There are countless suns and countless Earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous."-

Giordano Bruno, 1548 - 1600, in De L'Infinito Universo E Mondi

dison-Wesley

Announcements

Problem Set 4 now posted.
Please turn in today
We'll take it on Wednesday

Second Exam next Monday 25th
Next Observatory also 25th
Review session on Thursday

9. Formation of the Solar System

The evolution of the world may be compared to a display of fireworks that has just ended: some few red wisps, ashes, and smoke. Standing on a cool cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds.

George Lemaître (1894 – 1966)
Astronomer and Catholic Priest

Origin of the Solar System

Our theory must explain the data

1. Large bodies in the Solar System have orderly motions.
2. There are two types of planets.
   - small, rocky **terrestrial** planets
   - large, hydrogen-rich **Jovian** planets
3. Asteroids & comets exist in certain regions of the Solar System
4. There are exceptions to these patterns.

Catastrophe Theory

- Viable until the space program started
- Stars form without planets
- Two stars randomly have close pass
- Material is thrown from the stars
- Settles into planets
- Means there would be only one planetary system per galaxy
- Planets would be younger than parent star

Origin of the Solar System

Nebular Theory – our Solar System formed from a giant, swirling cloud of gas & dust.

Depends on two principles of Physics:

- Law of Gravity

  gravitational potential energy $\Rightarrow$ heat

- Conservation of angular momentum

  and

- Basic chemistry

The Solar Nebula

- The nebular theory holds that our Solar System formed out of a nebula which collapsed under its own gravity.
- observational evidence
  - We observe stars in the process of forming today.
  - These are always found within interstellar clouds of gas.

newly born stars in the Orion Nebula

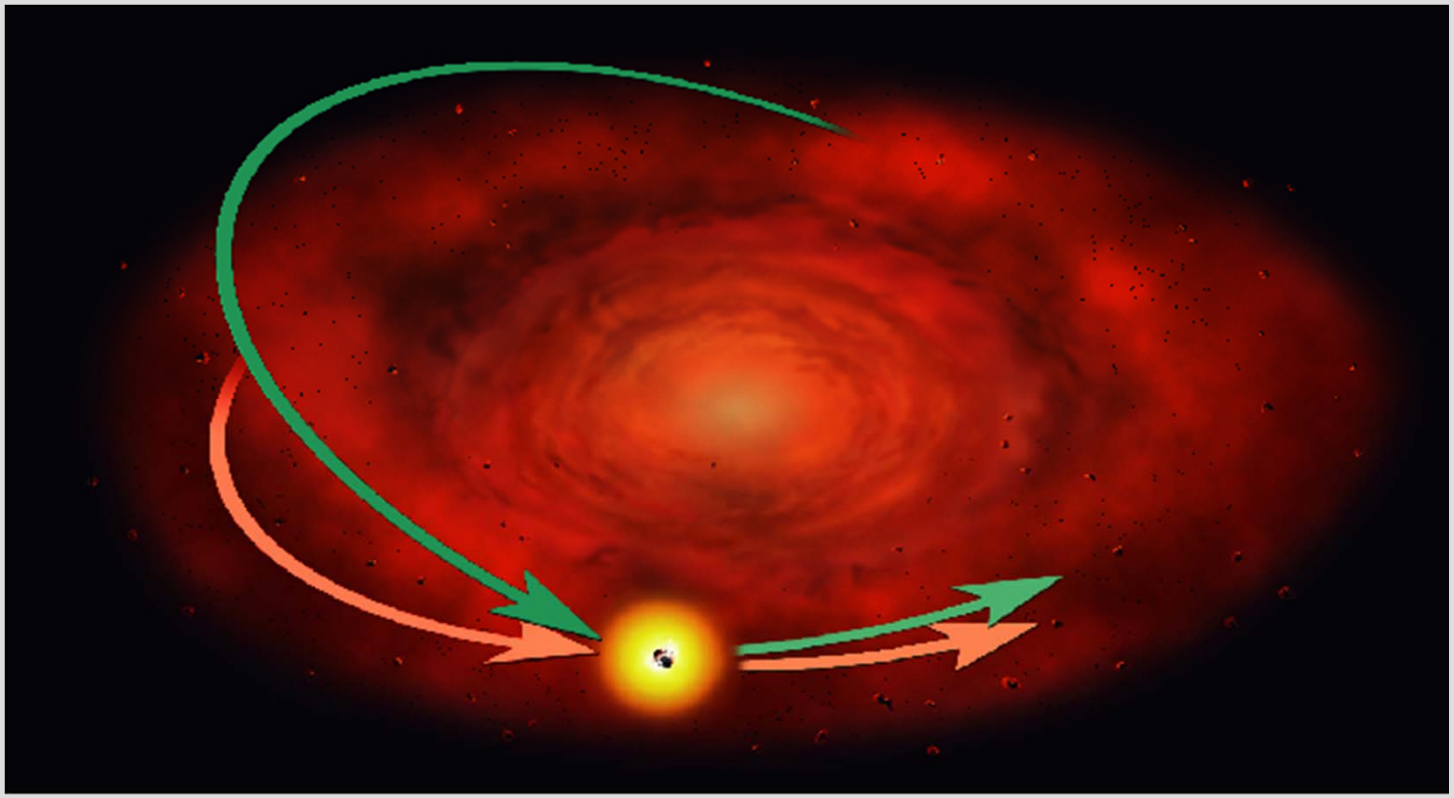
solar nebula – name given to the cloud of gas from which our own Solar System formed

