but they are not large enough to become planets.
3. Asteroids locate in the asteroid belt between Mars and Jupiter. Comets are in Kuiper belt beyond Neptune.
4. Comets are likely extra-solar system objects!

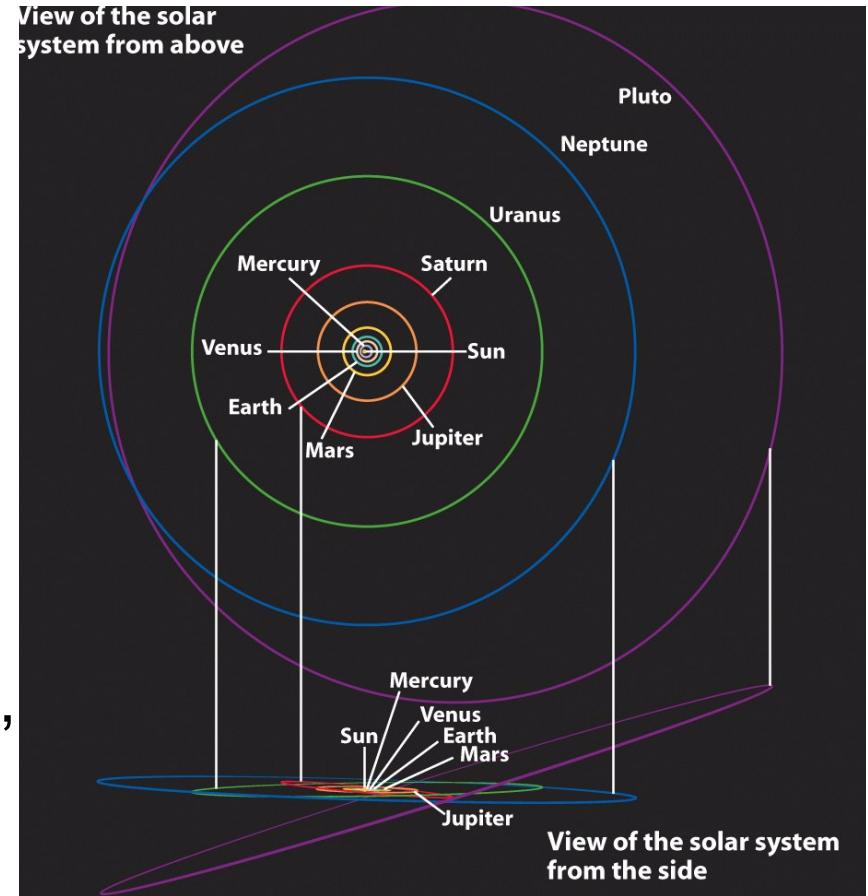
## 4.3 Orbits of Planets - Kepler's laws

- Most planets orbit the Sun in the same direction and in almost the same plane: ecliptic is the plane of the Earth's orbit.
- Most planets have nearly circular orbits - the eccentricity of the orbit is very small.
- The farther away from the Sun, the longer the orbital period:

**Kepler's third law:**  $P^2 = a^3$

( $P$  = sidereal period, in year,  $a$  = semimajor axis of orbit, in AU)

Ex.1 Saturn's distance to the Sun is about 10 AU. A year on Saturn is as long as how many Earth years?



$$P^2 = a^3$$

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**.

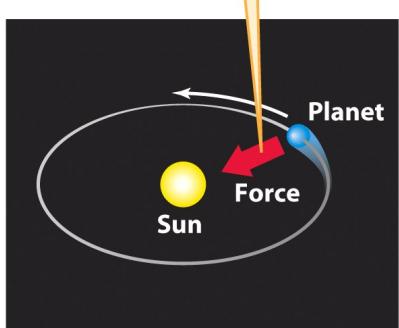
Newton's law of the universal gravitation accounts for Kepler's laws.

## Newton's form of Kepler's third law

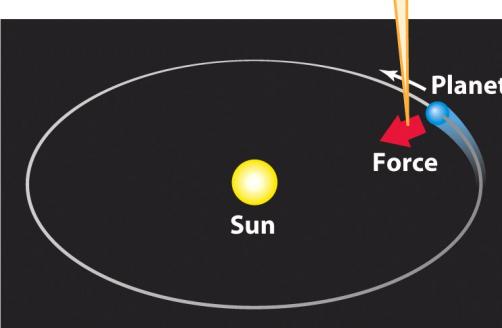
The gravitational (pull or attractive) force keeps the planets orbiting the Sun.

$$F = m\omega^2 r = \frac{4\pi^2 mr}{P^2} = F_G$$

To make a planet move at a high speed in a small orbit requires a strong gravitational force.



To make the same planet move at a low speed in a larger orbit requires only a weak gravitational force.



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  
 $= 6.67 \times 10^{-11}$

Scaling the equation to Sun-Earth system: Kepler's third law.

## 4.4 The atmosphere is retained by gravity

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

- **planet's mass and size:** gravity can retain gas particles.
- **gas composition:** light gases run faster than heavy gases.
- **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:

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

(see Box 7.2 for escape speed at each planet)

$M$  = mass of the planet(kg);  $R$  = radius of the planet(m);

$G$  = gravitational constant =  $6.67 \times 10^{-11}$  N m<sup>2</sup>/kg<sup>2</sup>.

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

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

**(thermal speed)**

$m$  = gas mass(kg);

$T$  = temperature (K=kelvins);

$v_{th}$  = speed (m/sec);

$k$  = Boltzmann constant =  $1.38 \times 10^{-23}$  J/K

(optional) Maxwellian distribution of particles in thermal equilibrium.

A good thumb rule goes:

If  $6 v_{th} > v_{esc}$ , the particles (atoms or molecules) escape.

If  $6 v_{th} < v_{esc}$ , the particles (atoms or molecules) stay!

$$6v_{th} = 6\left(\frac{3kT}{m}\right)^{1/2} \Leftrightarrow v_{esc} = \sqrt{\frac{2GM}{R}}$$

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.

