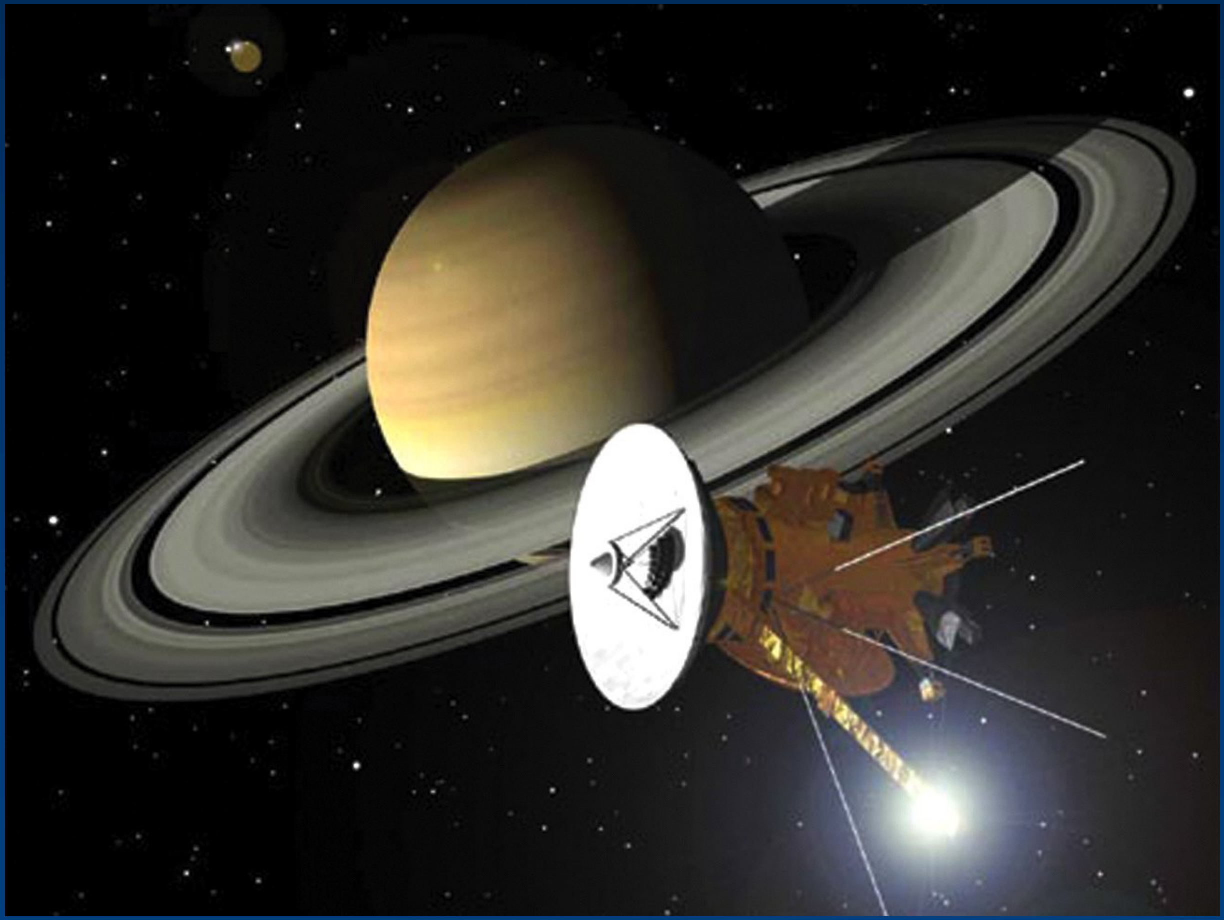
Announcements

- HW5 Due Today
- Review on Tuesday Feb 27
  - Collect all your old HW and Worksheets
- Exam 1 on Thursday Feb 29

Overview of the Solar System



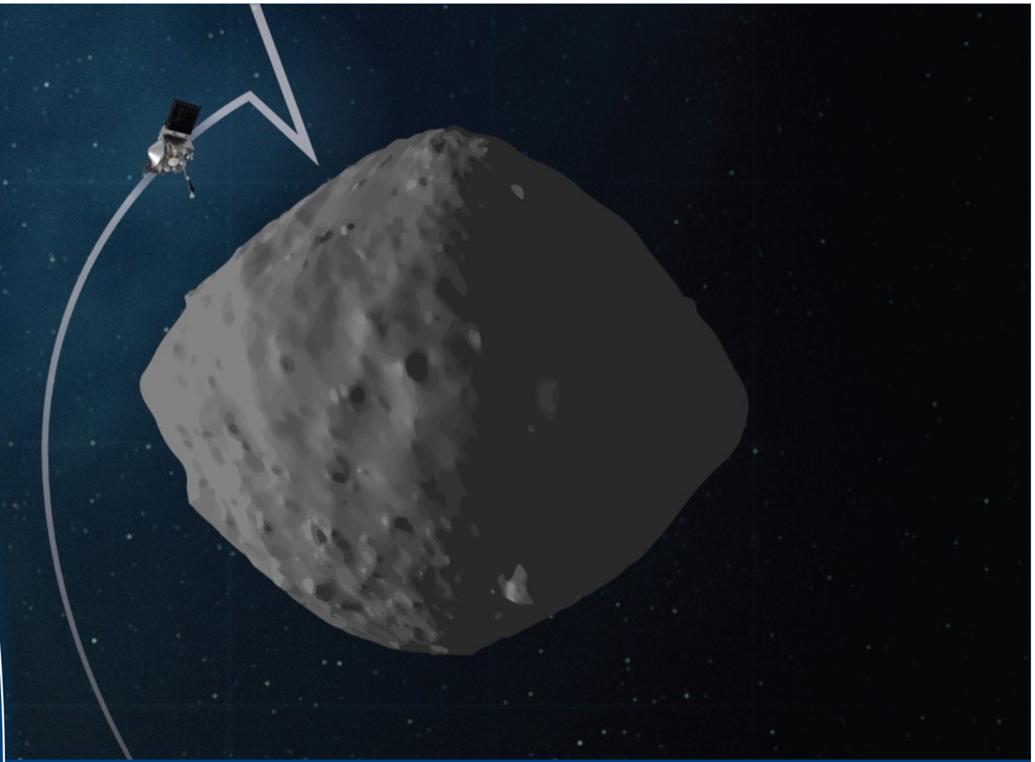
You live in a special age

- Landings on Moon, Venus, Mars, Titan and asteroids 433 Eros, 25143 Itokawa
- Rosetta spacecraft landing on comet 67P
- New Horizons spacecraft at Pluto in July 2015
- Atmospheres probed on Venus, Mars & Jupiter
- Fly-bys past all planets, some with spacecraft put into orbit
- MASCOT and MINERVA rovers on Ryago asteroid
- Fly-bys past asteroids and comets, and Pluto

All of this in past ~50 years - and more to come!

OSIRIS-REx on Asteroid Bennu

- Touch and Go (TAG) on October 20, 2020
- First US-led sample return from an asteroid
- Next up: Asteroid Mining?



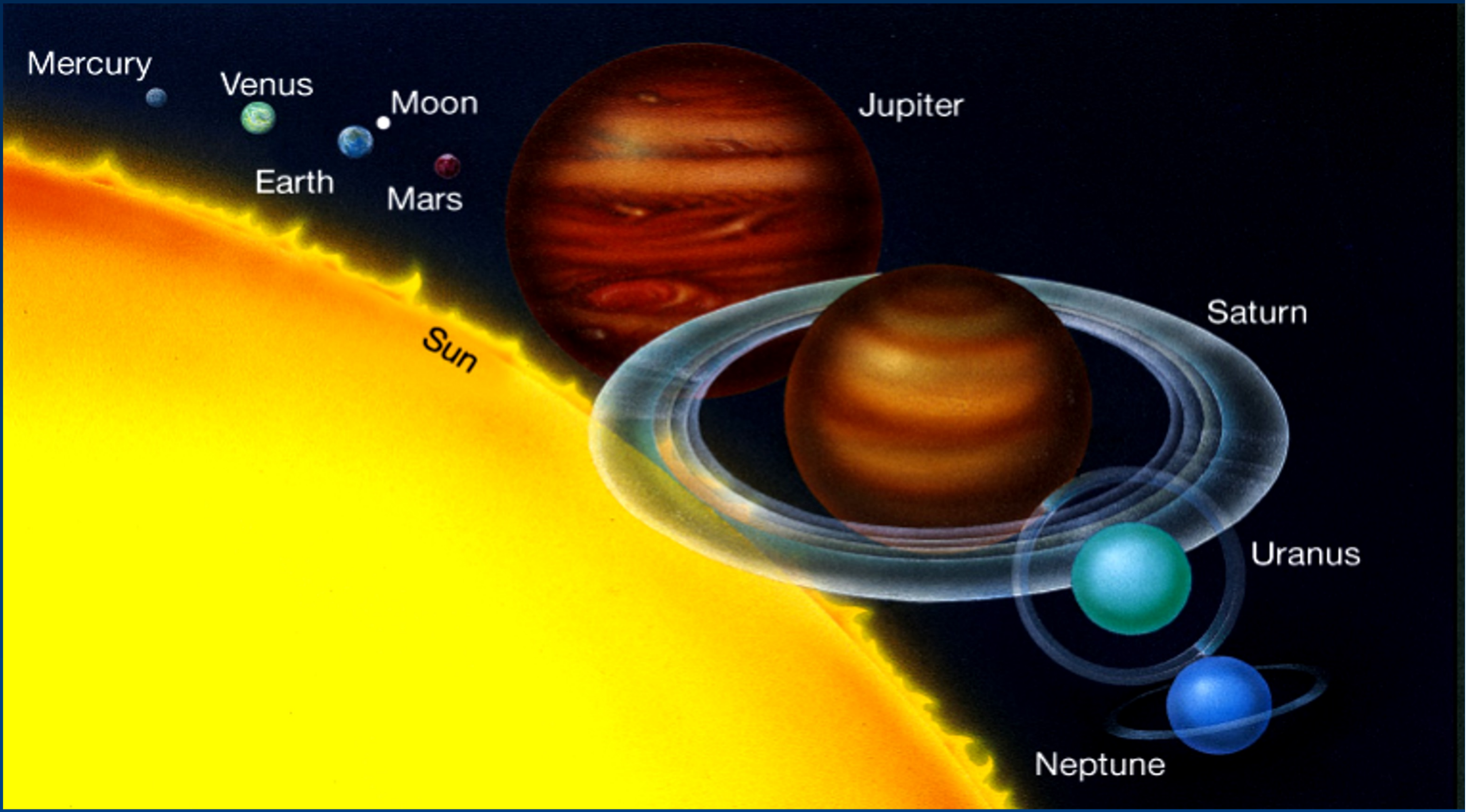
Contents of the Solar System

- Sun in center, contains most of the mass
- Planets
- Moons
- Rings
- Asteroids – mostly between Mars and Jupiter. Rocky material
- Comets – High eccentricities orbits, icy material
- Trans-Neptunian Objects

