The Cosmos

Planets & Life

PHYS 214

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Please start all class related emails with "214:"

Today's Lecture

- Formation of planets

- No lecture Friday Feb 9th
- Monday 5th Feb, guest lecture: Dr Martin Duncan (Astronomy) on formation of the outer solar system

Relative scales in the Solar System

- If the Sun (diameter 1.5 million km) is a basketball
  - Mercury (diameter 4878 km) is a miniscule ball bearing 9 m away
  - Earth (diameter 12756 km) is 27 m away, and the size of a pinhead
  - Jupiter (diameter 142800 km) is 2.5 cm in diameter and 120 m away
  - Pluto (diameter 2390 km) is another miniscule ball bearing 900 metres away

General properties of the planets we have to explain

(1) All the planets orbit within a few degrees of the equatorial plane of the Sun (recall the definition of the ecliptic)

(2) Most of the planets have a rotation axis roughly perpendicular to the plane of the solar system

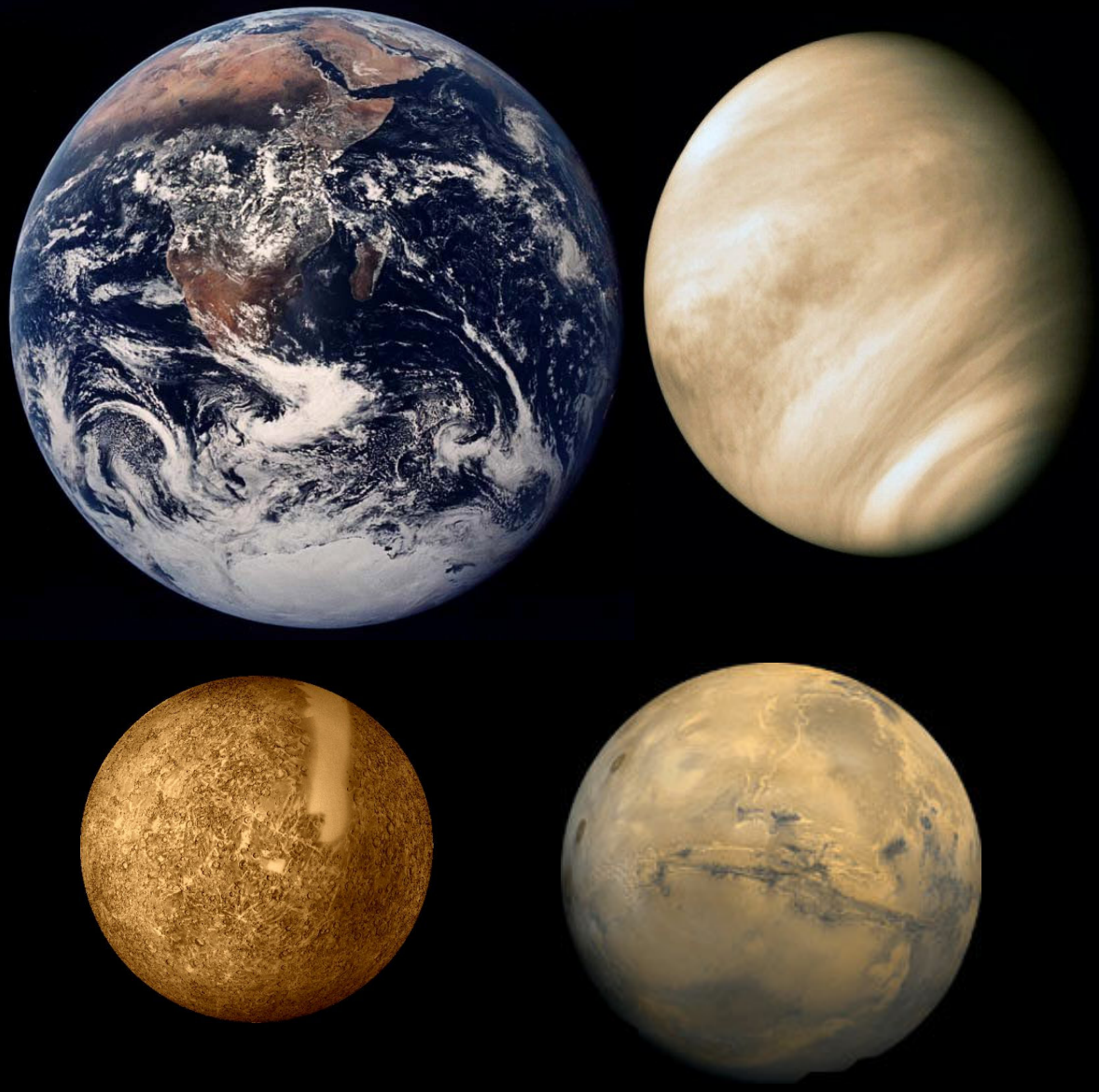
- Note both Pluto and Uranus have rotations that are highly inclined to the plane of the solar system

(3) "Planets" are divided into rocky (terrestrial), gas giants and icy bodies (if we include Pluto)

(4) There are a lot of sub-planet sized objects (asteroids) in the solar system (mainly between Mars & Jupiter)