Q: among 8 planets, 1 does not have appreciable atmosphere. Which one and why?

**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.

**Gravity and distance to the Sun are crucial!**

escape temperature:

$$T_{esc} > \frac{1}{54} \frac{GMm}{kR}$$

Ex 2: compare the abilities of Earth and the Moon to retain molecular oxygen ( $O_2$ ) gas in the atmosphere. (see Box-7.2)

We may calculate the escape temperature for molecular oxygen on Earth and on the Moon. For Earth,  $T_{esc} = 4500$  K, much greater than Earth's mean temperature. And for the Moon,  $T_{esc} = 200$  K, smaller than the Moon's mean temperature. Therefore, molecular oxygen gas is retained on Earth but not on the Moon.

Q: among 7 largest satellites in the solar system, Titan is the only one with an appreciable atmosphere. Why is that?

## 4.5 Composition

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

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

$\rho$  = density,  $M$  = mass of the object

$V$  = volume of the object

=  $4 \pi R^3 / 3$  (for spheres)

$R$  = radius of the spherical object

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

The terrestrial planets ( $\rho = 4000\text{-}5500 \text{ kg/m}^3$ ) are made of **rocky materials** and have dense **iron cores**.

The Jovian planets ( $\rho = 700\text{-}1700 \text{ kg/m}^3$ ) 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)

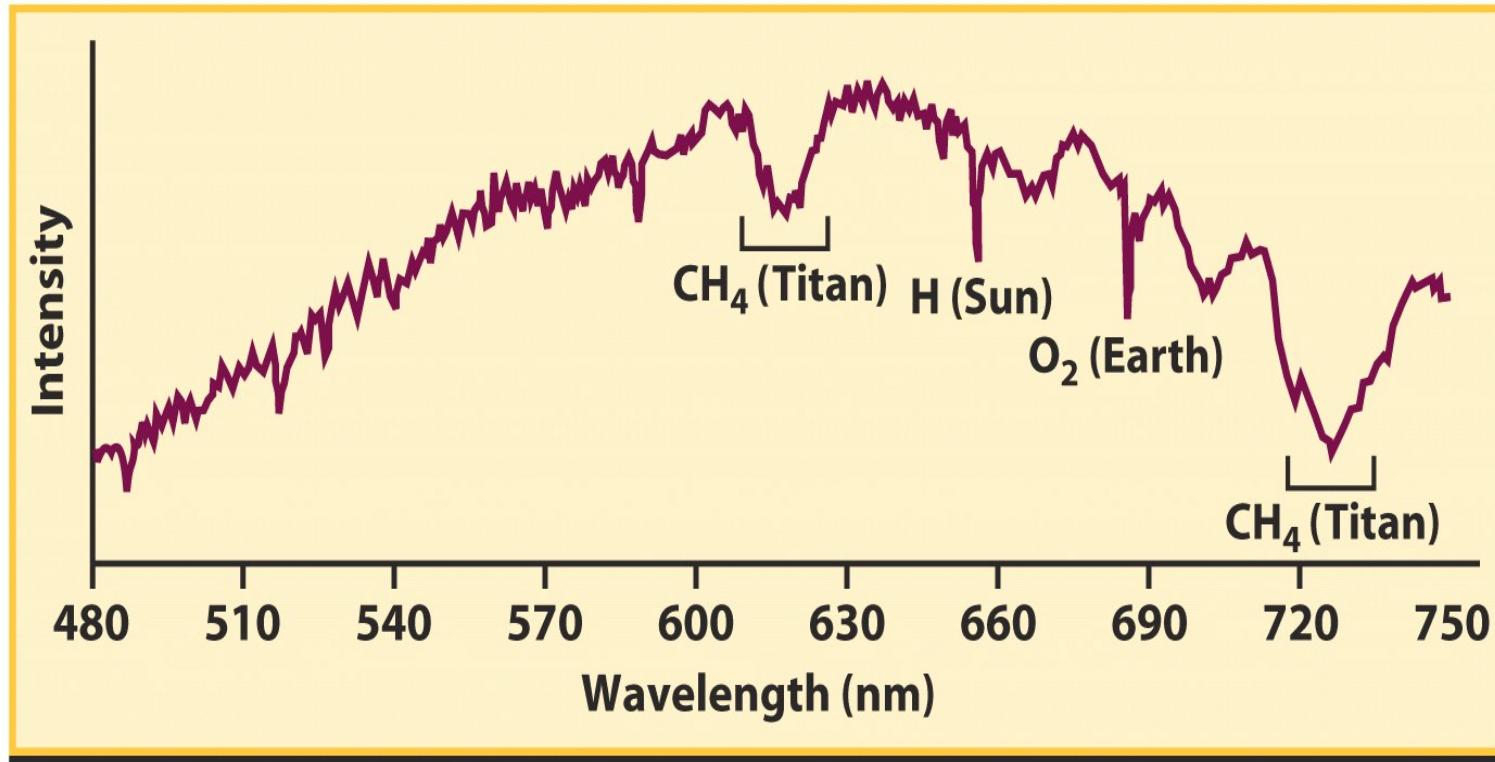
$M$  = mass of the Sun (in kilograms)

$r$  = distance between planet and Sun (in meters)

$G = 6.67 \times 10^{-11}$  newton  $\cdot$  m<sup>2</sup>/kg<sup>2</sup> , universal constant of gravitation