Key questions

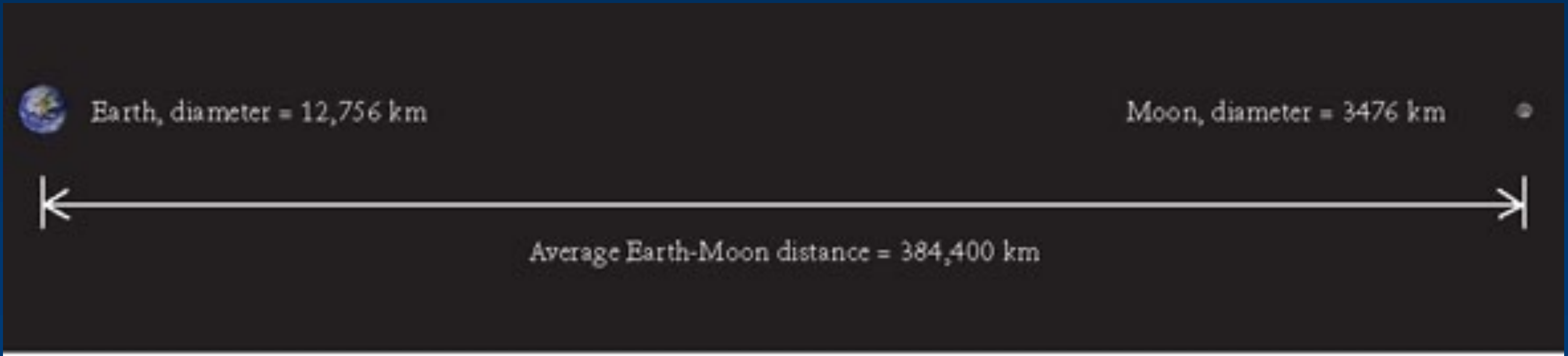
- Are all of the planets similar to Earth?
- Do other planets have moons like Earth's Moon?
- What are the planets made of and how do we know that?
- What is the difference between an asteroid and a comet? What can we learn from them?
- Why do some solar system objects have many craters and other few?
- Why do some planets have rings? How do they form?
- Why do some planets have strong magnetic fields, and some don't?
- *How did the Solar System form?*

Solar System objects to scale



The Solar System is BIG!

- It is difficult to make a correctly scaled model



(a) The Earth-Moon system

- Realize that most of the Solar System is empty space

The Sun

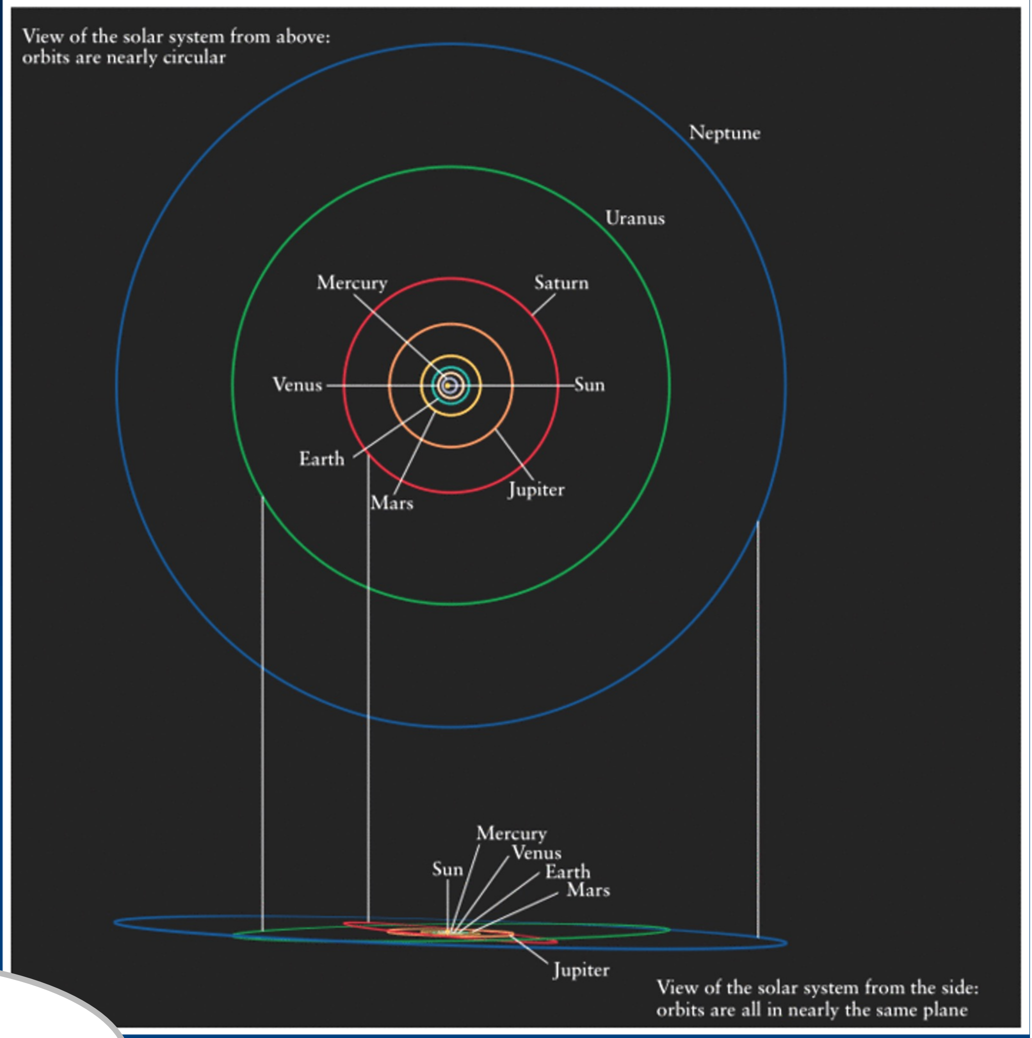
- Average-sized star (H, He)
- 99.8% of the mass of the Solar System
- ~4.6 Gyr old (middle-age)
- Surface (photosphere) about 5800 K (emits mostly in visible, UV, IR)
- Hot because of nuclear fusion in core
  - Builds He from H, a process that releases energy
- Space weather and solar winds

Planetary orbits

- All 8 planets orbit the Sun in same direction and almost same plane
- Orbits are close to circular

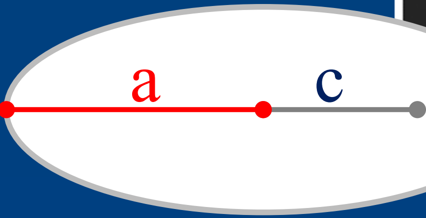
Main exception is Mercury:

orbital tilt 7°
eccentricity 0.21



Recall

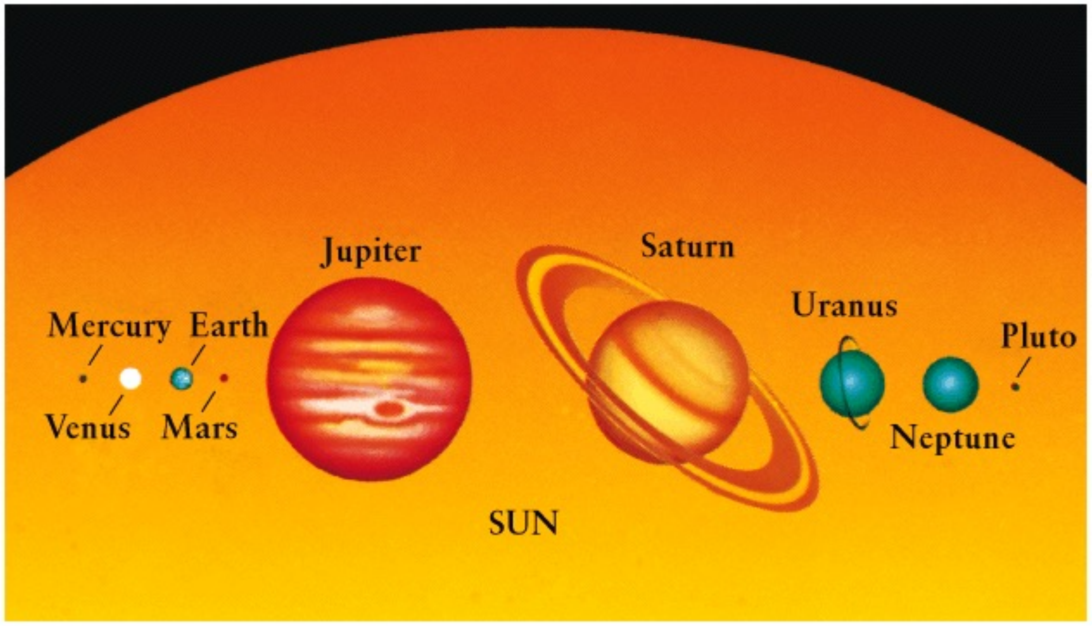
$$e = \frac{c}{a}$$



Recall relationship between P and a for the planets (Kepler’ s 3rd Law), and also