Gravitational Collapse

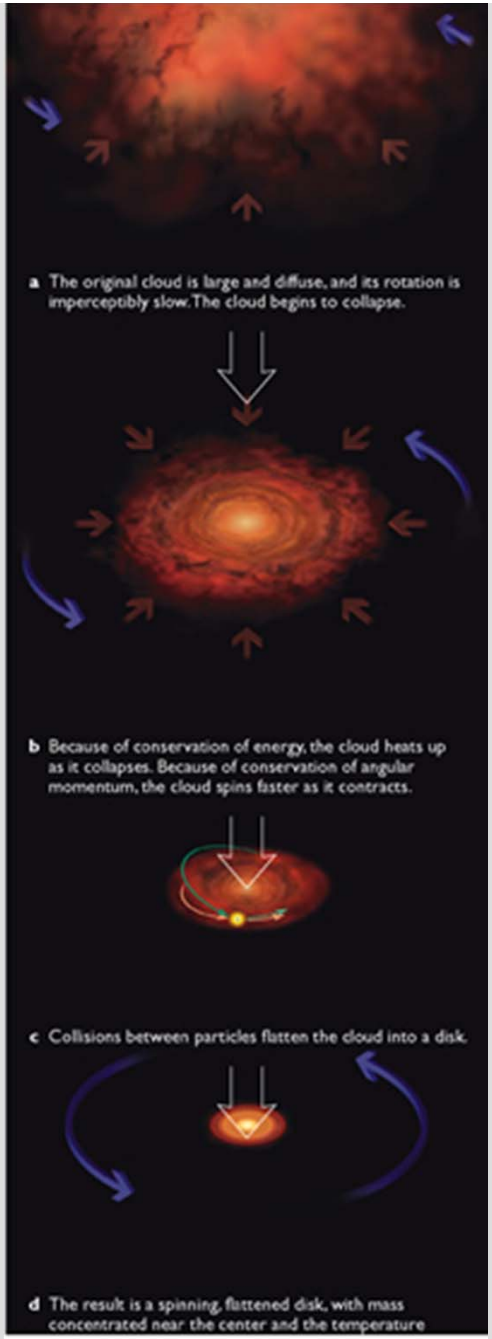
- The solar nebular was initially somewhat spherical and a few light years in diameter.
  - very cold
  - rotating slightly
- It was given a "push" by some event.
  - perhaps the shock wave from a nearby supernova
- As the nebula shrank, gravity increased, causing collapse.
- As the nebula "falls" inward, gravitational potential energy is converted to heat.
  - Conservation of Energy
- As the nebula's radius decreases, it rotates faster
  - Conservation of Angular Momentum

Flattening of the Solar Nebula

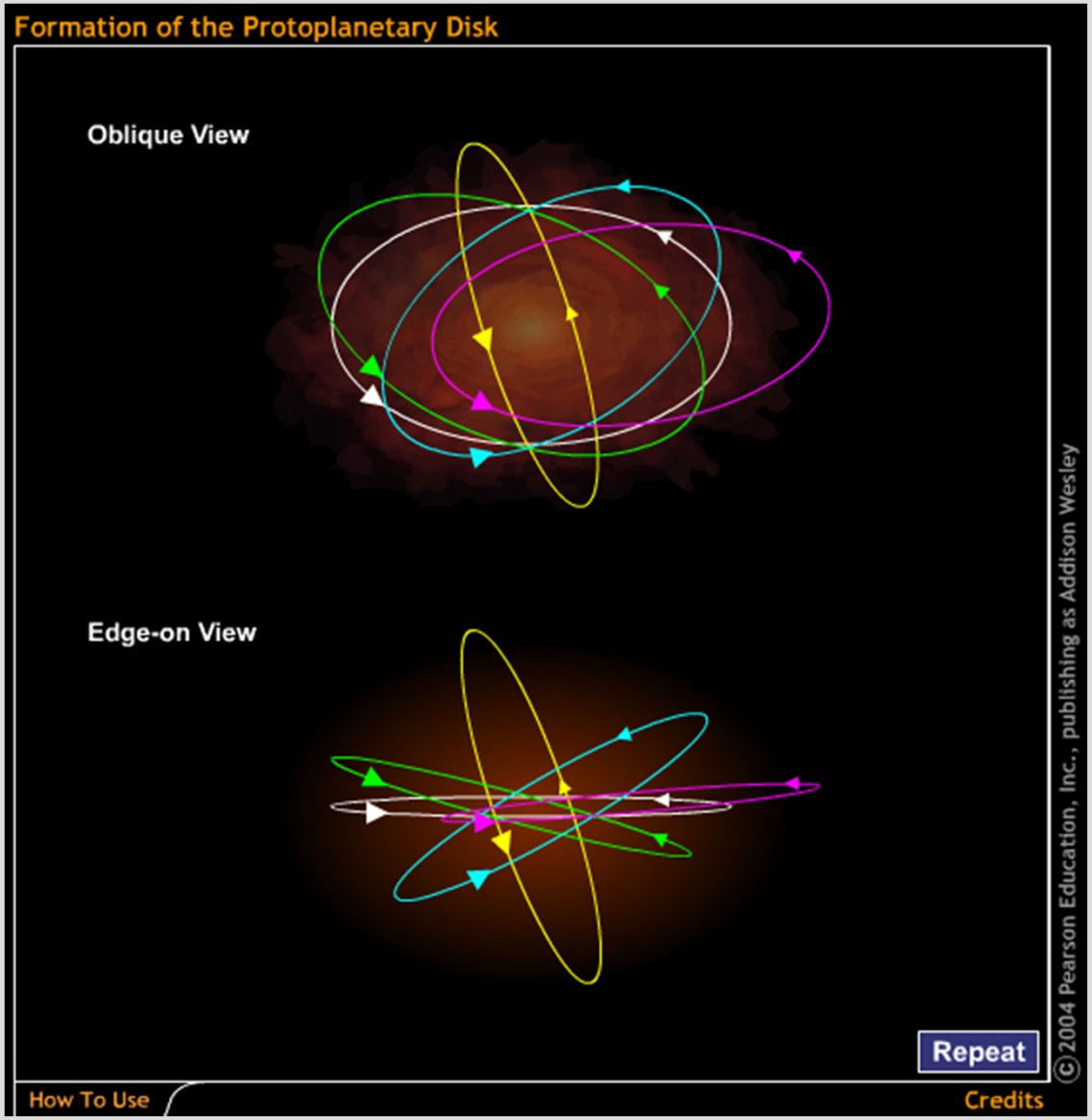
- As the nebula collapses, clumps of gas collide & merge.
- Their random velocities average out into the nebula's direction of rotation.
- The spinning nebula assumes the shape of a disk.