# Atmosphere composition

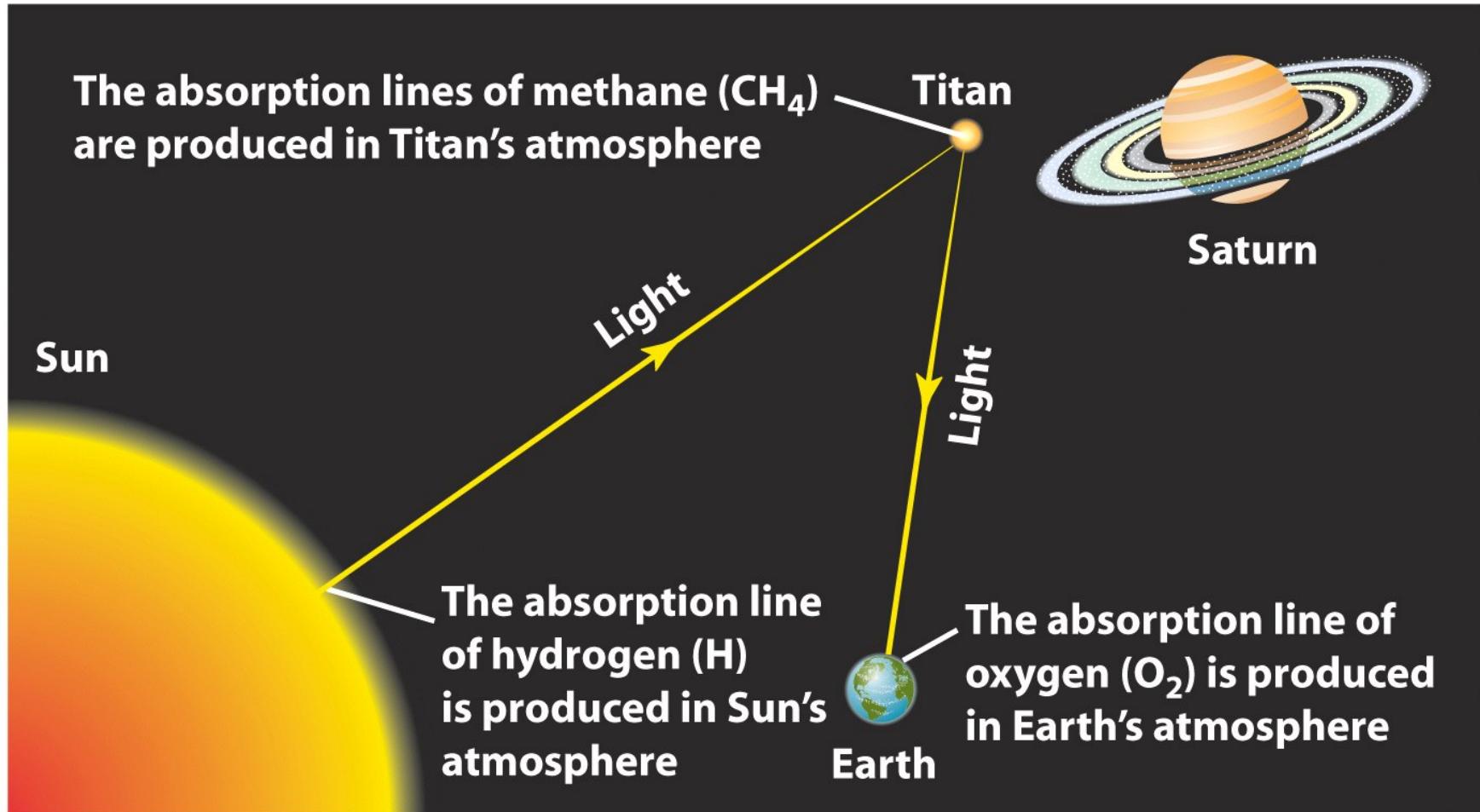
Ex 3: Atmosphere of Titan – Methane is dominant