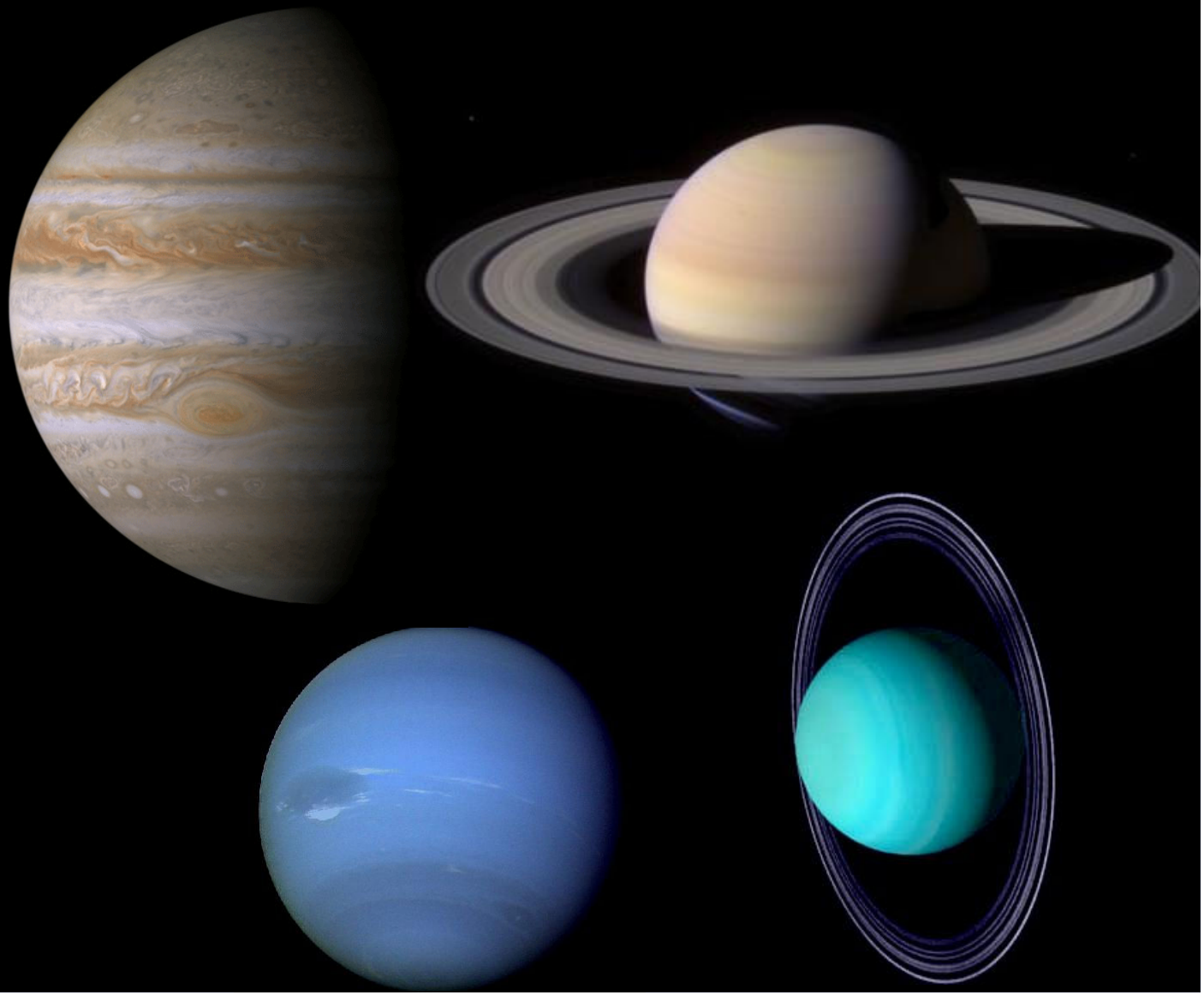
Terrestrial Planets

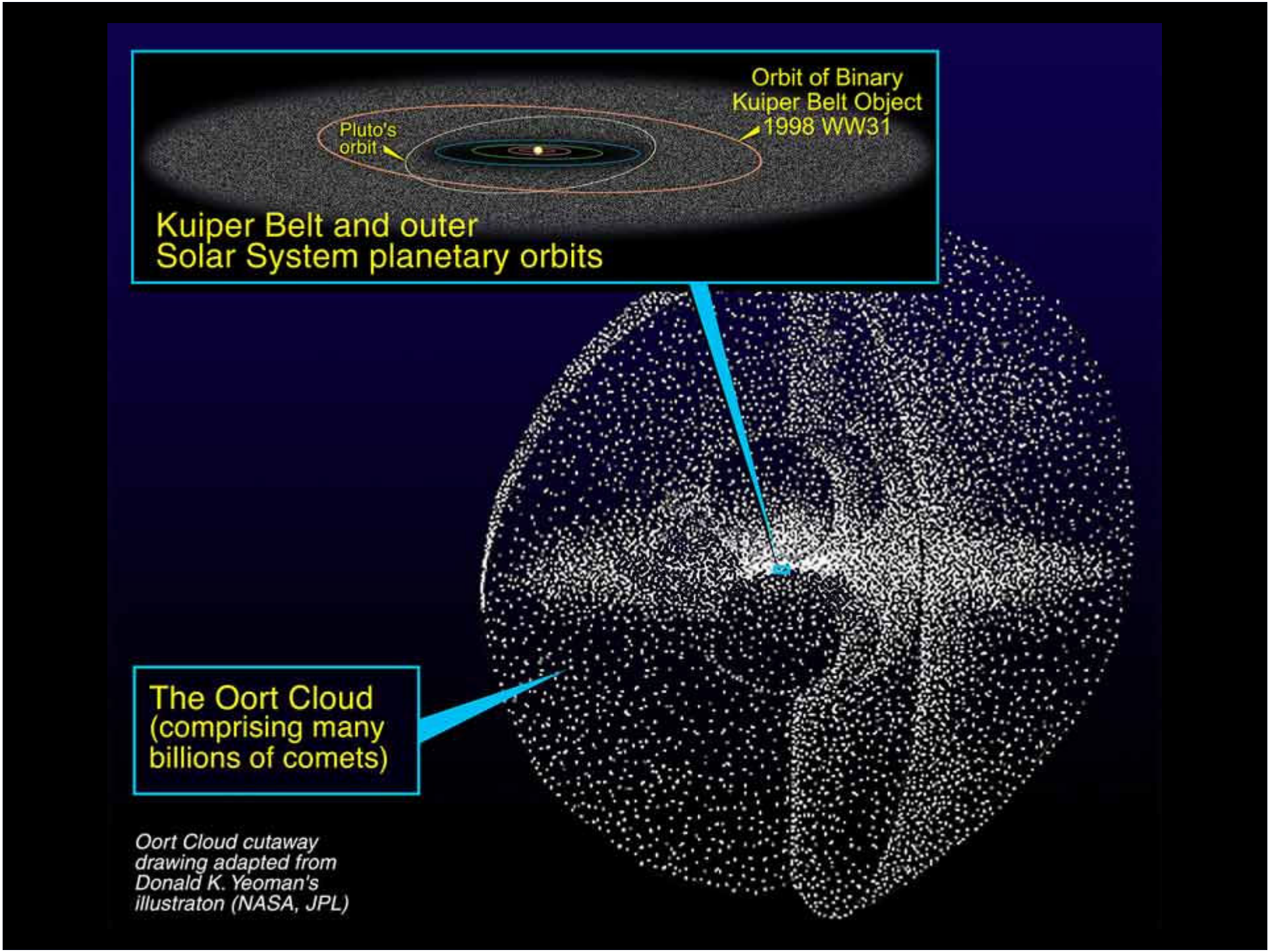
- Terrestrial planets share the following common traits:
  - Close to Sun (< 5 AU)
  - Small compared to Jovian planets
  - Have no or small number of moons
  - No rings



Jovian Planets

- Jovian planets share the following common traits:
  - Large (several Earth radii)
  - Rings
  - Many moons
  - Large distance from the Sun (> 5 AU)




Orbit of Binary
Kuiper Belt Object
1998 WW31
Pluto's
orbit
Kuiper Belt and outer
Solar System planetary orbits
The Oort Cloud
(comprising many
billions of comets)
Oort Cloud cutaway
drawing adapted from
Donald K. Yeoman's
illustraton (NASA, JPL)

Solar system formation theories

(1) The solar nebula theory

- Planets are formed at the same time the Sun is forming, from the collapse of the interstellar cloud that forms the Sun
- Fits the facts very well…

(2) An alternative theory was put forward by Sir James Jeans in the early 1900s

- "Tidal interaction theory" – passing star strips matter from the Sun that forms the planets
- Doesn't fit the distribution of angular momentum, and besides the possibility of a close enough encounter is too low