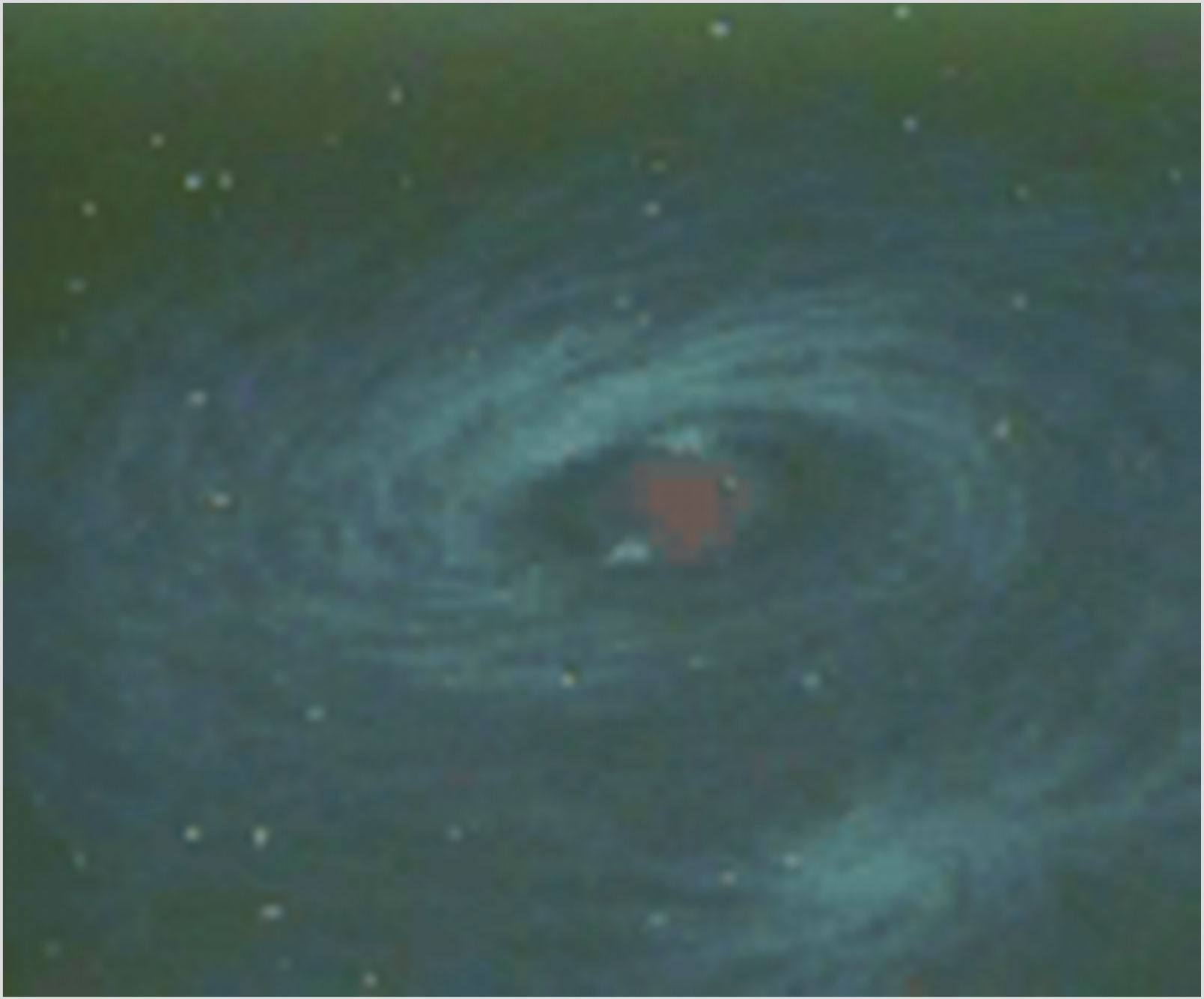


As the nebula collapses, it heats up, spins faster, and flattens.



Collapse of the Solar Nebula





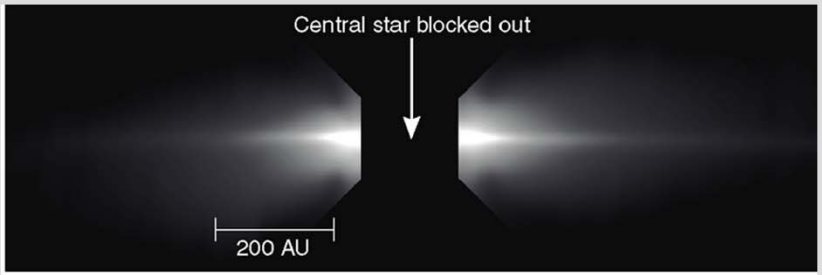
Orderly Motions in the Solar System

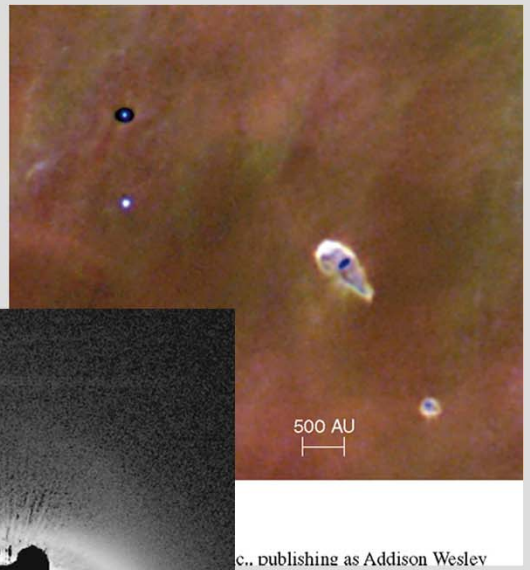
- The Sun formed in the very center of the nebula.
  - temperature & density were high enough for nuclear fusion reactions to begin
- The planets formed in the rest of the disk.
- This would explain the following:
  - all planets lie along one plane (in the disk)
  - all planets orbit in one direction (the spin direction of the disk)
  - the Sun rotates in the same direction
  - the planets would tend to rotate in this same direction
  - most moons orbit in this direction
  - most planetary orbits are near circular (collisions in the disk)

More Support for the Nebular Theory

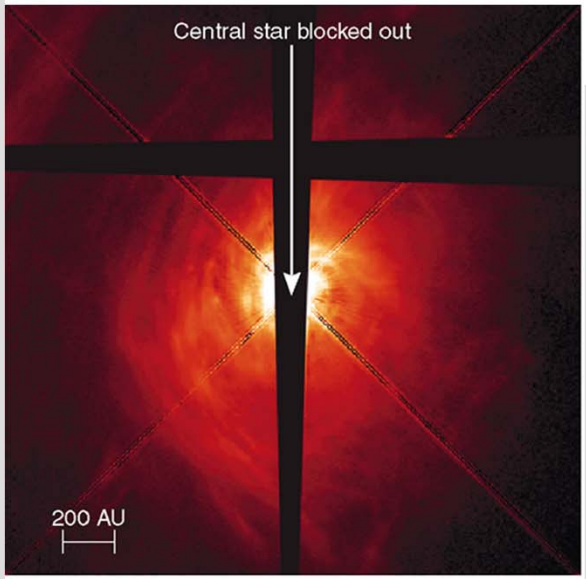
- We have observed disks around other stars.
- These could be new planetary systems in formation.

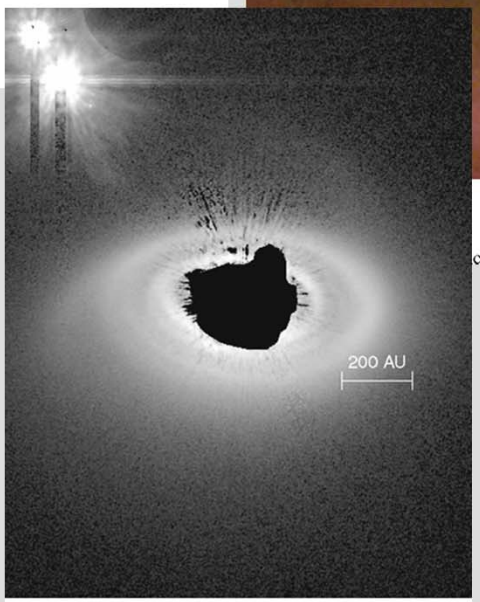
β Pictoris





AB Aurigae





9.3 Creating Two Types of Planets

Our goals for learning:

- What key fact explains why there are two types of planet?
- Describe the basic steps by which the terrestrial planets formed.
- Describe the basic steps by which the Jovian planets formed.