(a) The spectrum of sunlight reflected from Titan

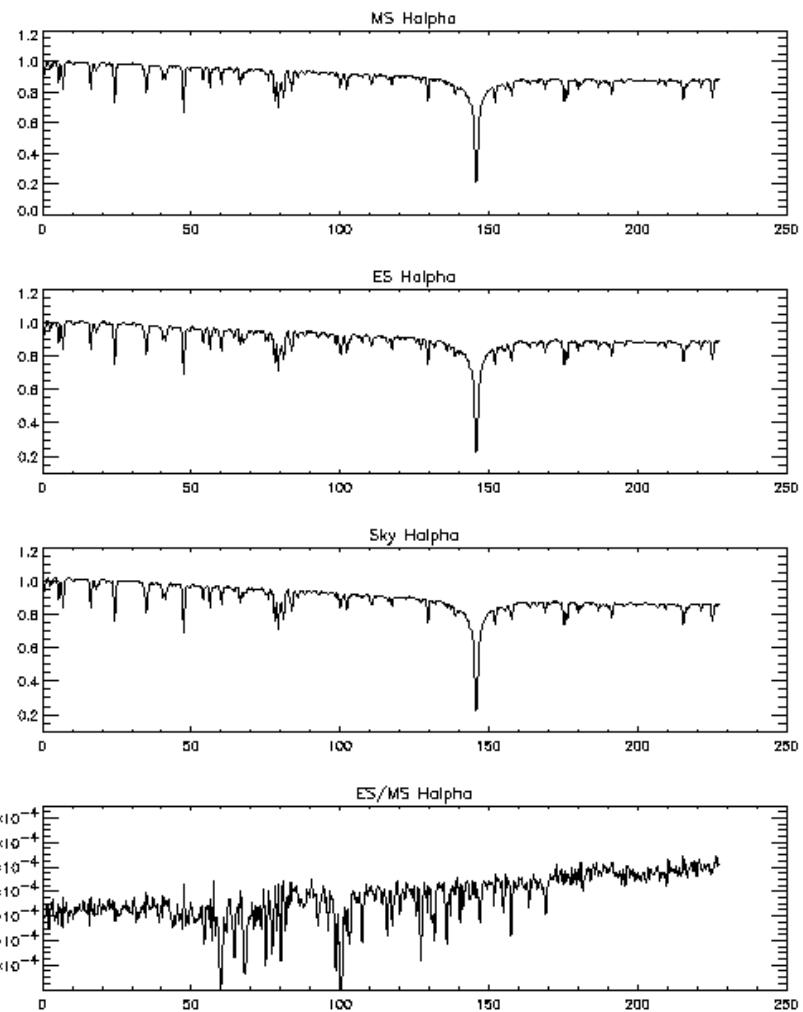
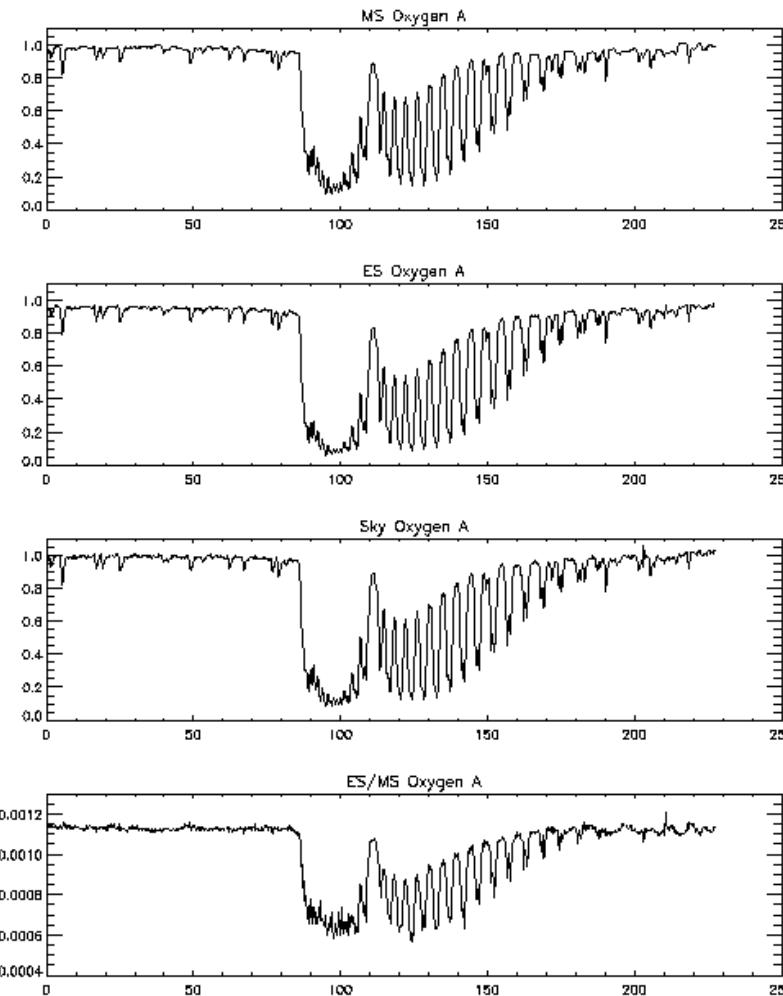
**Absorption features** reveal the atmosphere composition. The amount of absorption depends on the **abundance** of the elements and **temperature** and **density** of the atmosphere.

## Formation of Titan Spectra



**(b) Interpreting Titan's spectrum**

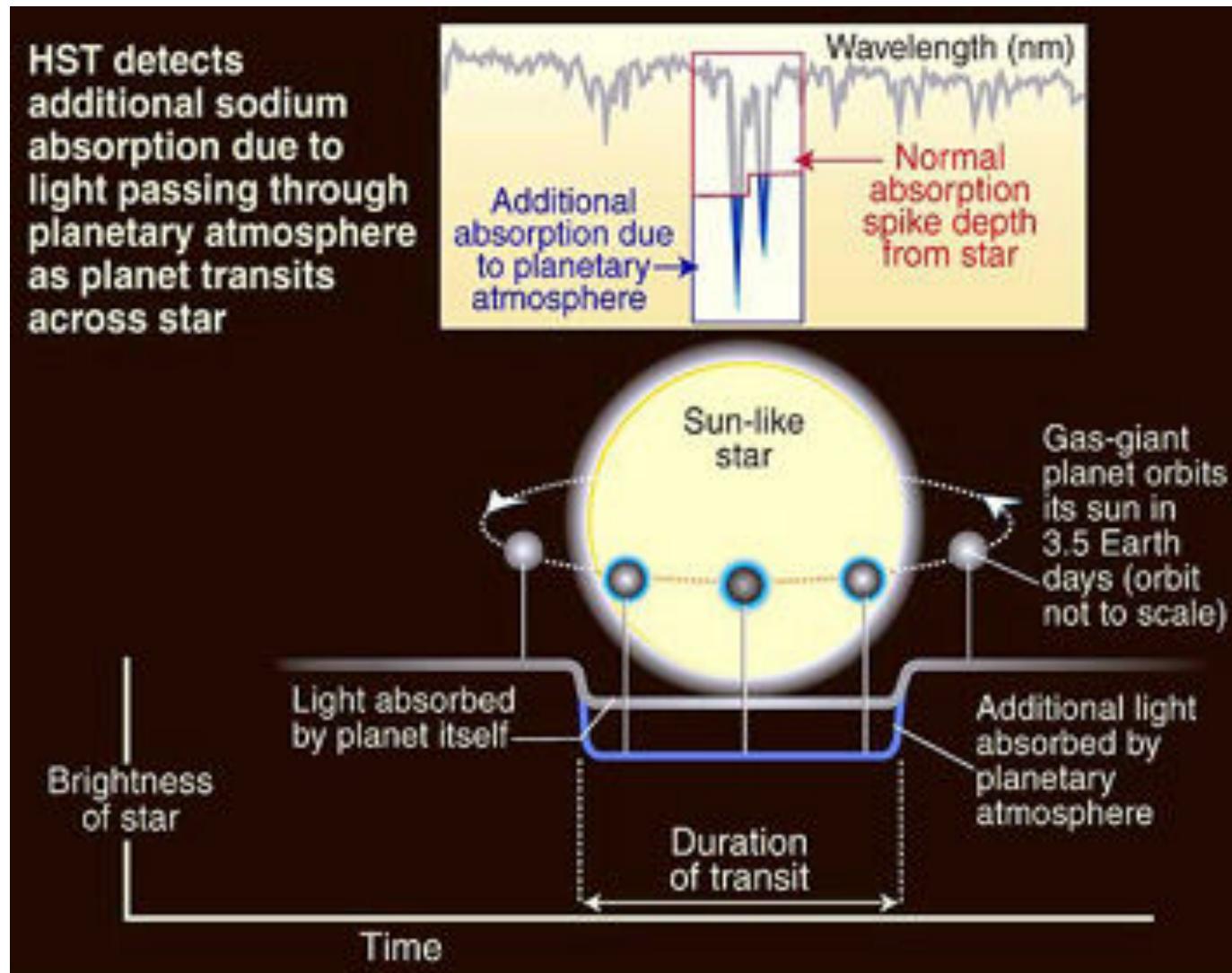
## Ex.4 Moonshine and earthshine spectra reflecting atmosphere properties