$$V_{circular} = \sqrt{\frac{GM}{r}}$$

Density of the Planets



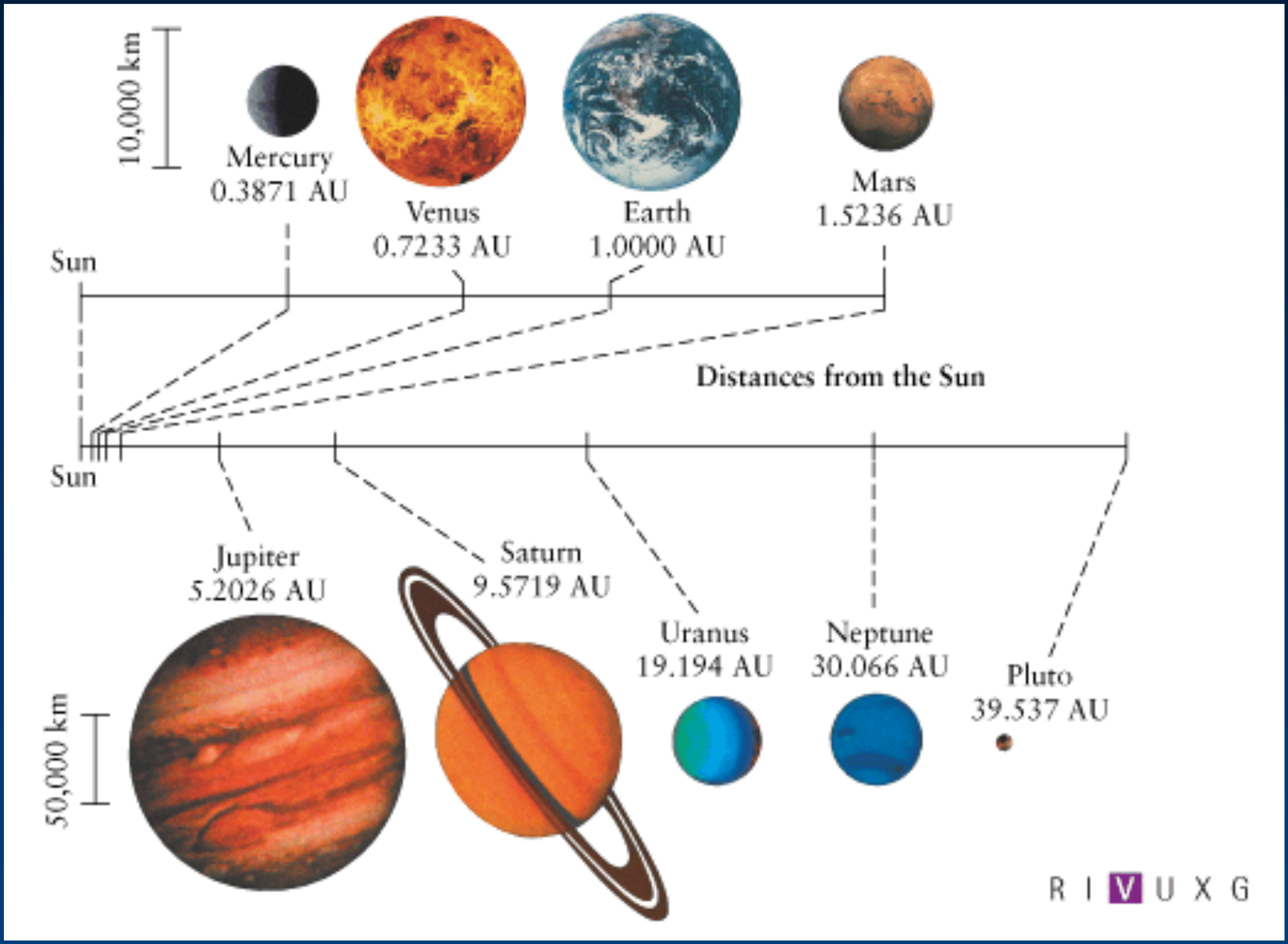
ρ = mass/volume. Depends on composition and compression by gravity

Can compare to density of water:

$\rho_{water} = 1000\ kg/m^3 = 1\ g/cm^3$

Planet	Diameter (Earth=1)	Mass (Earth=1)	ρ (g/cm^3)	
Mercury	0.383	0.055	5.4	Mostly rocky
Venus	0.949	0.815	5.2	
Earth	1.000	1.000	5.5	
Mars	0.533	0.107	3.9	
Jupiter	11.21	317.8	1.3	Mostly gas and liquid
Saturn	9.45	95.2	0.7	
Uranus	4.01	14.5	1.3	
Neptune	3.88	17.2	1.6	

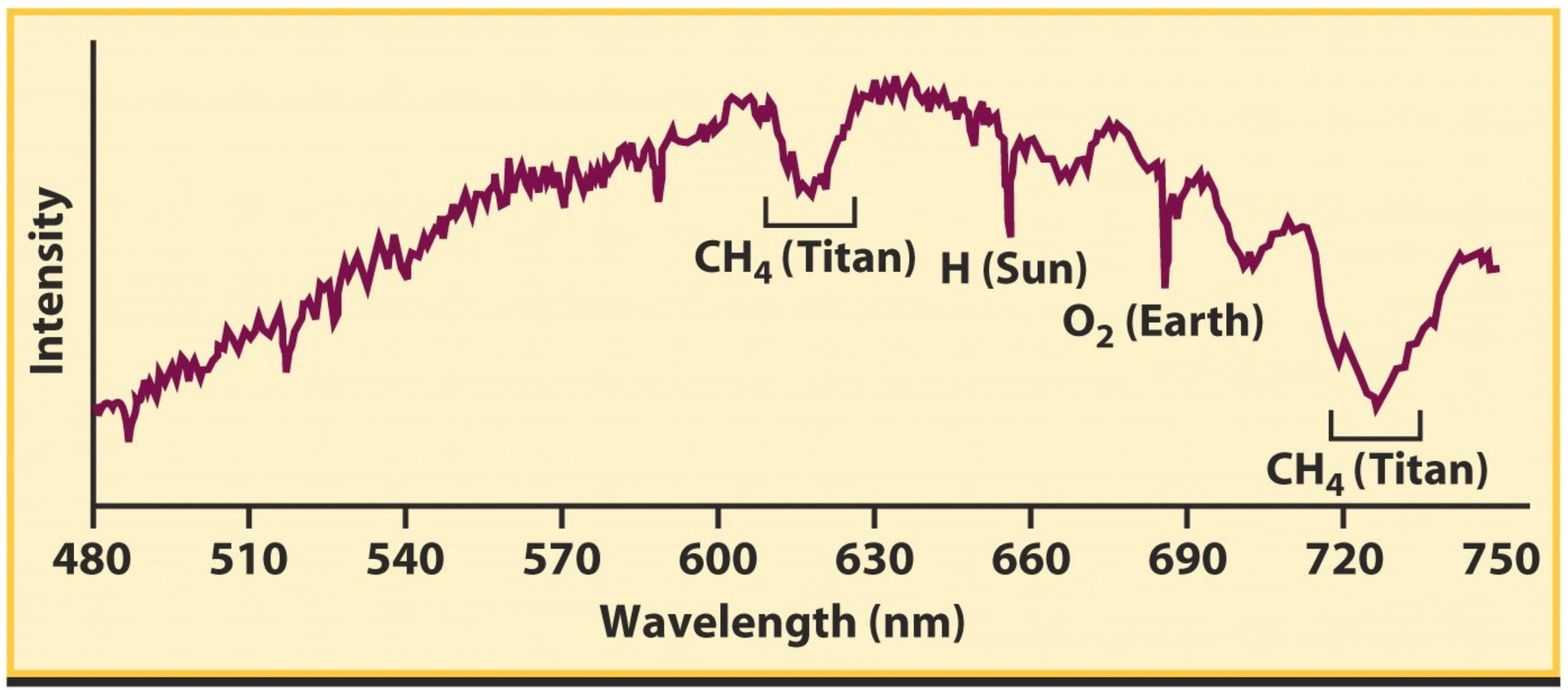
Must give clues to formation!



High density vs. low density planets are near vs. far from Sun – must also give clues about formation