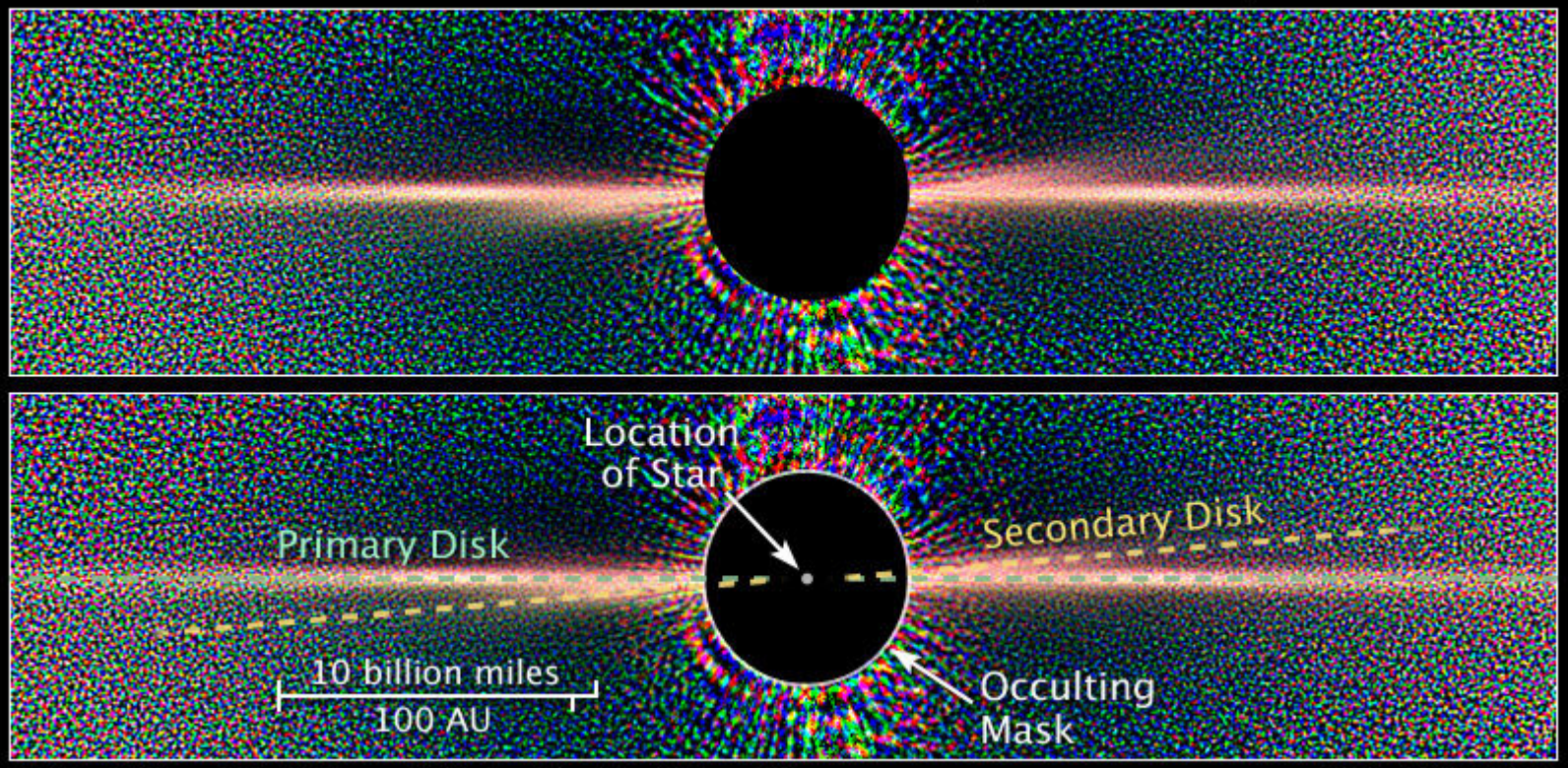
The Solar Nebula Theory

- The starting point is a cloud in the interstellar medium that beginnings contracting under its own weight
  - The cloud initally has a very small rotation
  - Centrifugal force keeps the material in the plane of rotation from falling in and a disk is formed
  - Conservation of angular momentum forces the cloud to spin more quickly as it contracts in size

Solar System formation movie a la 1986(!)

From the NASA movie "I Will See Such Things"

Disks around other stars



Pluto's orbit for scale

Increase in rotation speed

- We can very quickly estimate how much the speed of rotation will increase
- The (vector) formula for angular momentum is

$$\vec{L} = \vec{r} \times m\vec{v}$$

- Although we can work with just the magnitude of the vector in this case, which is given by the formula