Atmosphere molecular line:  
oxygen A bands

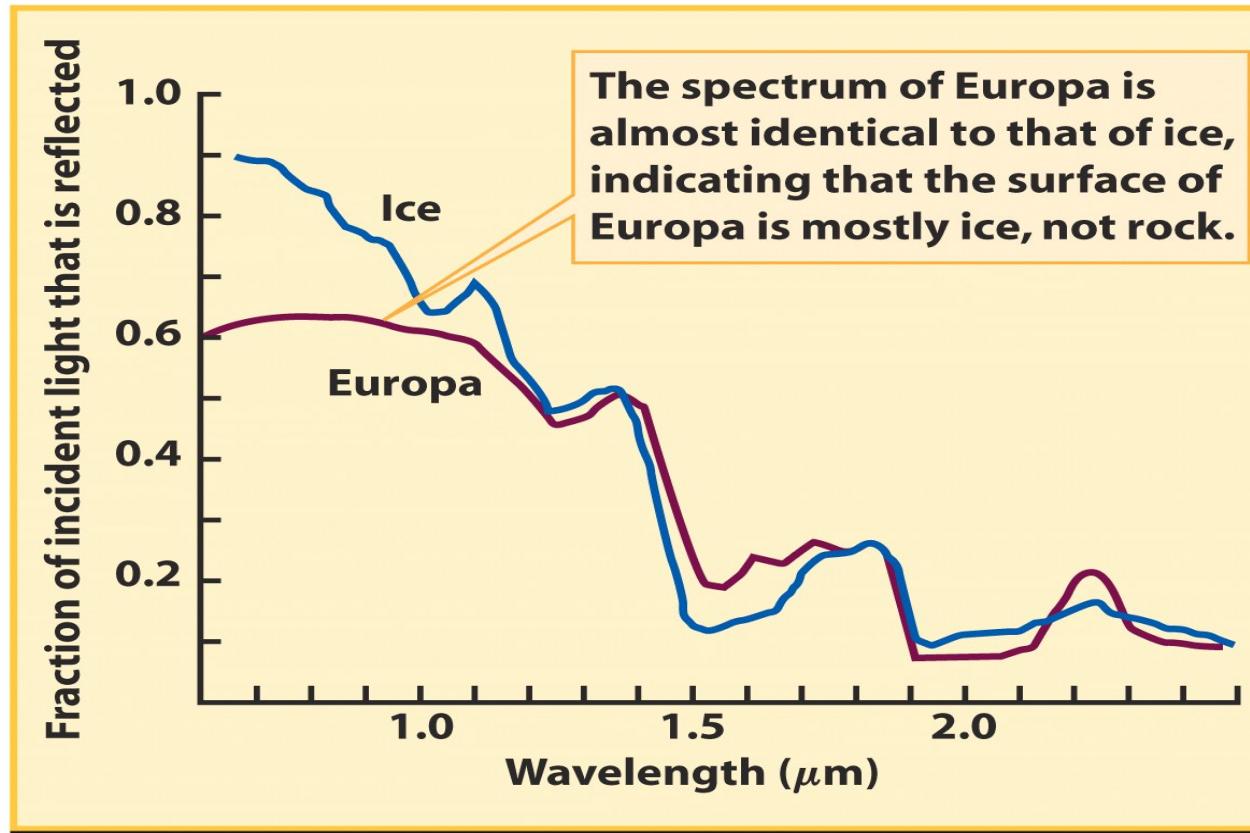
Solar line: H-alpha line

Ex.5: Additional sodium absorption found in the spectroscopy data of the planet transit shows evidence of HD 209548b having an atmosphere. *Credit: [SpaceRef.com](http://SpaceRef.com)*