Building the Planets

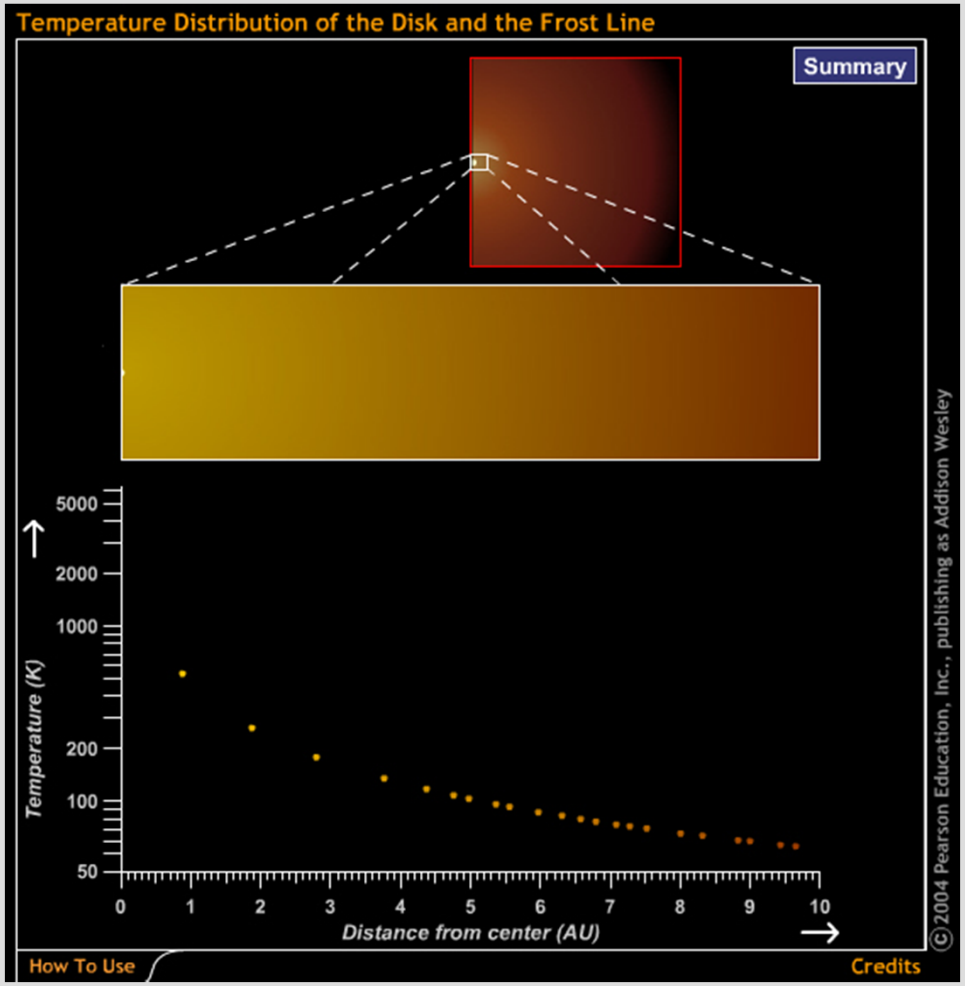
Condensation – elements & compounds began to condense (i.e. solidify) out of the nebula…. depending on temperature!

Materials in the Solar Nebula

	Metals	Rocks	Hydrogen Compounds	Light Gases
				
Examples	iron, nickel, aluminum	silicates	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	(do not condense in nebula)
Relative Abundance (by mass)	▪	▪	■	
	(0.2%)	(0.4%)	(1.4%)	(98%)

Building the Planets

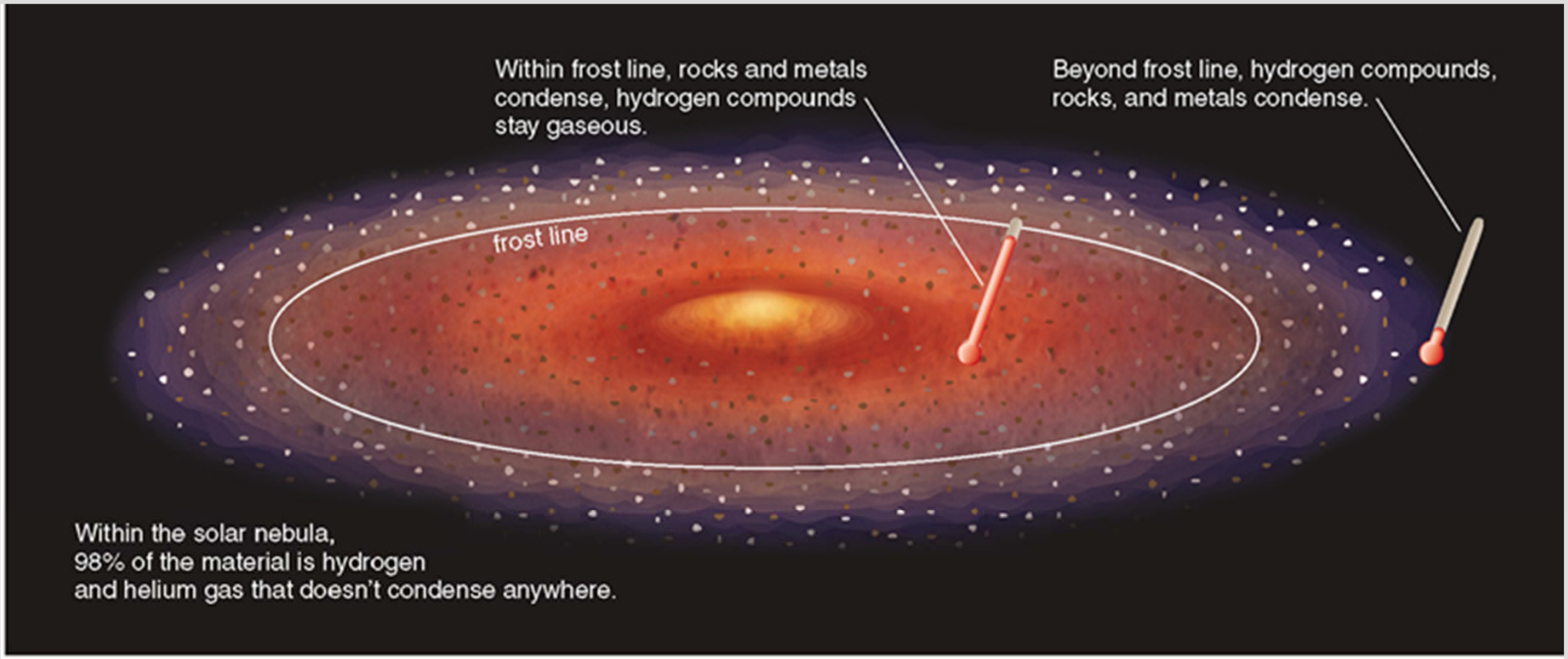
…and temperature in the Solar nebula depended on distance from the Sun!