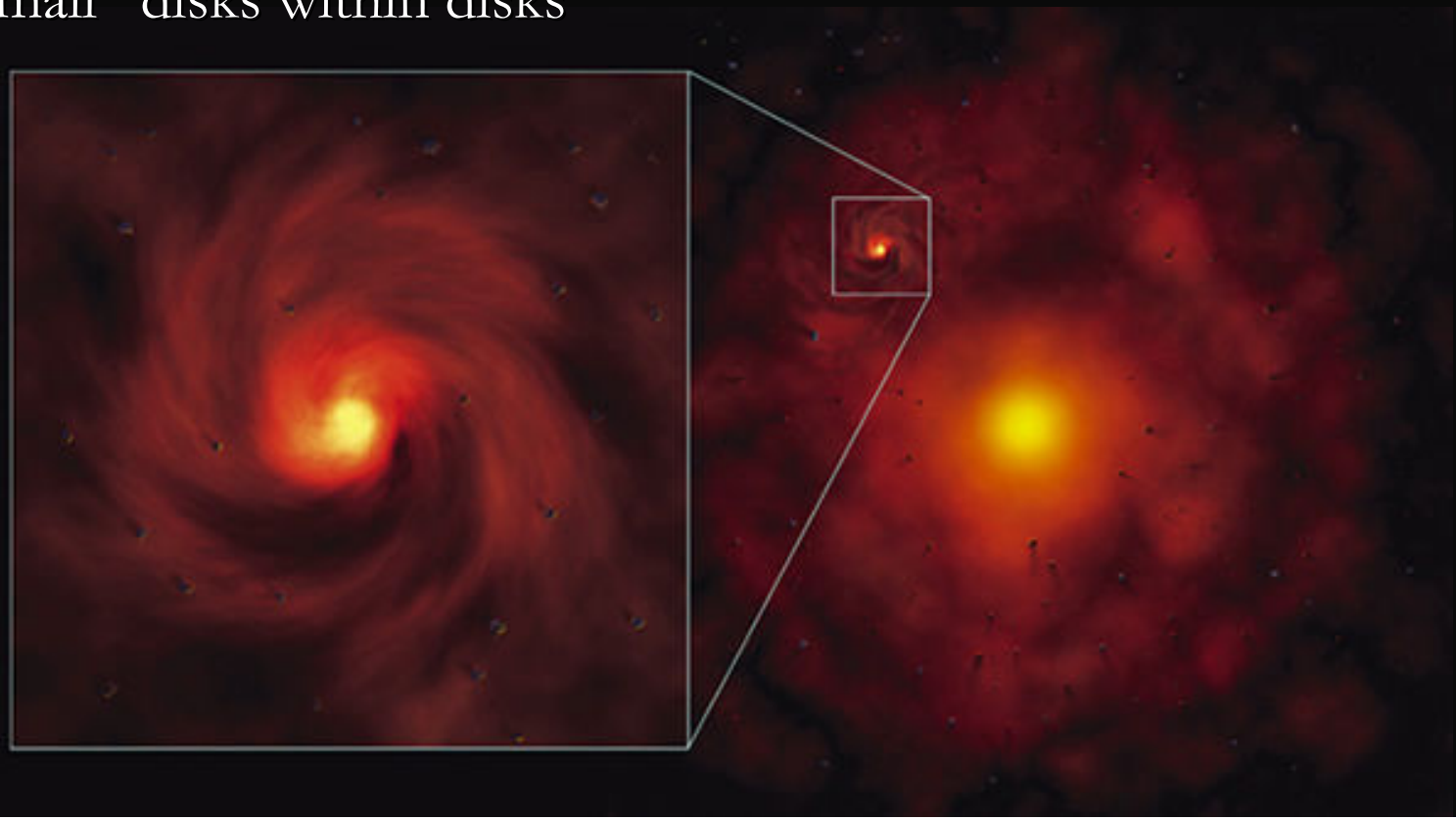
$$l = mr^2\omega$$

where the speed of a point a distance r from the centre of rotation is given by $v=r\omega$

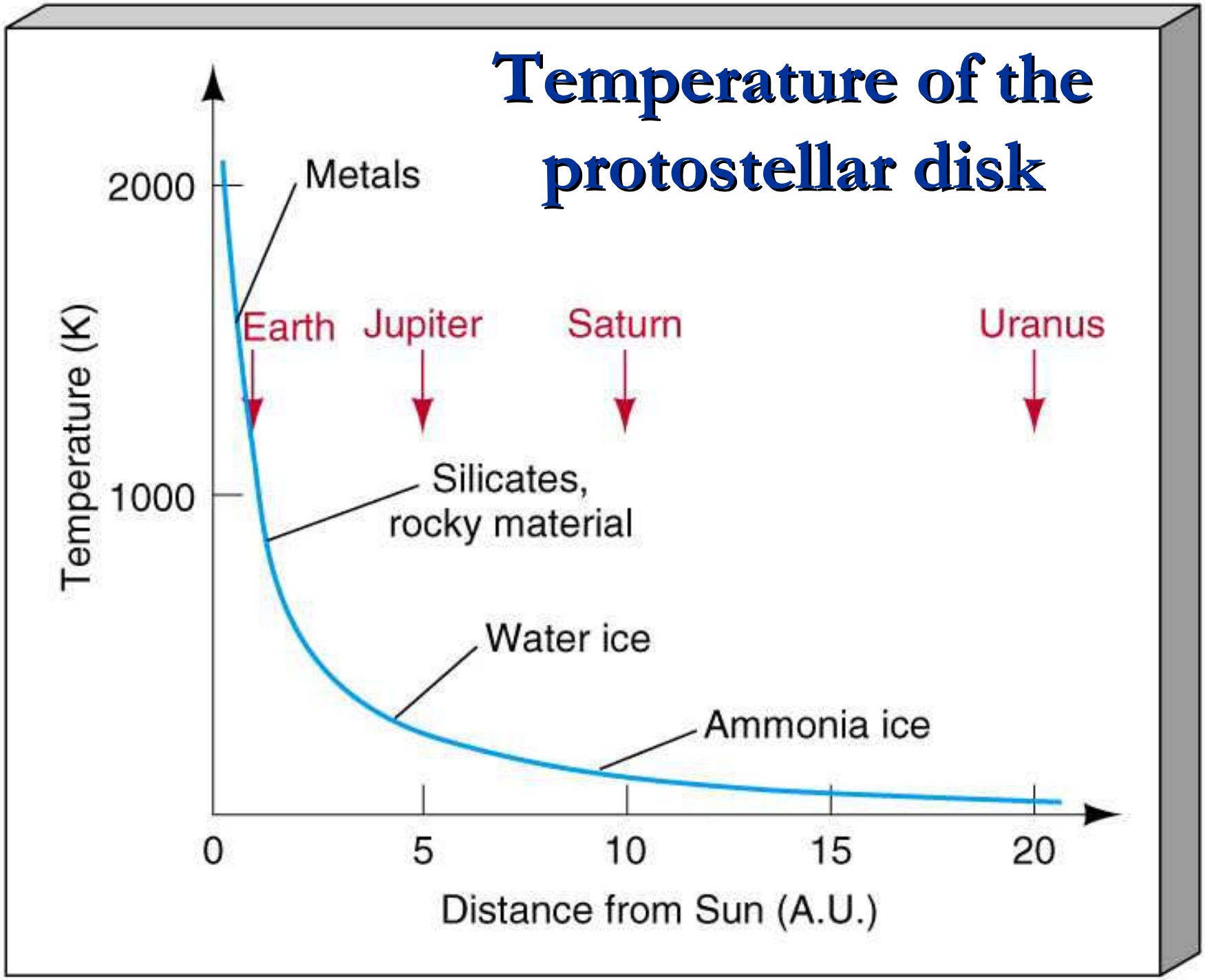
  - ω is called the angular speed, if r=1 m and $\omega=2\pi$ s^{-1}, $v=2\pi$ m s^{-1}
- To make l stay constant, if r goes down the angular speed ω must change in proportion to $1/r^2$