# Surface Composition

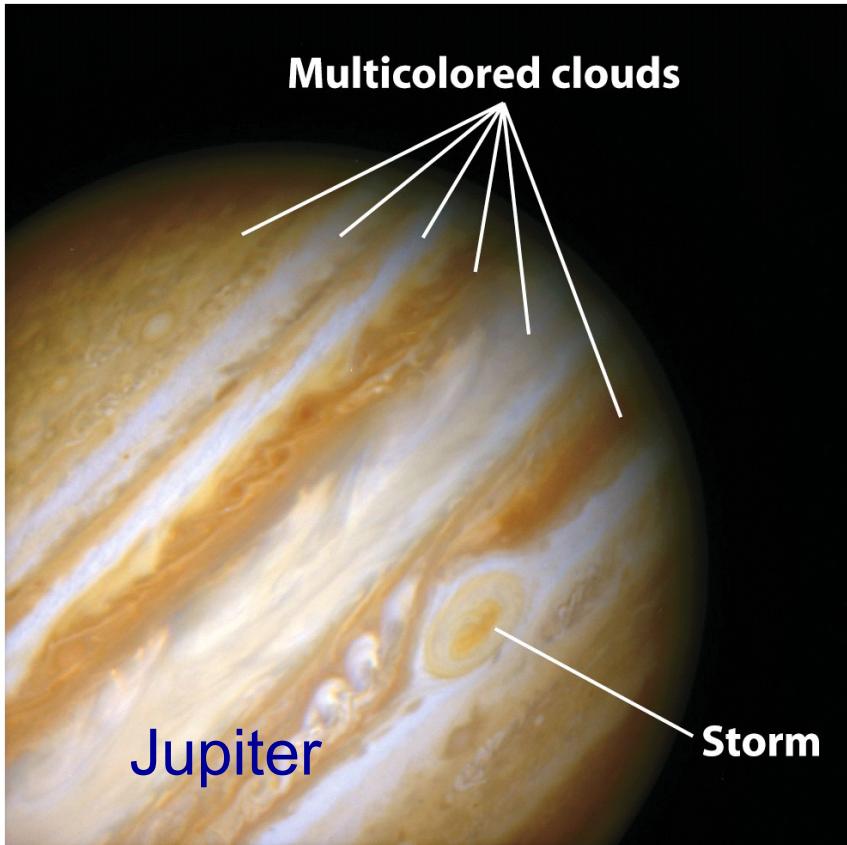
Ex 6: Surface of Europa - Ice dominated



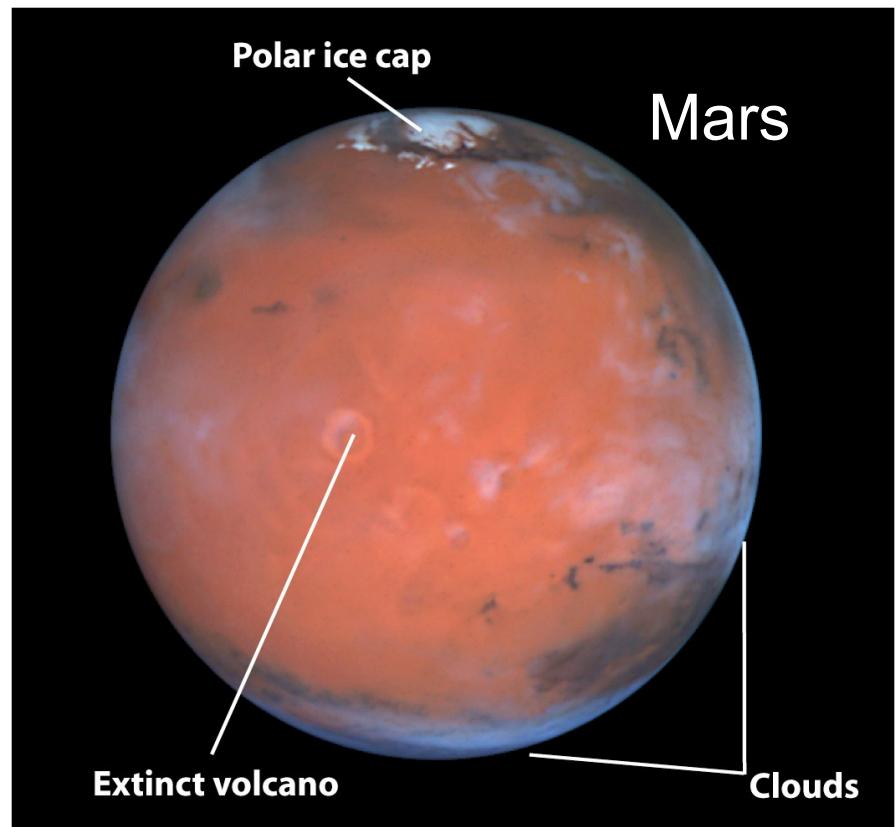
A solid surface, unlike an atmosphere, does not produce sharp spectral lines.

The broad absorption and reflection spectrum of Jupiter's moon Europa compared with ice.

Hydrogen and helium are abundant on the Jovian planets, whereas the terrestrial planets are composed mostly of heavy element.



Surface composition



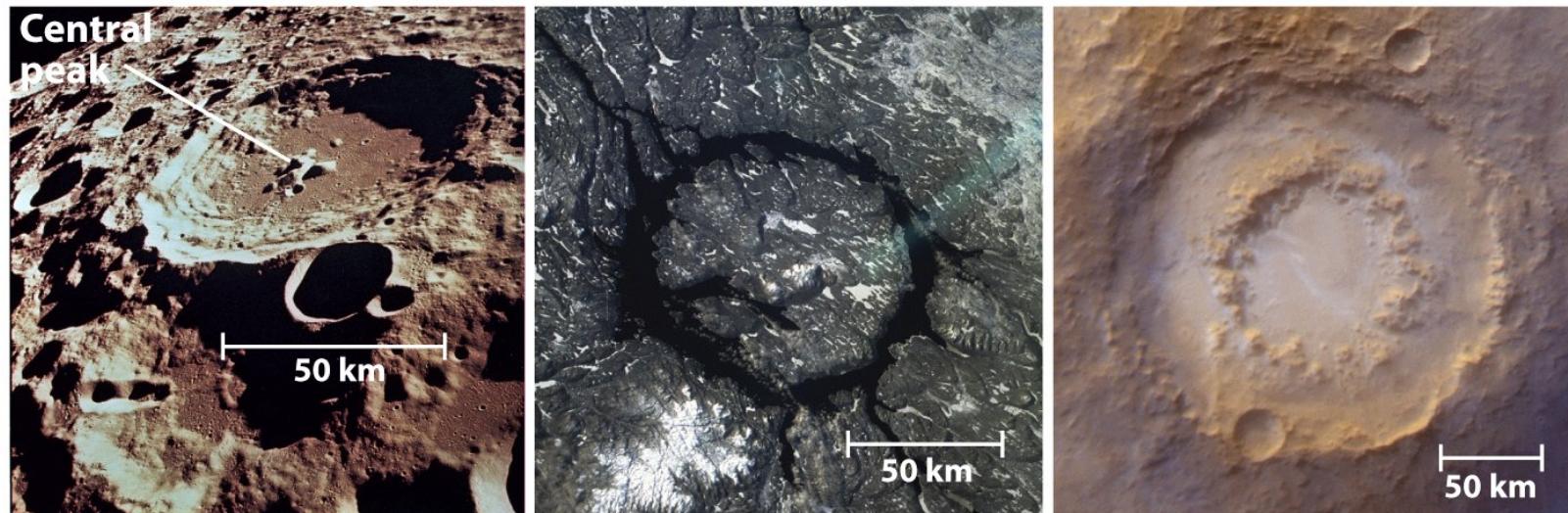
**Spectroscopy** more accurately reveals the chemical composition of surface and atmosphere of planets.