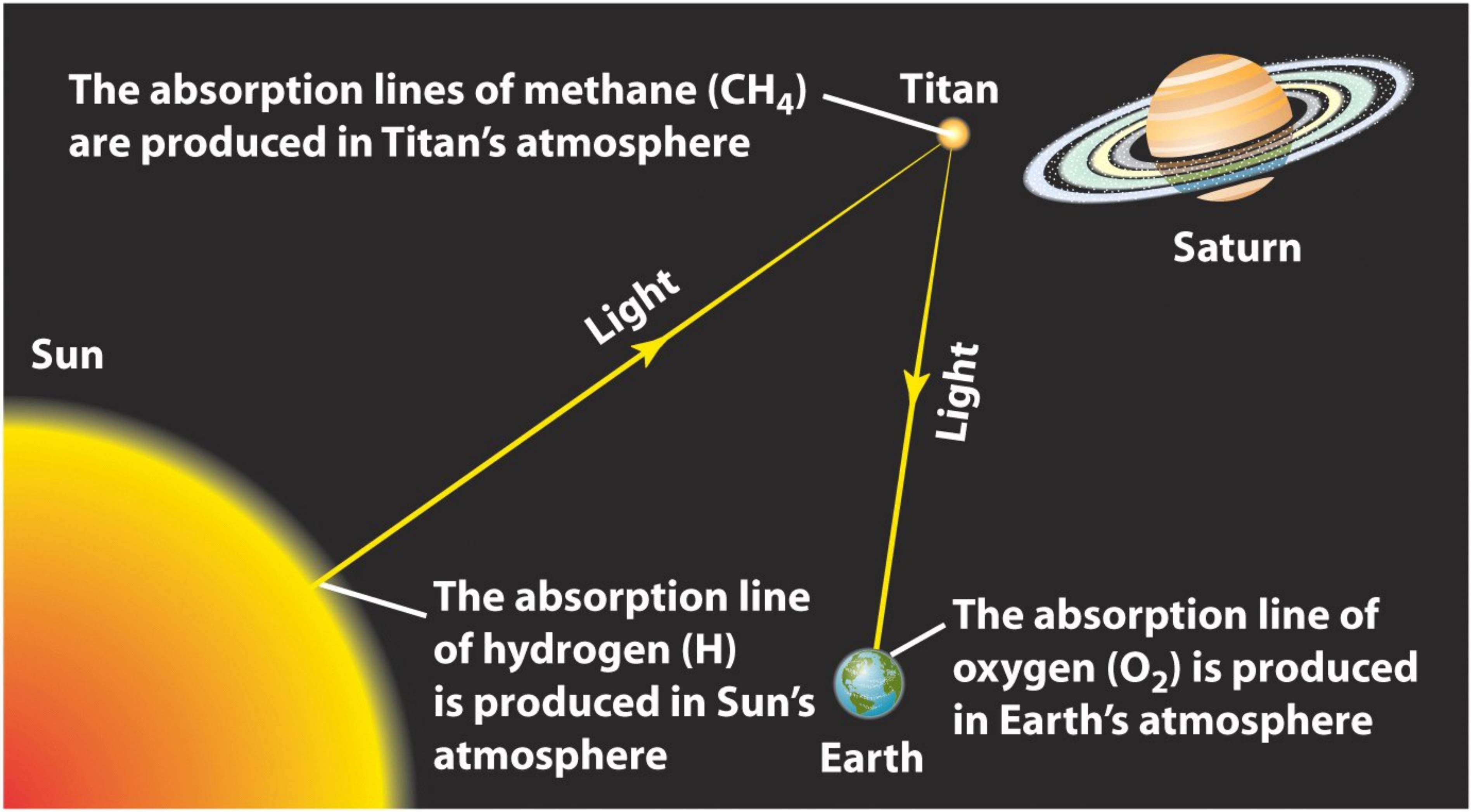
What are the planets made of?

- *Chemical composition* - determined by spectroscopic observations or sometimes direct chemical analysis.
- The spectrum of a planet with an atmosphere reveals the atmosphere's composition
- If there is no atmosphere, the spectrum indicates the composition of the surface.
- To a large extent, we must infer what the interiors are made of.



(a) The spectrum of sunlight reflected from Titan

Visible light from planets, moons, comets, etc. is dominated by reflected sunlight. In IR, might see blackbody radiation.

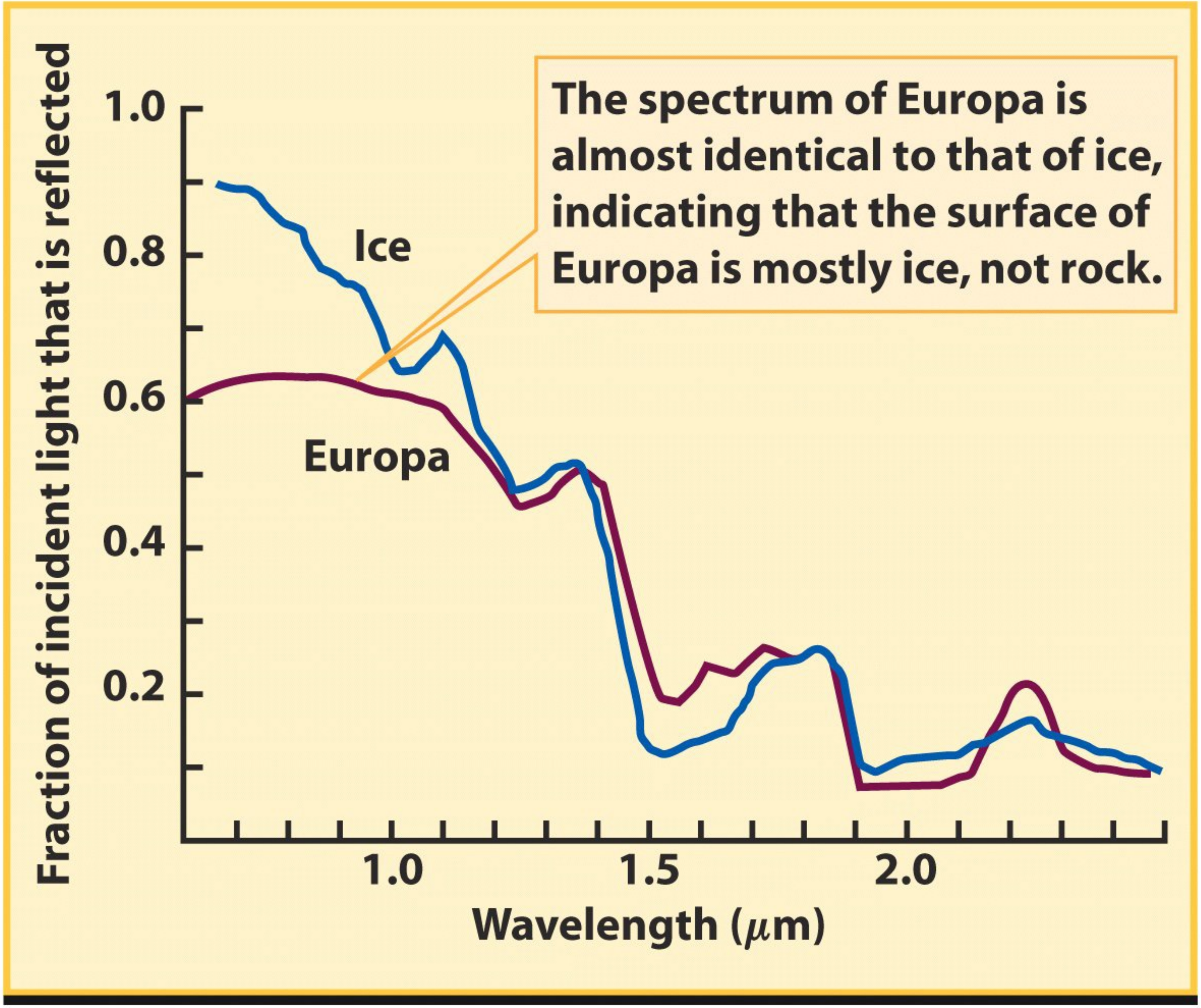


The absorption lines of methane (CH_4) are produced in Titan's atmosphere

The absorption line of hydrogen (H) is produced in Sun's atmosphere

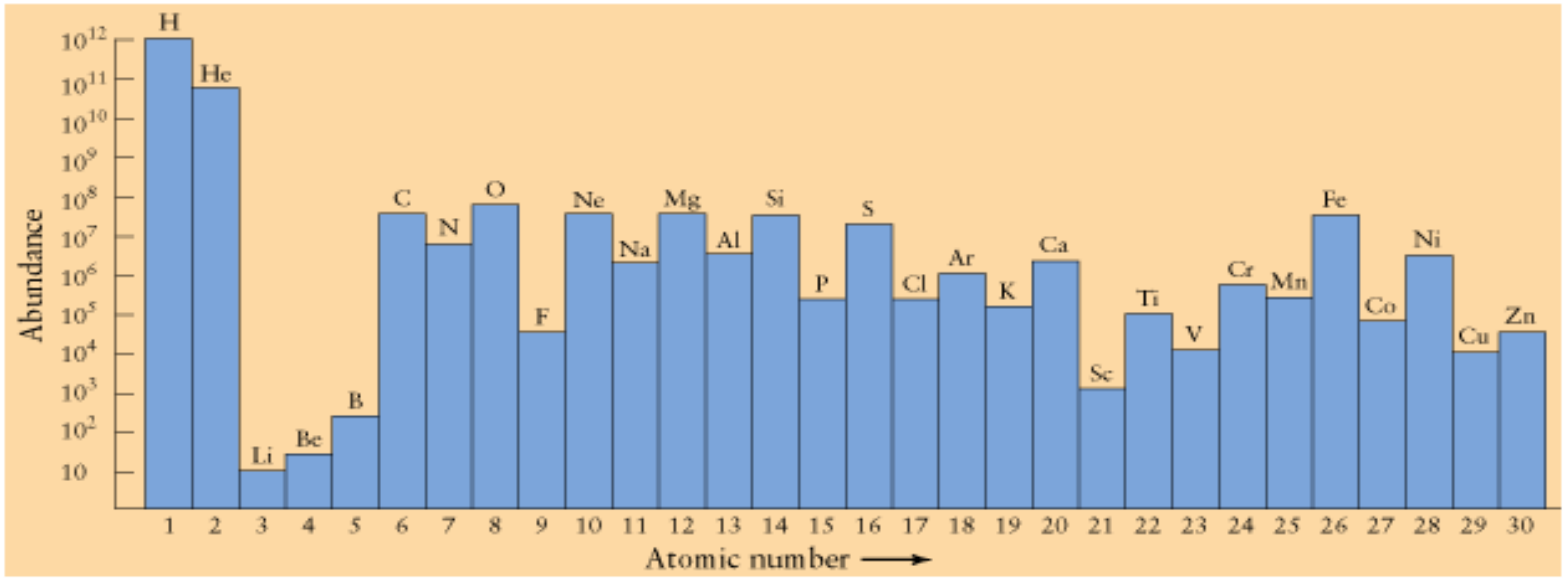
The absorption line of oxygen (O_2) is produced in Earth's atmosphere

(b) Interpreting Titan's spectrum



The spectrum of Europa is almost identical to that of ice, indicating that the surface of Europa is mostly ice, not rock.