Planet formation in the disk

- While the disk is forming, initial asymmetry will introduce structure within the disk which can grow under it's own gravitational field
  - Small "disks within disks"

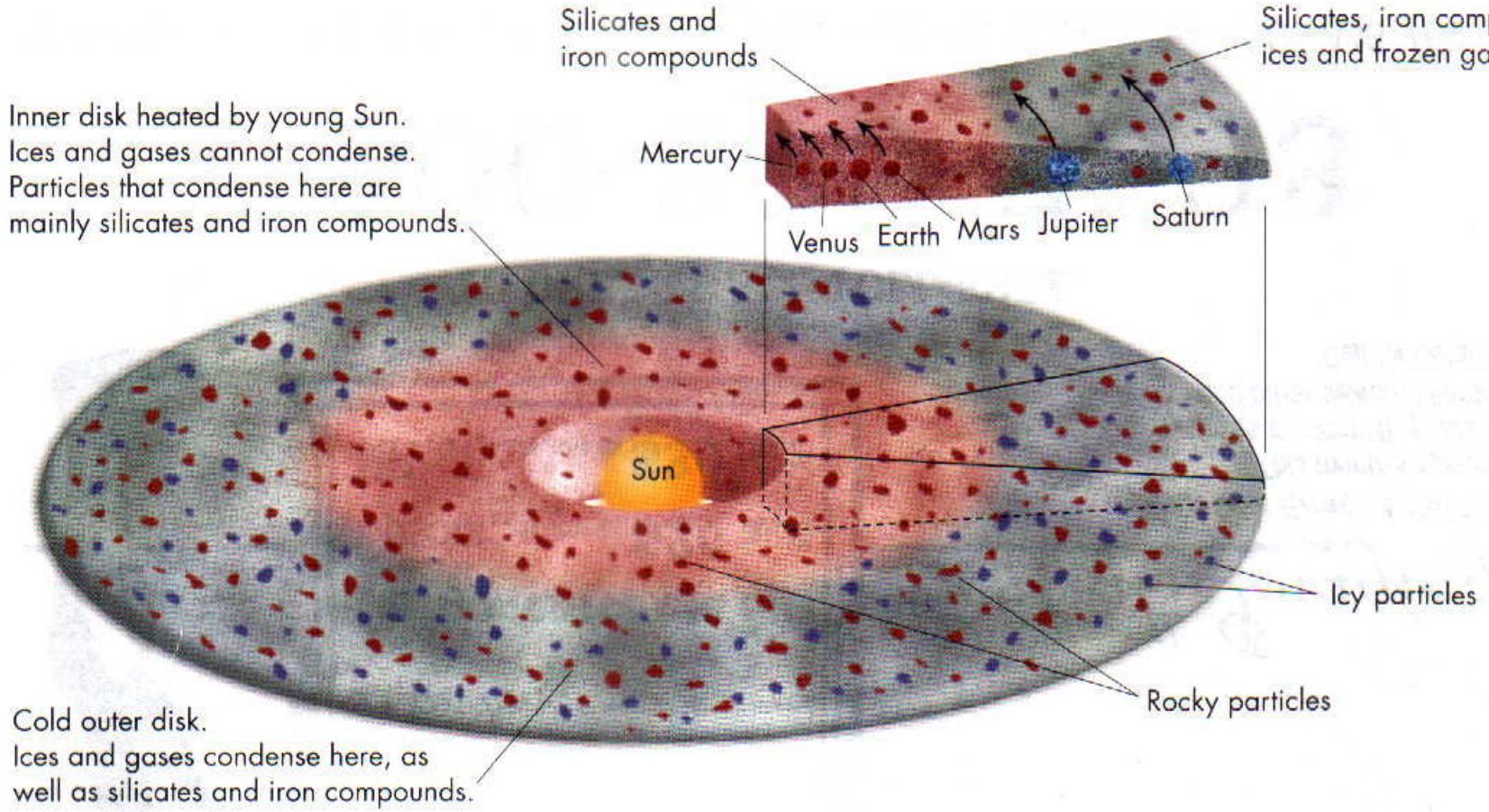


Temperature of the protostellar disk



Differentiation in the protostellar disk

The radial temperature profile sets regions where some compounds can condense to form solids. C,N,O are the most common elements after H,He