- The spectrum of a planet or satellite with an atmosphere reveals the atmosphere's composition.
- If there is no atmosphere, the spectrum indicates the composition of the surface.
- The substances that make up the planets can be classified as gases, ices, or rock, depending on the temperatures at which they solidify.
- The terrestrial planets are composed primarily of rocky materials, whereas the Jovian planets are composed largely of gas.

## 4.6 Cratering and age

Cratering on planets and satellites is the result of impacts from interplanetary debris

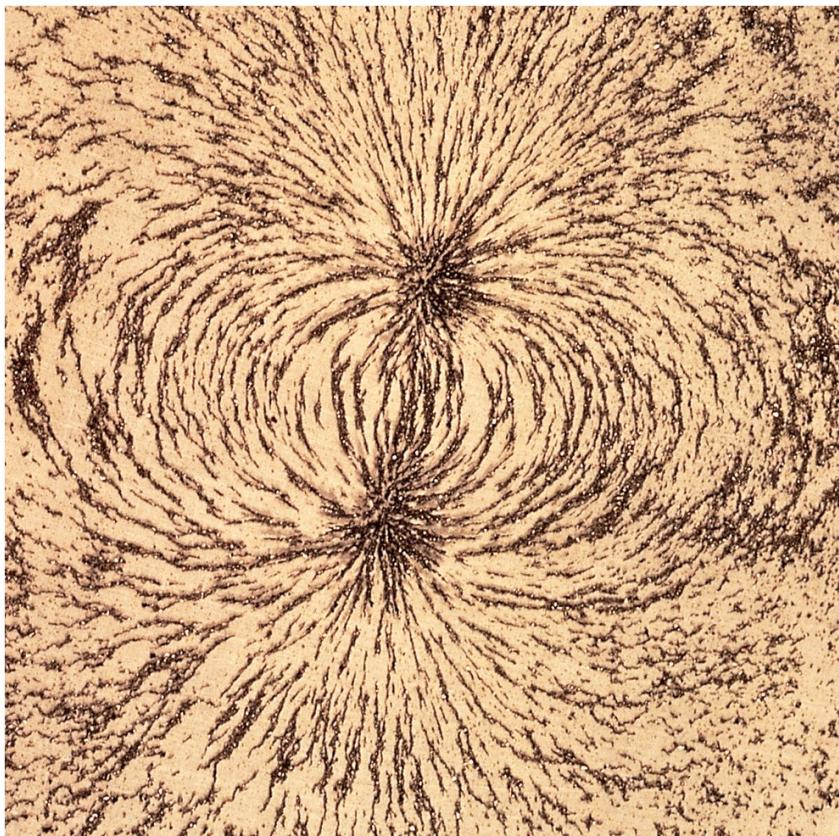
- When an asteroid, comet, or meteoroid collides with the surface of a terrestrial planet or satellite, the result is an **impact crater**.
- **Geologic activity** renews the surface and erases craters, so a terrestrial world with extensive cratering has an old surface and little or no geologic activity.



Craters on Moon, Earth, and Mars.

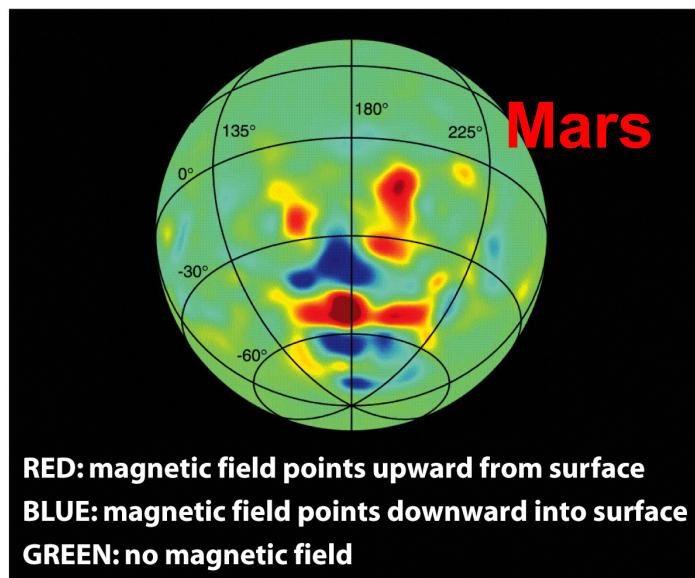
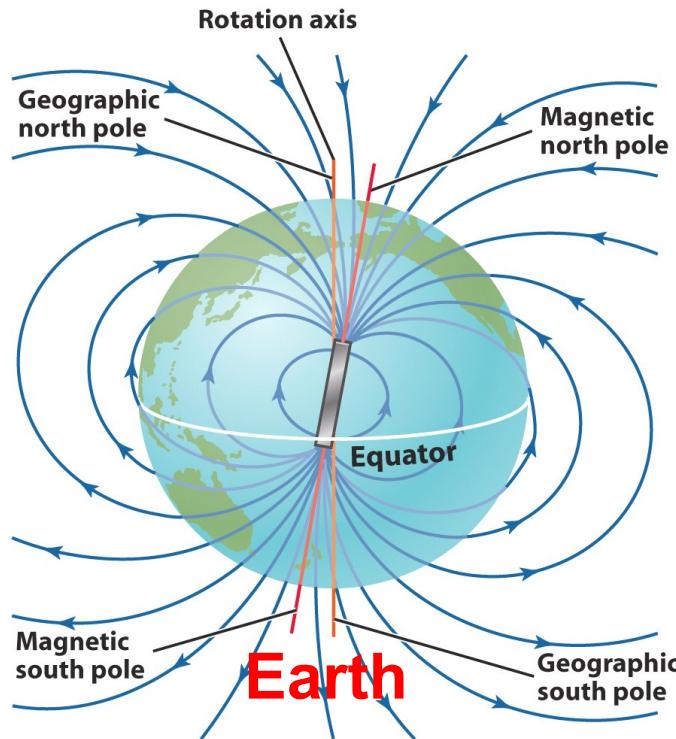
## 4.7 Magnetic fields