Cosmic abundance: average relative amounts of the elements in the Universe



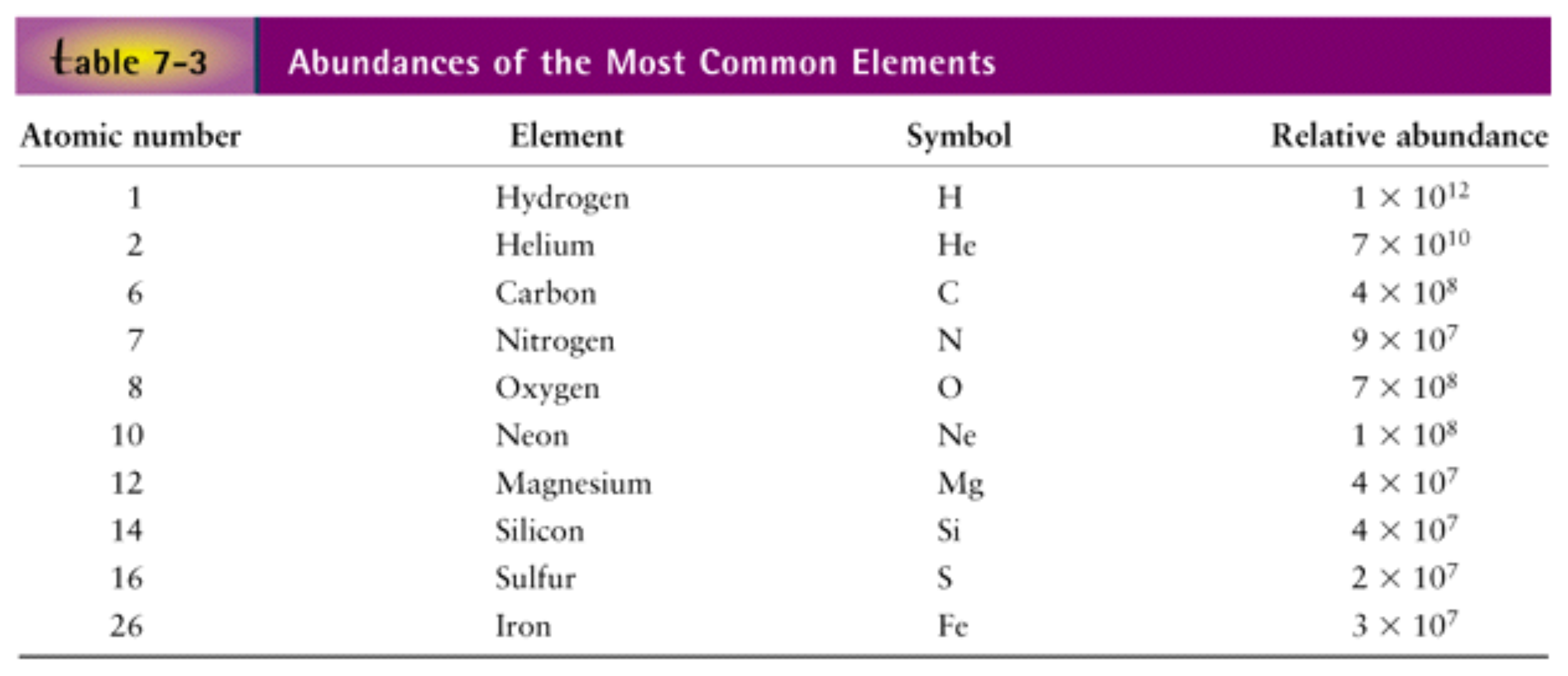


table 7-3 Abundances of the Most Common Elements

Atomic number	Element	Symbol	Relative abundance
1	Hydrogen	H	1×10^{12}
2	Helium	He	7×10^{10}
6	Carbon	C	4×10^{8}
7	Nitrogen	N	9×10^{7}
8	Oxygen	O	7×10^{8}
10	Neon	Ne	1×10^{8}
12	Magnesium	Mg	4×10^{7}
14	Silicon	Si	4×10^{7}
16	Sulfur	S	2×10^{7}
26	Iron	Fe	3×10^{7}

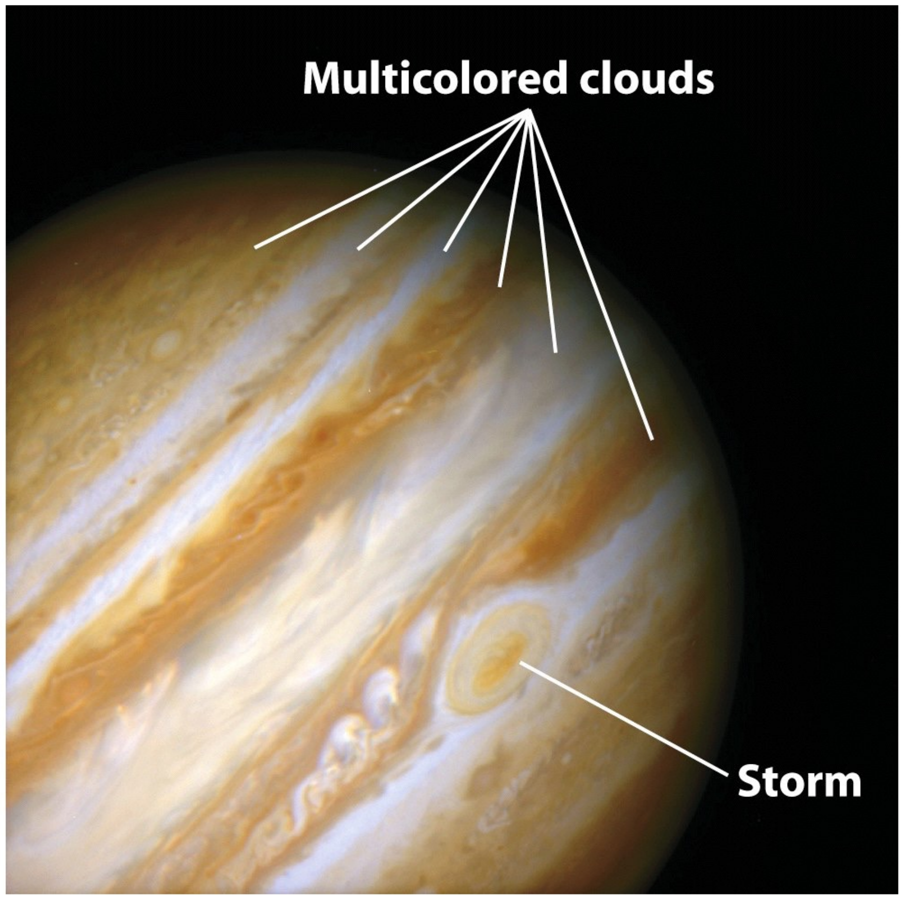
Where in the Solar System is a cosmic abundance found?

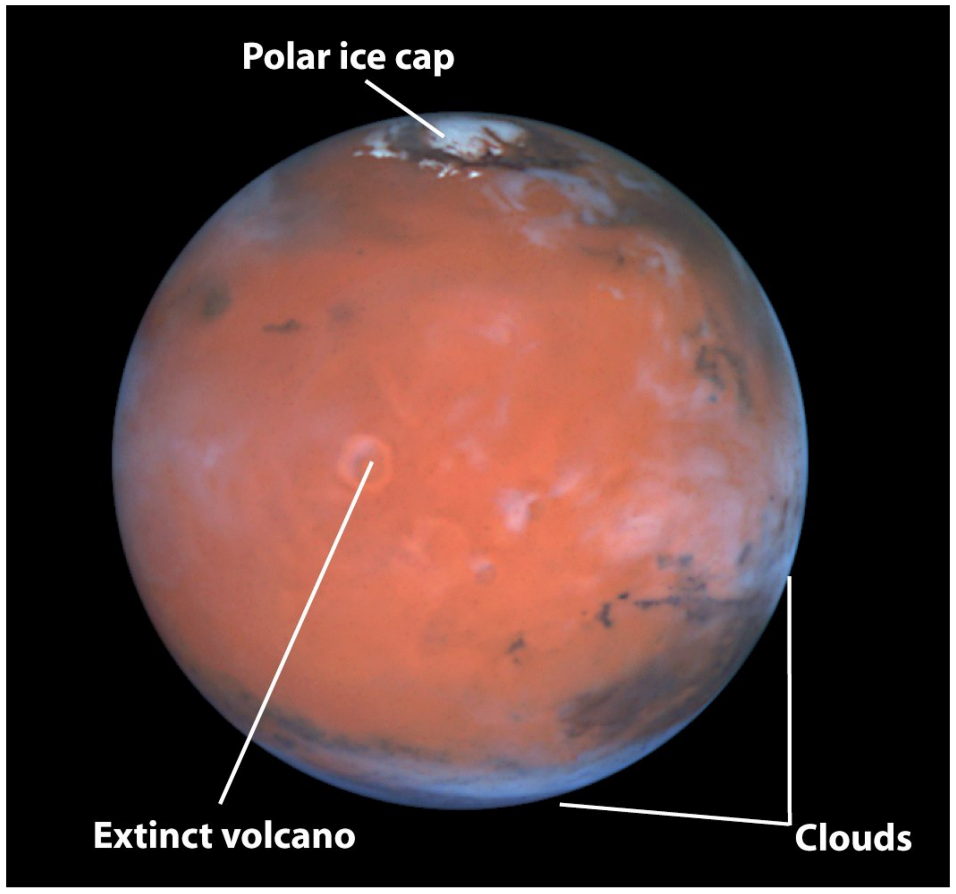
Sun, Jupiter, Saturn, Uranus, Neptune (but not in their cores)

Where is it NOT found?

Mercury, Venus, Earth, Mars, Moon, asteroids, comets

H and He abundant on the Jovian planets. The terrestrial planets are composed mostly of heavier elements (e.g. Fe, Al, Si, Ca, C).





Planetary Atmospheres

- Why do some planets have atmospheres, and others don't?
- Why do they have different atmospheric compositions?

Consider an atom or a molecule:

$$\mathrm{KE} = \frac{1}{2} m V^2$$

For gas at temperature T,
average KE is:

$$\overline{\mathrm{KE}} = \frac{3}{2} kT$$

Equate:

$$\frac{1}{2} m V^2 = \frac{3}{2} kT \quad \Rightarrow V = \sqrt{\frac{3kT}{m}}$$

At a given T, all kinds of atoms and molecules will have the same KE, but their speeds will depend on their masses. Even for each mass, this V is only an average. Particles have a spread of speeds around the average.