Planet formation is heirarchical

(1) Condensation nuclei (minute dust grains) attract other matter and begin to grow in size. The dust grains are present in the initial solar solar nebula

(2) This accretion phase continues, forming ever larger systems baseball size→basketball size→continent sized

(3) Planetesimals have enough gravity to now starting "sweeping up" material around their orbits. Collisions occur as well as cratering from smaller objects

Forming the Jovian planets

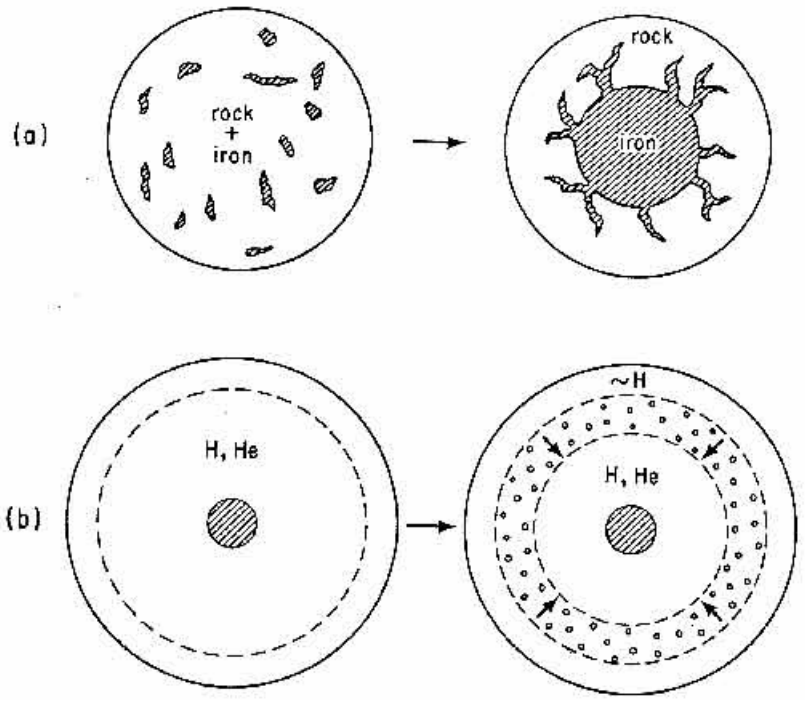
- Astronomers are not sure if the hierarchical picture applies to the Jovian planets
- Recent research has shown that the gas in the protostellar disk can become quite unstable to gravitational collapse far out from the Sun
  - Allows the giant planets to be formed in just a few hundred years – much shorter than previously thought millions of years
- Much research still to be done

Evolution of planets

- The components (elements) in solar nebula are initially well "mixed", and planets begin in a hot almost liquid state
  - This allows lighter elements to float, and heavier elements to sink: ***differentiation***
  - Heat is released:

    Gravitational energy → kinetic infall energy → increase in temperature

  - Thus the more radioactive elements (heavier) accumulate in the core of the planet
  - This is why the Earth's core is still hot
  - The same process continues today in the giant planets



Formation of terrestrial planet atmospheres

- As the heavy elements sink, gases rise and begin to form early planetary atmospheres
  - Vulcanism leads to the rapid ejection of water, CO_2, N_2, NH_3, H_2S (but almost no gaseous oxygen)
  - The strong ultraviolet radiation in the solar nebula breaks down ammonia and water, the liberated hydrogen is light enough to escape
  - Concentration of nitrogen ensues, and the liberated oxygen forms oxides
  - H_2S combines with H_20 to form sulphuric acid, resulting in the deposit of sulphates
- The net result is that the atmosphere is left with very high concentrations of CO_2 and N_2

Removal of remaining gas

- Once nuclear ignition is achieved the star releases a massive wind of material off of its outer edges which serves to sweep out the remaining gas
  - This is called the T Tauri phase
- The remaining planetesimals close to the Sun will almost all impact with planets in this region
  - This is believed to be how the Moon was created
  - About 20,000 of these objects left between Mars & Jupiter
  - The rate of impacts was clearly much higher in the past than it is now
- Planetesimals farther out, which are mostly icy, interact with the Jovian planets and can be thrown out of the solar system!
  - These wind up becoming comets

More on Monday on this!