Building the Planets

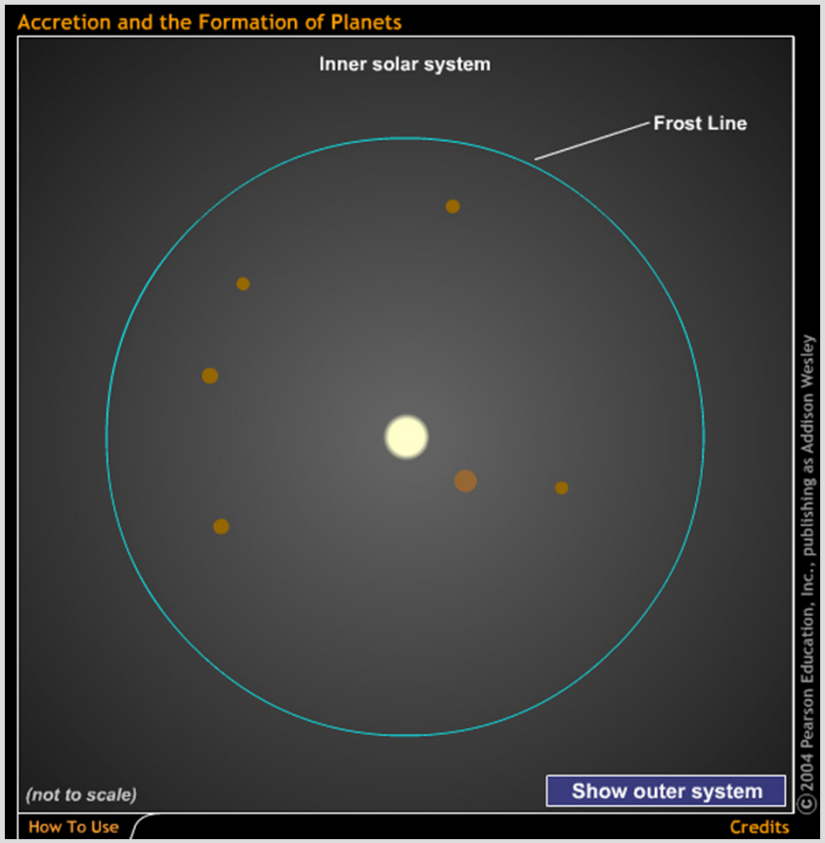
So only rocks & metals condensed within 3.5 AU of the Sun… the so-called **frost line**.

Hydrogen compounds (ices) condensed beyond the frost line.



Building the Planets

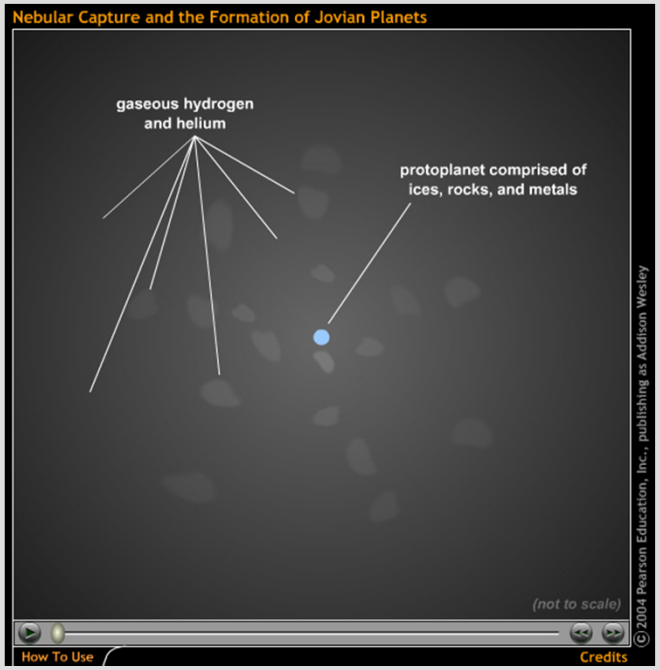
accretion -- small grains stick to one another via electromagnetic force until they are massive enough to attract via gravity to form...



Building the Planets

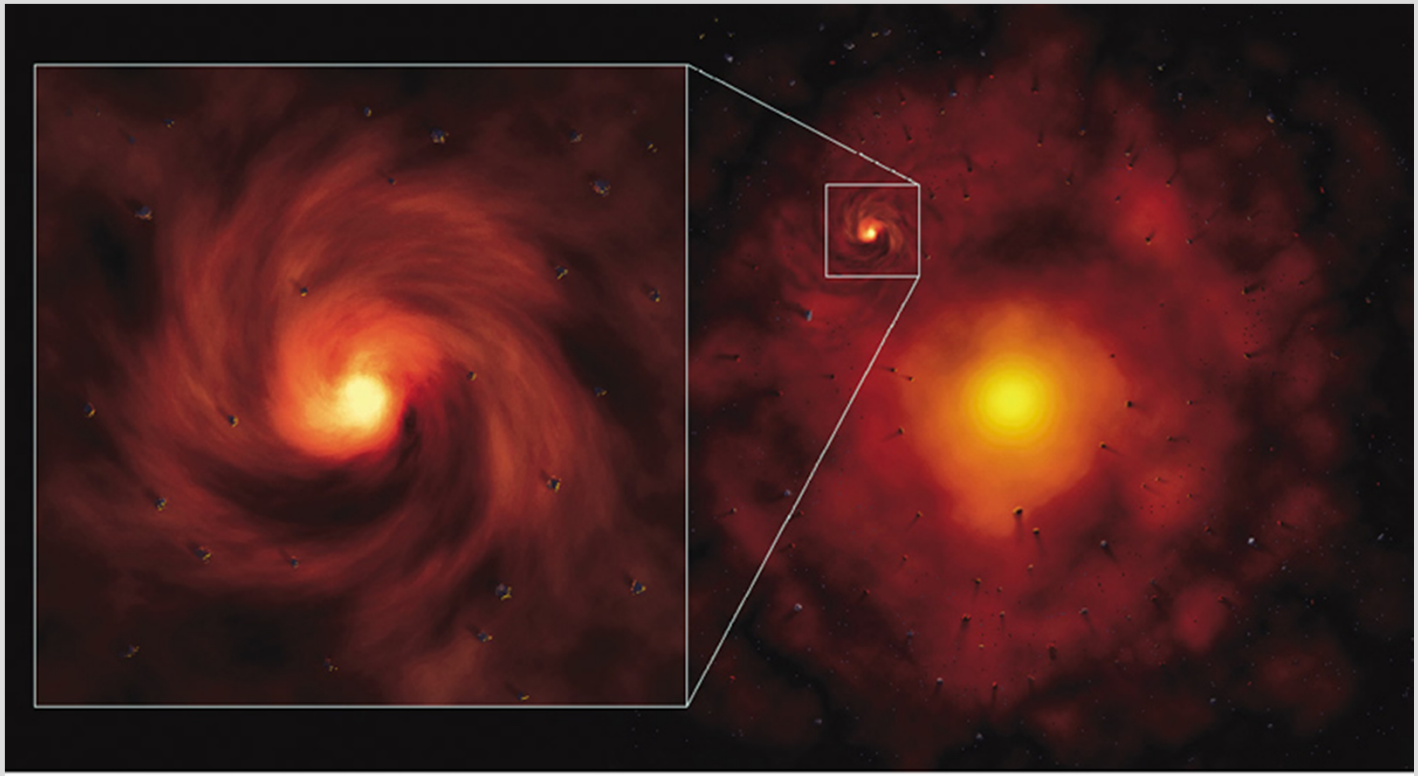
…**planetesimals** which will:

- combine near the Sun to form rocky planets
- combine beyond the frostline to form icy planetesimals which…
- capture H/He far from Sun to form gas planets



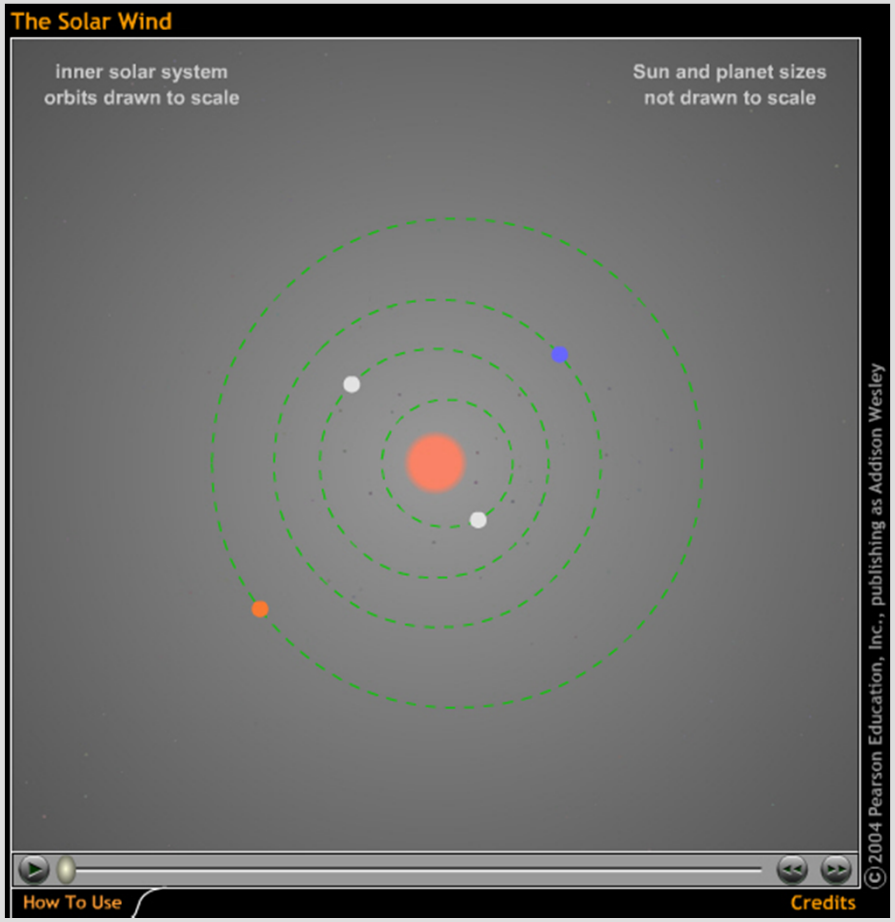
Building the Planets

- Each gas (Jovian) planet formed its own “miniature” solar nebula.
- Moons formed out of the disk.



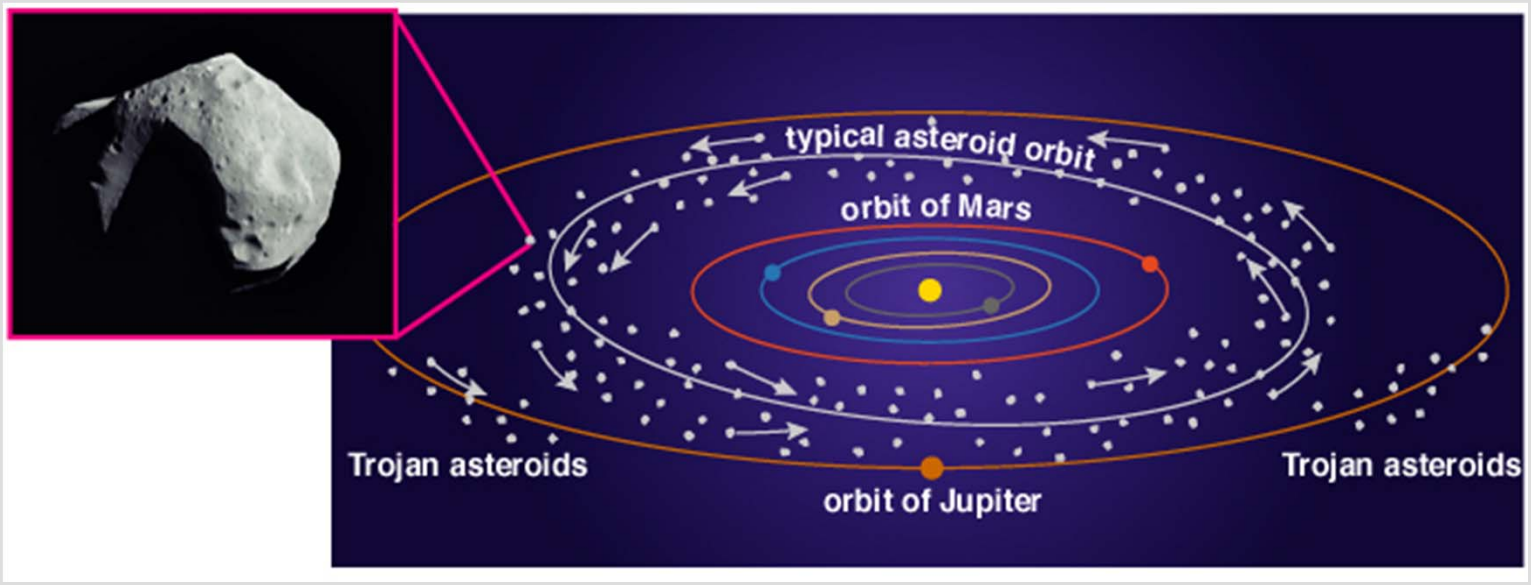
Building the Planets

solar wind --- charged particles streaming out from the Sun cleared away the leftover gas