Now recall escape speed from a planet

$$V_{\mathrm{esc}} = \sqrt{\frac{2GM}{r}}$$

If a particle is moving too fast, the planet can't retain it

Rule of thumb: a gas will be retained in the atmosphere if $V_{\mathrm{esc}} > 6V$

WS#9

Maxwell – Boltzmann Velocity Distribution

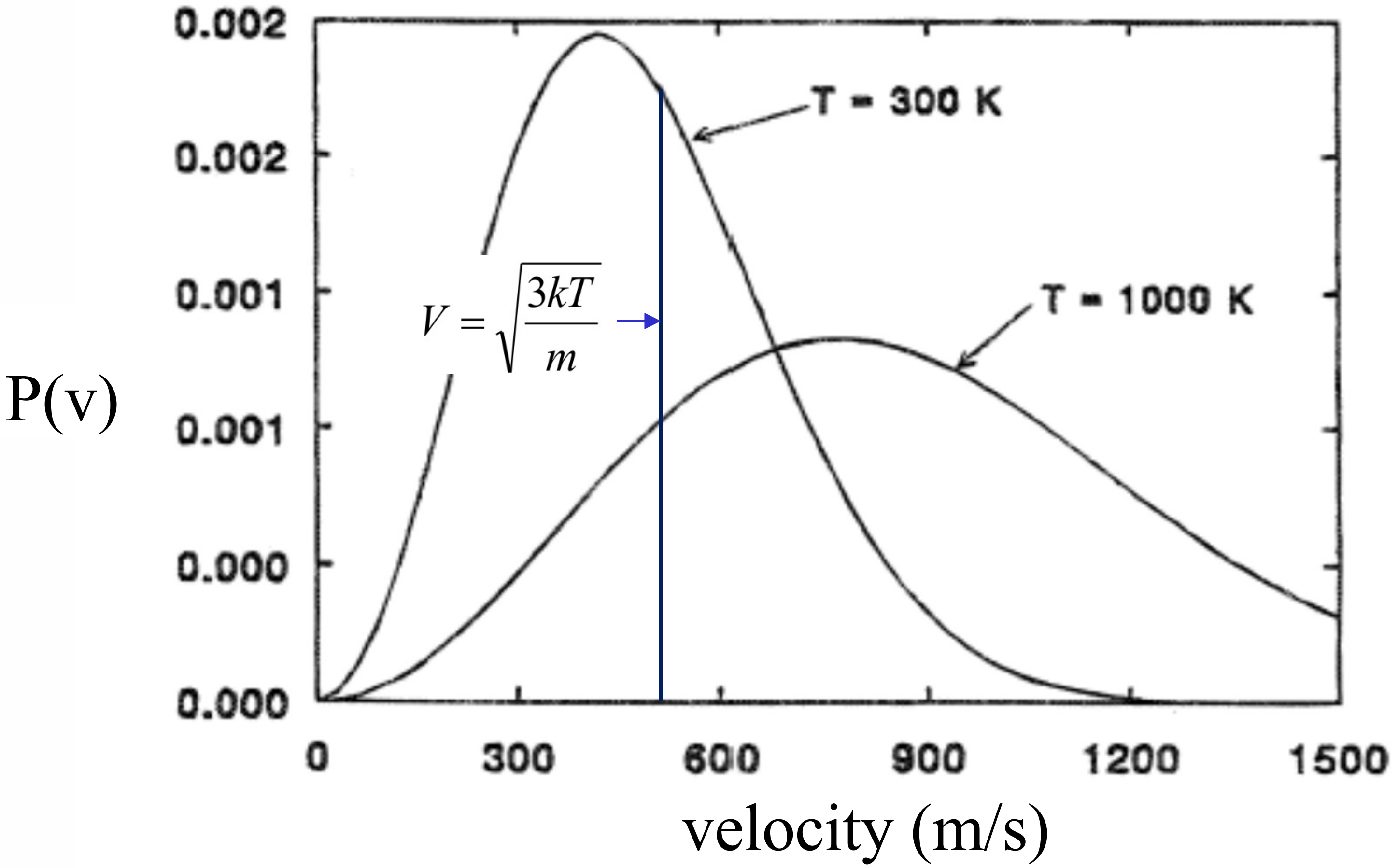


Figure 1. Maxwell-Boltzmann distribution of molecular speeds for nitrogen gas.

Example: For Mars at -40 F = -40C = 233 K

[recall that C = (F – 30) x 5/9]

Can H_2 or O_2 be retained?

- V_{H2} = 1.7 km/s, and 6 times 1.7 km/s = 10.2 km/s
- V_{O2} = 0.6 km/s, and 6 times 0.6 km/s = 3.6 km/s

The escape speed from surface of Mars is 5 km/s.

⇒ Molecular oxygen is easily retained, but hydrogen is not.

Guess which planets have atmospheres:

Planet	V_{esc} (km/s)
Mercury	4.3
Venus	10.4
Earth	11.2
Moon	2.4
Mars	5.0
Jupiter	59.5
Saturn	35.5
Uranus	21.3
Neptune	23.5

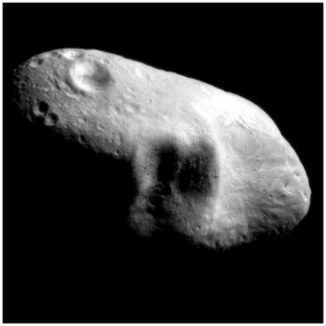
Two Kinds of Planets

"Terrestrial"	"Jovian"
Mercury, Venus, Earth, Mars	Jupiter, Saturn, Uranus, Neptune
Close to the Sun	Far from the Sun
Small (D=5000-13000 km)	Large (D=50,000-143,000 km)
Mostly Rocky	Mostly Gaseous
High Density (3.9 -5.5 g/cm^3)	Low Density (0.7 -1.6 g/cm^3)
Slow Rotation (1 - 243 days)	Fast Rotation (0.41 - 0.72 days)
Few Moons	Many Moons
No Rings	Rings
Main Elements Fe, Si, C, O, N	Main Elements H, He

Also in the Solar System

- Seven giant moons: ~ size of Mercury

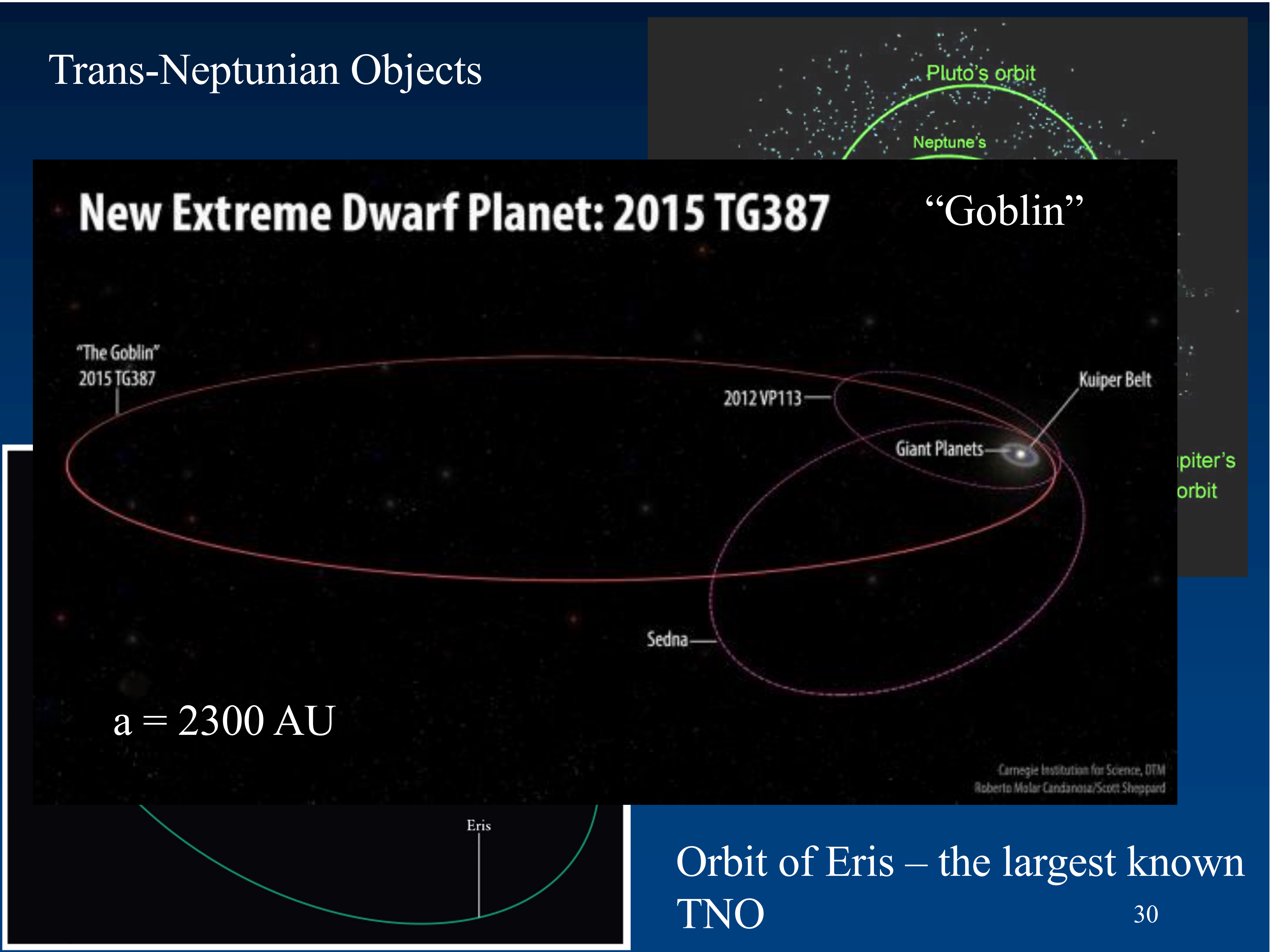
- Comets
- Asteroids (most orbit between Mars and Jupiter)
- Meteoroids
- Trans-Neptunian objects