Testing this theory against what we observe

- Our first issue was to explain the orbit of the planets in the plane of the solar system
  - ☑ Solar nebula theory explains this: disk is formed naturally
- Second issue: rotation axis of planets is perpendicular to the plane of the solar system
  - ☑ The disks embedded within the protostellar disk are expected to closely aligned to it
  - ☑ Also helps explain why the moons of the gas giants tend to be in the equatorial plane of the planet

More tests

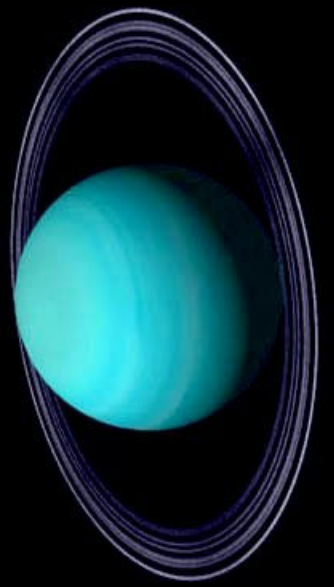
- We have terrestrial planets interior to the gas giants
  - ☑ The temperature gradient meant that only rocks & metals could condense in the inner part of the solar system
  - ☑ The outer parts were cold enough for gas to be swept up by the giant planets
  - ☑ The ices & rock left in the outer regions forms the Kuiper belt (these will later create the Oort cloud)

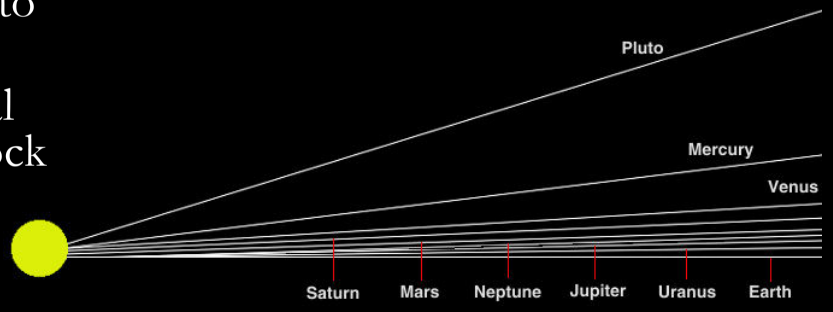
Yet more tests…

- Planetary cores are rocky, for the gas giants they are surrounded by gas
  - ☑ Differentiation also occurs within planets meaning that the heaviest elements sink to the core
  - ☑ Gases are released, which are captured by gas giants but they escape from the terrestrial planets
  - ☑ Icy bodes in the outer solar system never get large enough to do this
- Where do the asteroids come from?
  - ☑ They are left over planetesimals from the end of the accretion phase

Dealing with the problems

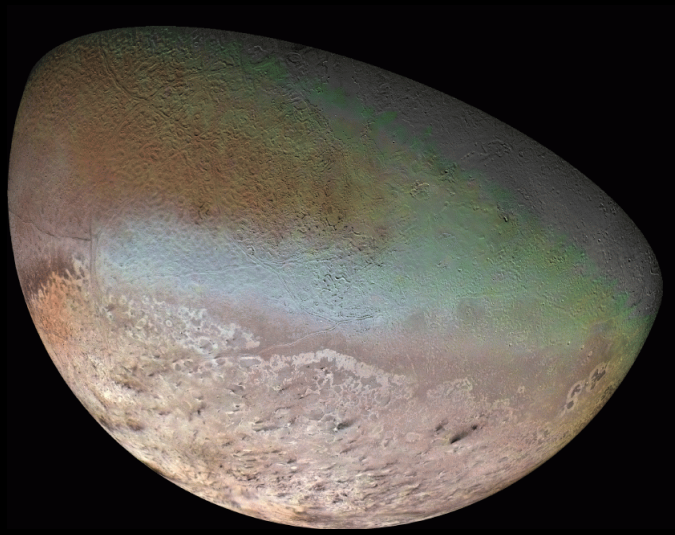
- Uranus is tilted at 98° to the plane of the solar system – how did that happen?
  - Possibly an off-centre impact, or the fact that the solar nebular is less dense in the outer parts allowing a higher probability of being at an angle
  - Same argument applies to Pluto's rotation axis
- Pluto and mercury lie at 7 and 17 degrees relative to the plane of the solar system
  - Mercury probably suffered an impact during its formation (it is small and easy to perturb)
  - Pluto seems to be a left over planetesimal so probably had many encounters to knock it into a strange position

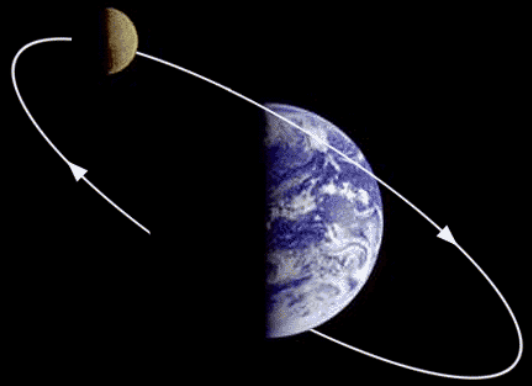




Other issues…

- What about moons with strange orbits, such as Triton, which orbits opposite to Neptune's rotation
  - Probably a captured planetesimal
- Earth's moon orbits in the plane of the solar system, not in the plane of the Earth's equator
  - The Earth-Moon system was probably caused by an impact event that occurred in the plane of the solar system





Summary of lecture 12

- The Solar Nebula theory is the leading explanation for the formation of the solar system
  - Explains all the key features of the solar system, and particularly why gas giants orbit farther out than terrestrial planets
  - The few pieces of data that do not at first appearances match the theory can be interpreted in terms of possible outcomes of collisions

Next lecture

- Guest lecture (Dr Martin Duncan)