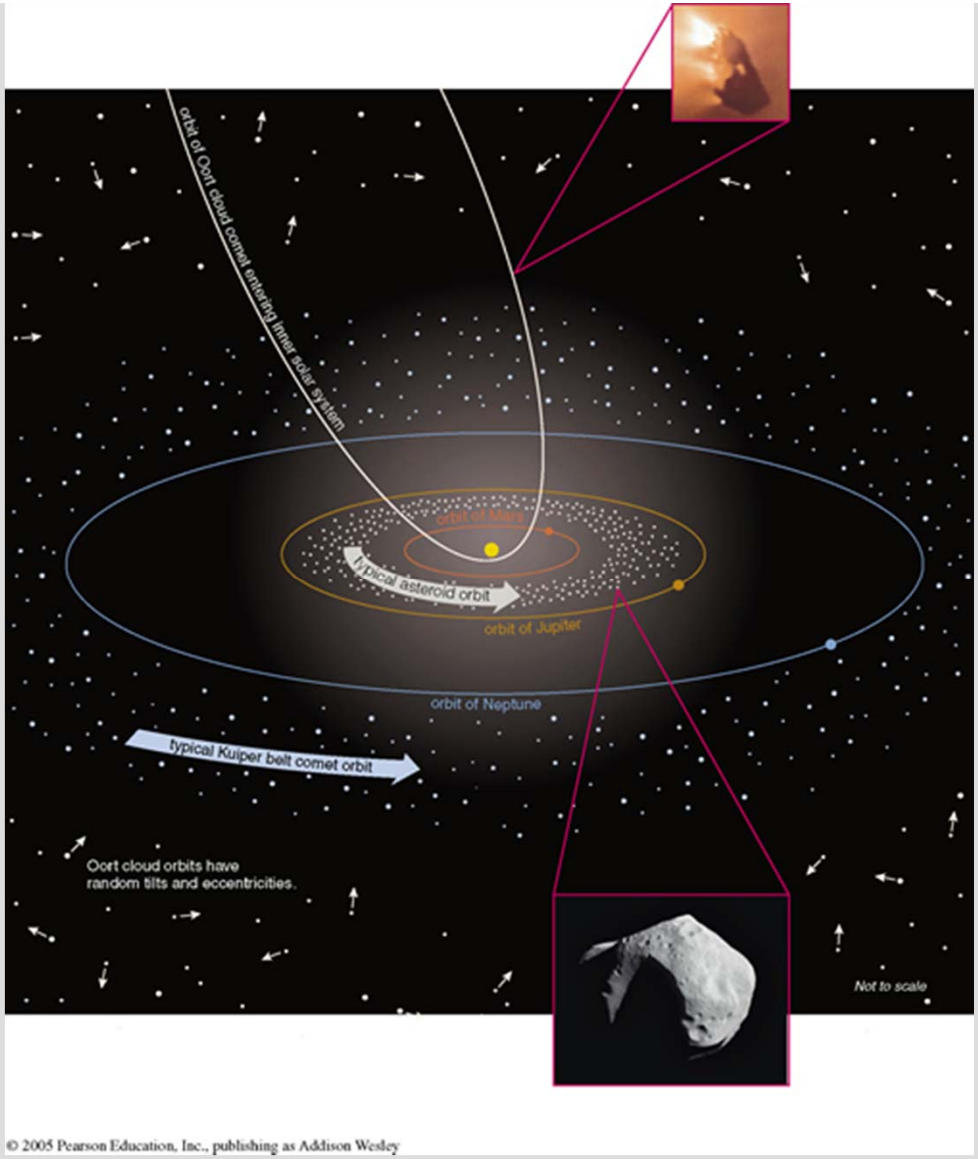


Origin of the Asteroids

- The Solar wind cleared the leftover gas, but not the leftover planetesimals.
- Those leftover rocky planetesimals which did not accrete onto a planet are the present-day **asteroids**.
- Most inhabit the **asteroid belt** between Mars & Jupiter.
  - Jupiter's gravity prevented a planet from forming there.



Origin of the Comets



- The leftover icy planetesimals are the present-day **comets**.
- Those which were located between the Jovian planets, if not captured, were gravitationally flung in all directions into the **Oort cloud**.
- Those beyond Neptune's orbit remained in the ecliptic plane in what we call the **Kuiper belt**.

The nebular theory *predicted* the existence of the Kuiper belt 40 years before it was discovered!

Exceptions to the Rules

So how does the nebular theory deal with exceptions, i.e. data which do not fit the model's predictions?

IMPACTS

- There were many more leftover planetesimals than we see today.
- Most of them collided with the newly-formed planets & moons during the first few 10^8 years of the Solar System.
- We call this the **heavy bombardment** period.

Exceptions to the Rules

Close encounters with and impacts by planetesimals could explain:

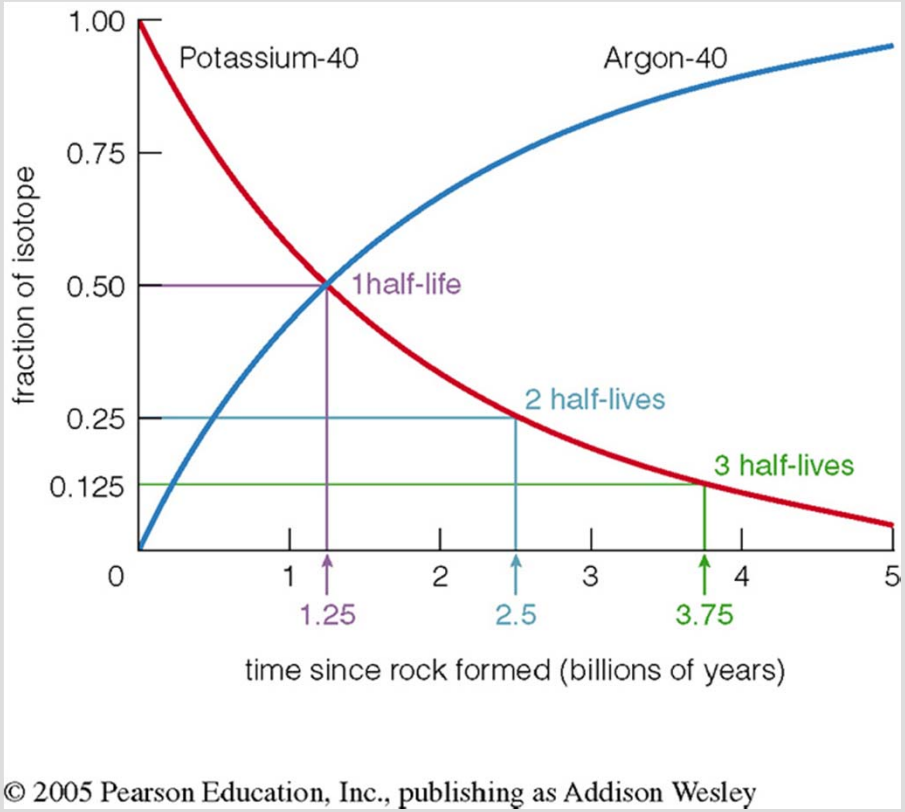
- Why some moons orbit opposite their planet's rotation
  - captured moons (e.g. Triton)
- Why rotation axes of some planets are tilted
  - impacts "knock them over" (extreme example: Uranus)
- Why some planets rotate more quickly than others
  - impacts "spin them up"
- Why Earth is the only terrestrial planet with a large Moon
  - giant impact

Formation of the Moon (Giant Impact Theory)

- The Earth was struck by a Mars-sized planetesimal
- A part of Earth's mantle was ejected
- This coalesced in the Moon.
  - it orbits in same direction as Earth rotates
  - lower density than Earth
  - Earth was "spun up"

Radiometric Dating

- Isotopes which are unstable are said to be **radioactive**.
- They spontaneously change in to another isotope in a process called **radioactive decay**.
  - protons convert to neutrons
  - neutrons convert to protons
- The time it takes half the amount of a radioactive isotope to decay is called its **half life**.



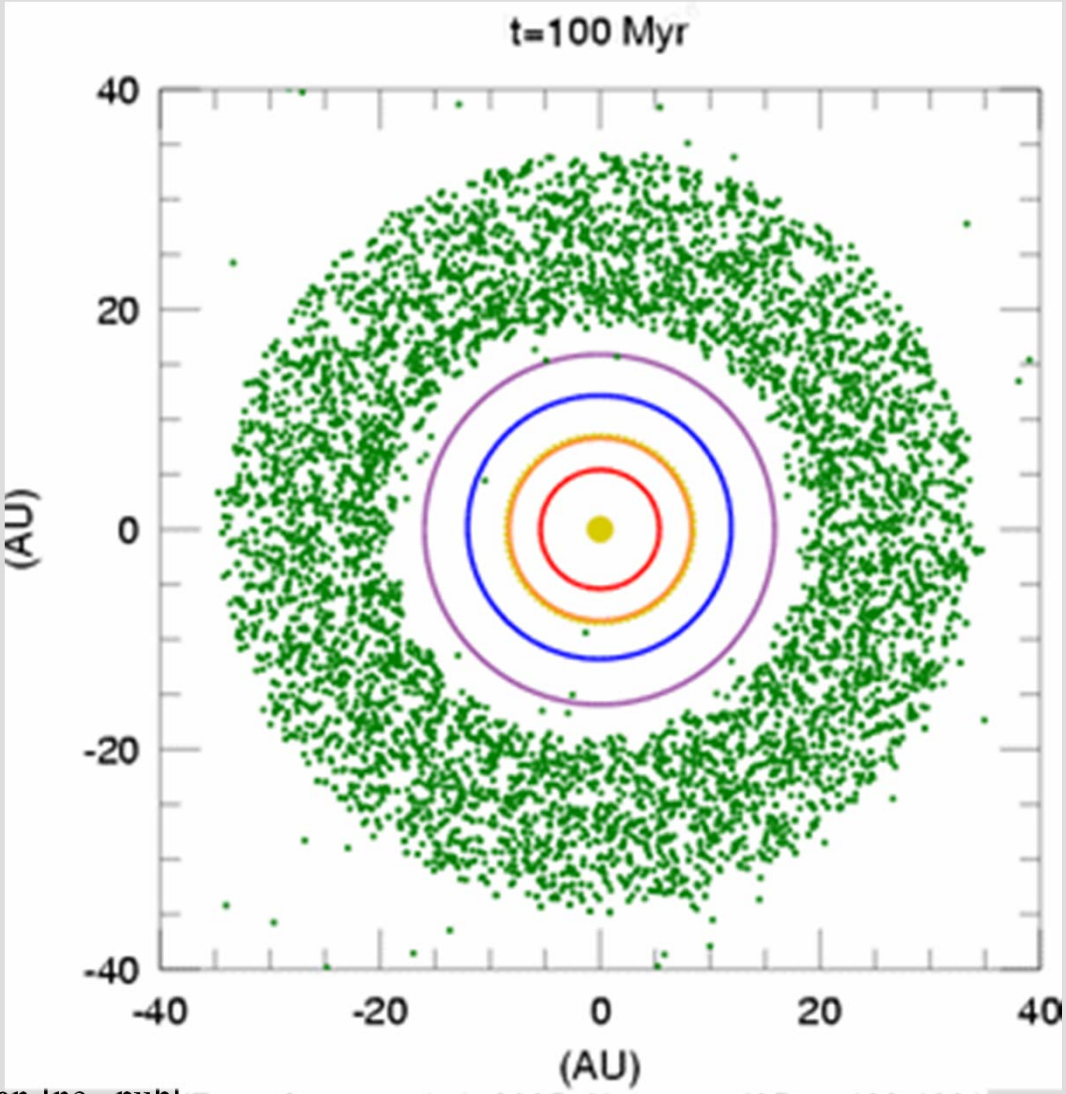
- By knowing rock chemistry, we chose a stable isotope which does not form with the rock…its presence is due solely to decay.
- Measuring the relative amounts of the two isotopes and knowing the half life of the radioactive isotope tells us the age of the rock.

The Age of our Solar System

- Radiometric dating can only measure the age of a rock *since it solidified*.
- Geologic processes on Earth cause rock to melt and resolidify.

  $\Rightarrow$ Earth rocks can't be used to measure the Solar System's age.
- We must find rocks which have not melted or vaporized since the condensed from the Solar nebula.
  - meteorites imply an age of 4.6 billion years for Solar System
- Radioactive isotopes are formed in stars & supernovae
  - suggests that Solar System formation was triggered by supernova
  - short half lives suggest the supernova was nearby

Supercomputer Calculations



(From Gomes, *et al.*, 2005, *Nature*, v. 435, p. 466-469.)

Sean Raymond's Calculations