Chunks of rock and ice

- Asteroids: small, rocky objects, most orbiting between Mars and Jupiter
- Comets: small, dirty ice balls whose orbits bring them into inner Solar System
- Trans-Neptunian Objects – icy bodies beyond Neptune’s orbit, includes Pluto and Eris
- Kuiper belt – zone 30-50 AU from Sun containing most of the TNOs
- All debris left over from planet making process

Trans-Neptunian Objects



Carnegie Institution for Science, DTM
Roberto Molar Candanosa/Scott Sheppard

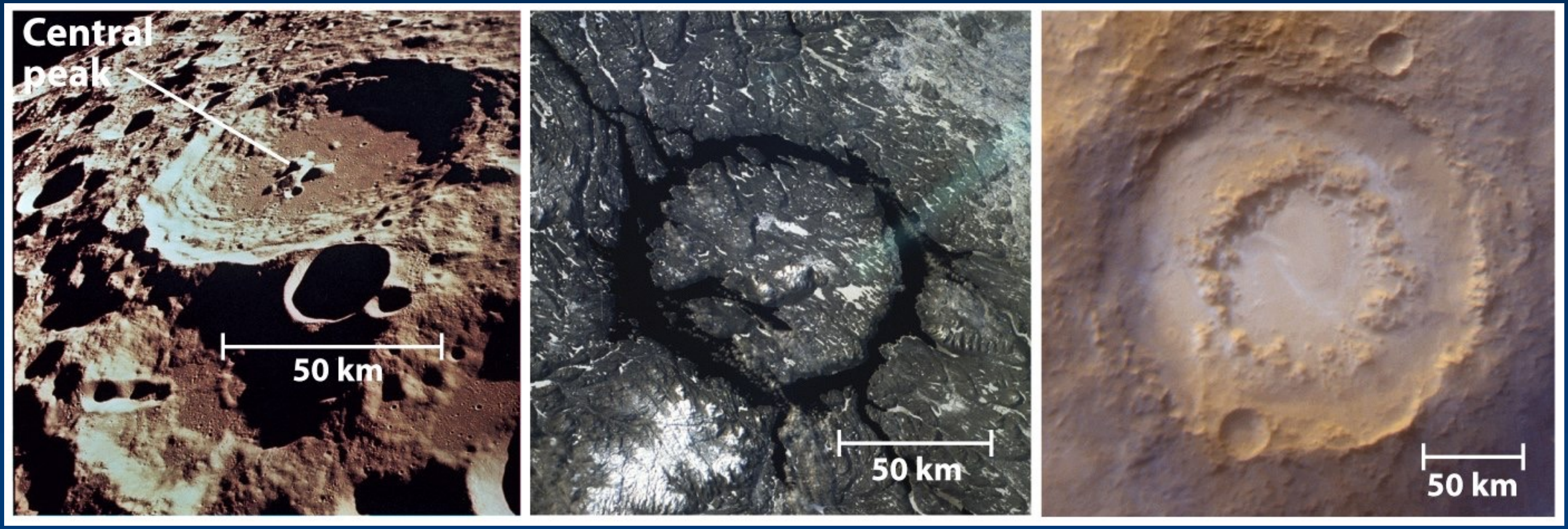
"Goblin"

a = 2300 AU

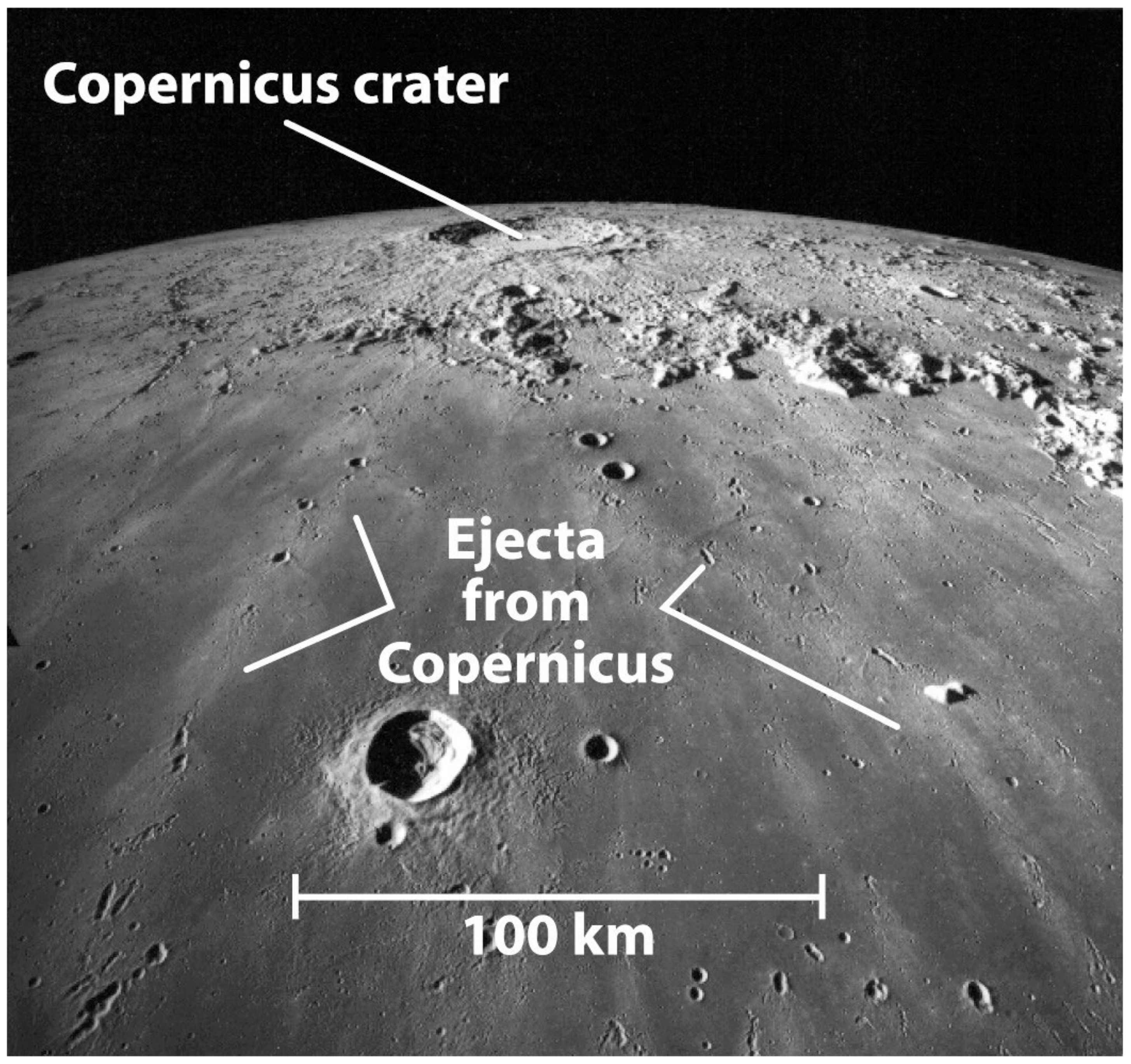
Orbit of Eris – the largest known TNO

Cratering on terrestrial planets

- Result of impacts from interplanetary debris

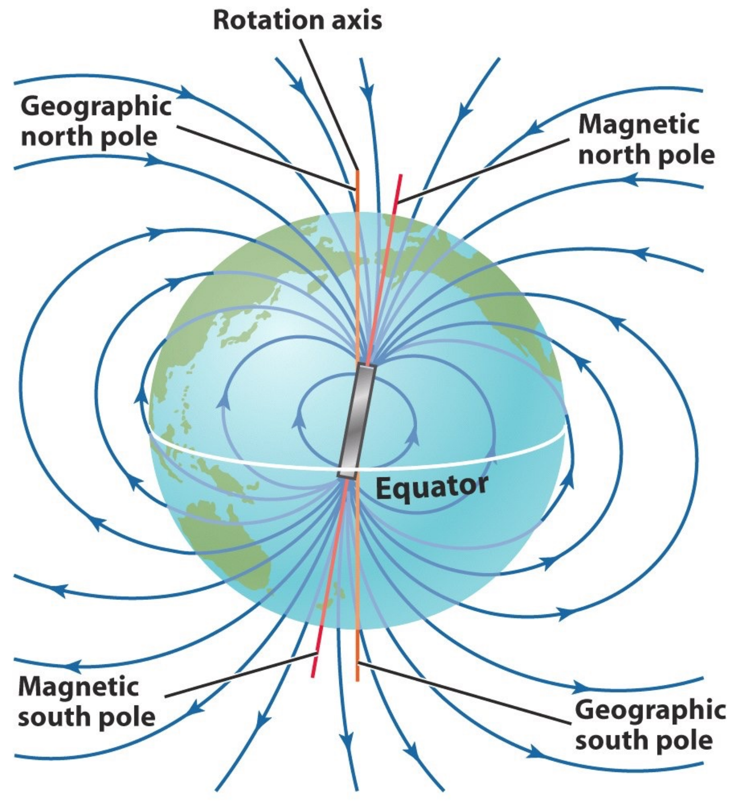


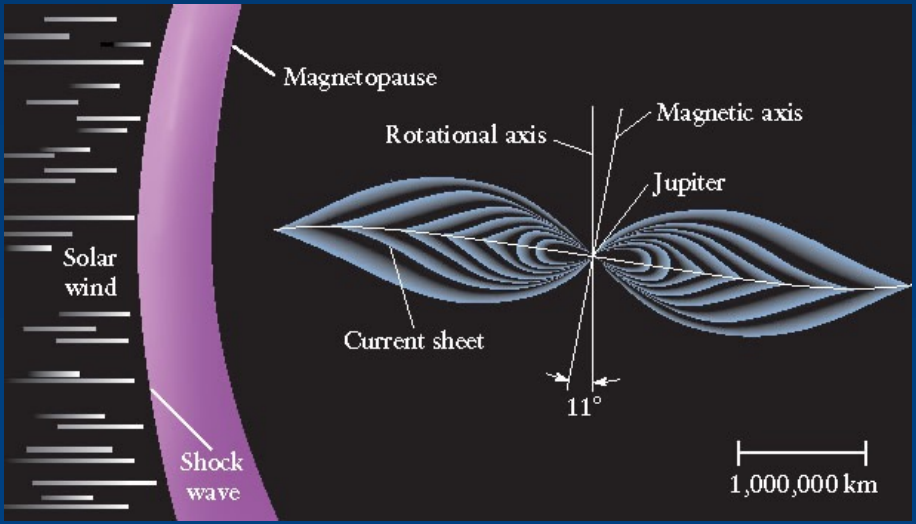
- Geological activity =>
  - Many craters means old surface and low geological activity
  - Smaller objects lose heat faster: more cratered


Copernicus crater
Ejecta from Copernicus
100 km

Direct indication of interior

- The presence of magnetic field indicates a molten interior (for terrestrial planets. The gas giants have another process)
- Need circulating currents to generate magnetic field, like in an electromagnet
- Occurs in molten, conducting, circulating interiors.