A planet with a magnetic field indicates a **fluid interior in motion**.

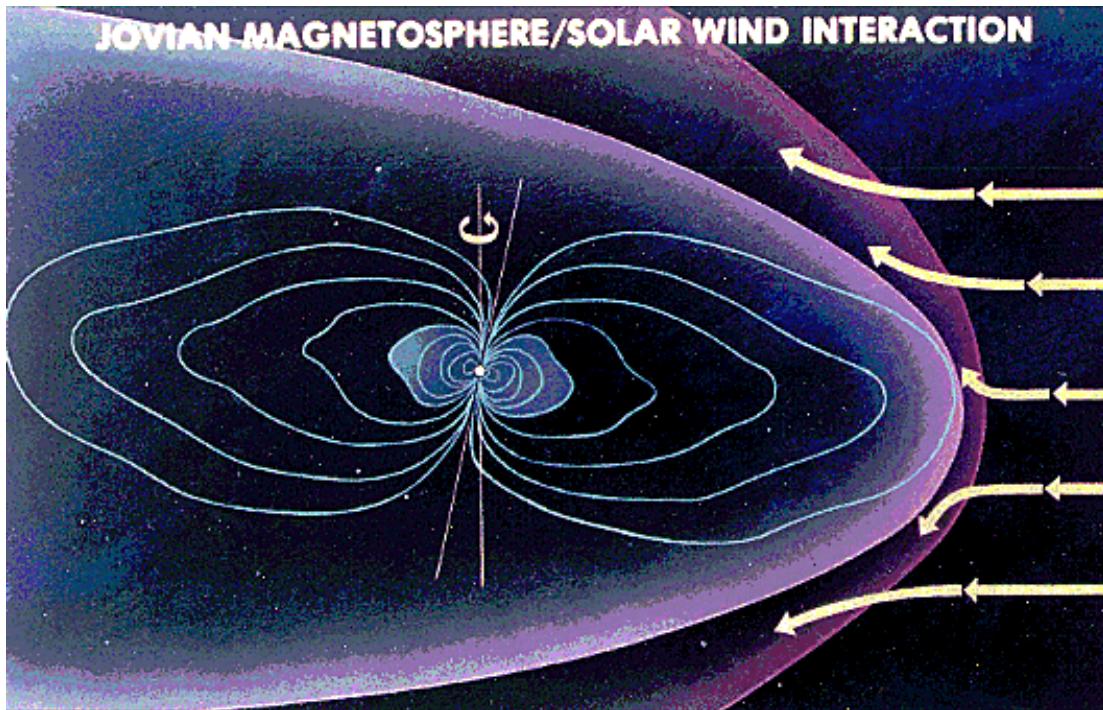


The magnetic fields of a  
bar magnet.

- 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, maybe due to its slow rotation.



Jupiter's strong magnetic field interacting with solar wind.  
(NASA)

- 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.

# How to determine properties of the planets?

- **orbit period**: direct observation
- **distance**: parallax, Kepler's third law
- **diameter**: direct observation of angular size, and small-angle formula
- **mass**: Newton's form of Kepler's third law
- **density**: mass/volume
- **chemical composition**: density, spectroscopic observation (can diagnose atmosphere and surface composition)
- **magnetic fields**: magnetometer observation, radio observation
- **internal structure**: inferred from craters, magnetic fields, quakes

# Key Words

- asteroid
- asteroid belt
- average density
- chemical composition
- comet
- dynamo
- escape speed
- ices
- impact crater
- Jovian planet
- kinetic energy
- Kuiper belt
- Kuiper belt objects
- liquid metallic hydrogen
- magnetometer
- meteoroid
- minor planet
- molecule
- spectroscopy
- terrestrial planet

# summary

- Planets are categorized as **terrestrial** and **Jovian** planets. The terrestrial planets are small inner planets, and Jovian planets are large outer planets.
- The terrestrial planets are rocky, dense, made of heavy elements, and the Jovian planets are gaseous and made of hydrogen, helium or ice.
- All planets but Mercury and Venus have **satellites**.
- **Asteroids** and **comets** are small objects orbiting around the Sun in asteroids belt (between Mars and Jupiter) or Kuiper belt. Asteroids are “terrestrial” and comets are “Jovian”.
- Whether a planet has a certain gas in the **atmosphere** depends on the **temperature** and **gravity** on the planet and the **mass of the gas**, which determine whether the gas can **escape**.
- Presence of **magnetic fields** reflects motion of electrically conducting liquids inside the planets.

**References:** FGK Chap 7, lecture notes.