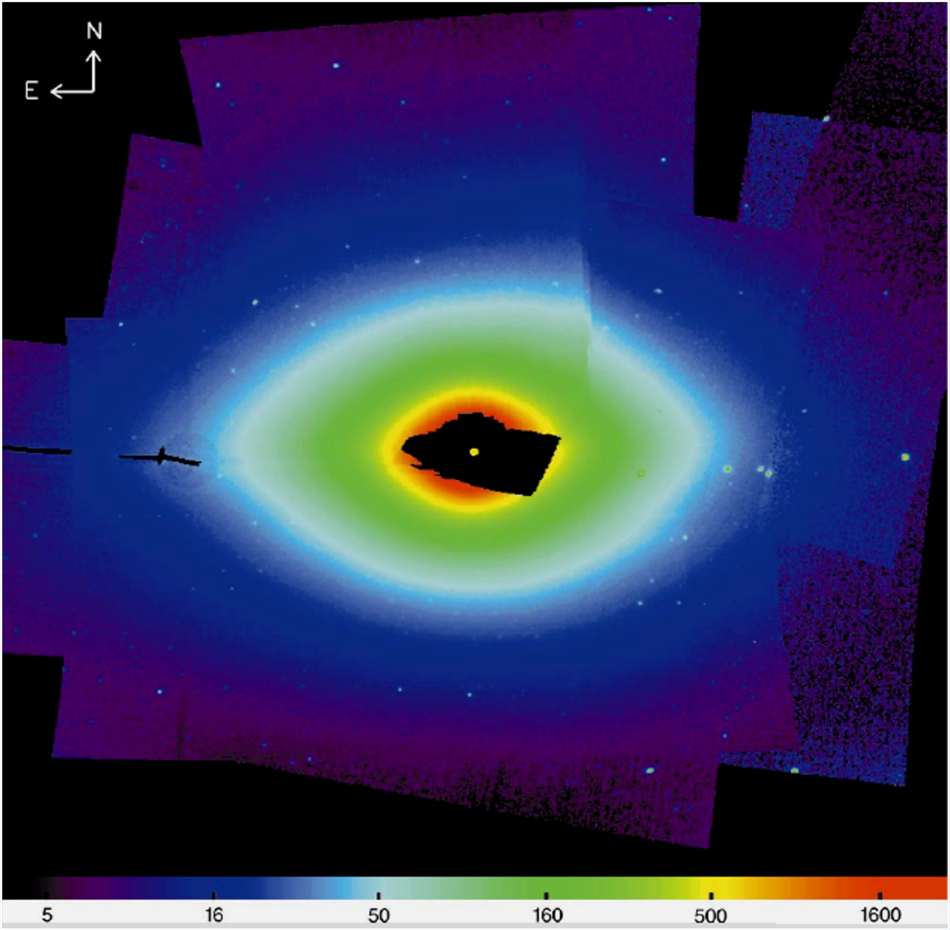




- The magnetic fields of terrestrial planets are produced by metals such as iron in the liquid state
- The stronger fields of the Jovian planets are generated by liquid metallic hydrogen or by water with ionized molecules dissolved in it

Zodiacal Dust

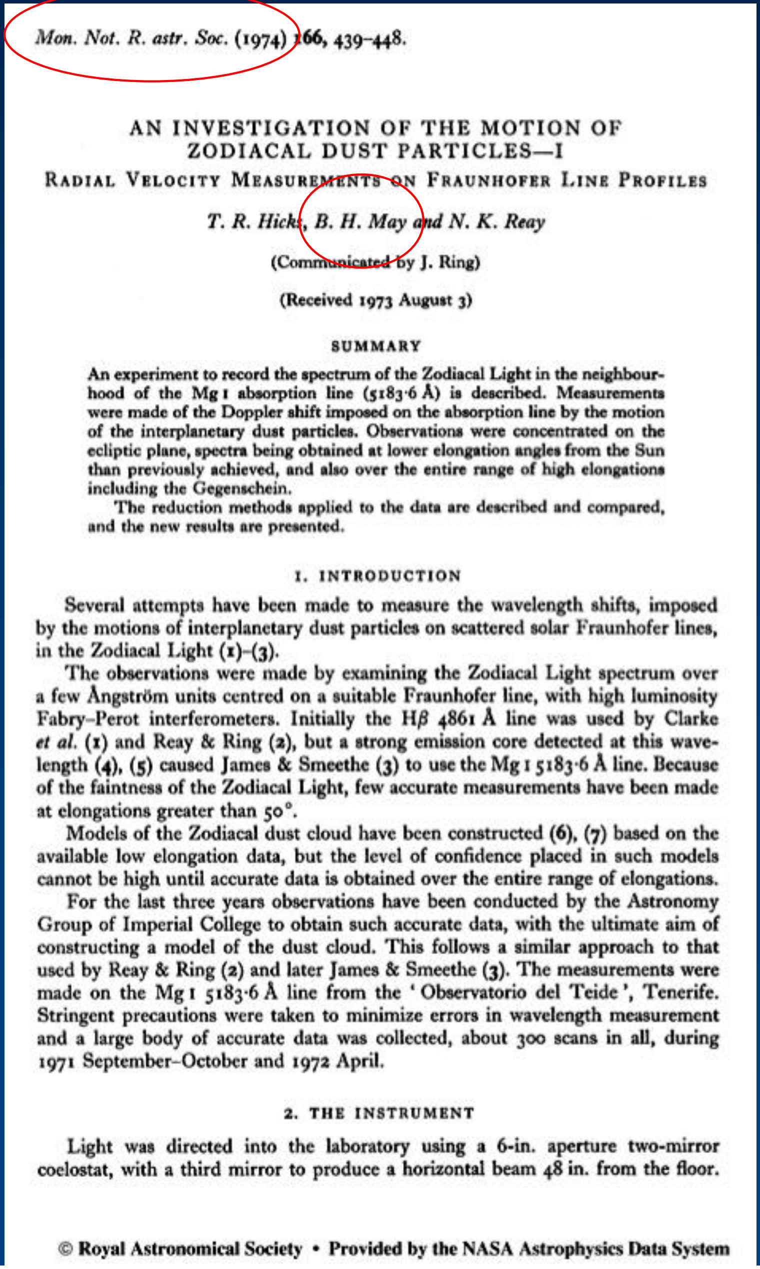
Looking outwards
(away from the sun)



Looking inwards (in infrared)

Zodiacal dust

Dust particles on the plane of the orbits of the planets. (size: 1 to 300 x 10^{-6} m)



Mon. Not. R. astr. Soc. (1974) **166**, 439–448.

AN INVESTIGATION OF THE MOTION OF ZODIACAL DUST PARTICLES—I

RADIAL VELOCITY MEASUREMENTS ON FRAUNHOFER LINE PROFILES

T. R. Hicks, B. H. May and N. K. Reay

(Communicated by J. Ring)

(Received 1973 August 3)

SUMMARY

An experiment to record the spectrum of the Zodiacal Light in the neighbourhood of the Mg I absorption line (5183·6 Å) is described. Measurements were made of the Doppler shift imposed on the absorption line by the motion of the interplanetary dust particles. Observations were concentrated on the ecliptic plane, spectra being obtained at lower elongation angles from the Sun than previously achieved, and also over the entire range of high elongations including the Gegenschein.

The reduction methods applied to the data are described and compared, and the new results are presented.

1. INTRODUCTION

Several attempts have been made to measure the wavelength shifts, imposed by the motions of interplanetary dust particles on scattered solar Fraunhofer lines, in the Zodiacal Light (1)–(3).

The observations were made by examining the Zodiacal Light spectrum over a few Ångström units centred on a suitable Fraunhofer line, with high luminosity Fabry–Perot interferometers. Initially the Hβ 4861 Å line was used by Clarke *et al.* (1) and Reay & Ring (2), but a strong emission core detected at this wavelength (4), (5) caused James & Smeethe (3) to use the Mg I 5183·6 Å line. Because of the faintness of the Zodiacal Light, few accurate measurements have been made at elongations greater than 50°.

Models of the Zodiacal dust cloud have been constructed (6), (7) based on the available low elongation data, but the level of confidence placed in such models cannot be high until accurate data is obtained over the entire range of elongations.

For the last three years observations have been conducted by the Astronomy Group of Imperial College to obtain such accurate data, with the ultimate aim of constructing a model of the dust cloud. This follows a similar approach to that used by Reay & Ring (2) and later James & Smeethe (3). The measurements were made on the Mg I 5183·6 Å line from the 'Observatorio del Teide', Tenerife. Stringent precautions were taken to minimize errors in wavelength measurement and a large body of accurate data was collected, about 300 scans in all, during 1971 September–October and 1972 April.

2. THE INSTRUMENT

Light was directed into the laboratory using a 6-in. aperture two-mirror coelostat, with a third mirror to produce a horizontal beam 48 in. from the floor.

Solar system formation

- All objects formed from the same cloud of gas and dust
- Composition determined by cosmic history
- Different objects formed in different environments depending on their distance to the Sun