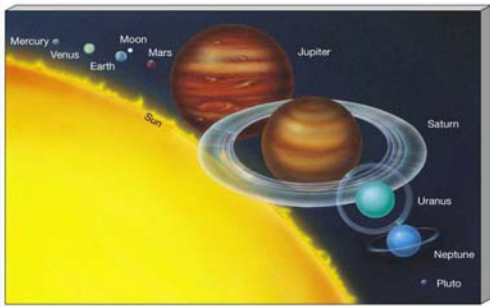


Lecture 29: Solar System Formation



The Solar System

	Distance (AU)	Radius (Earth's)	Mass (Earth's)	Rotation (Earth's)	# Moons	Orbital Inclination	Orbital Eccentricity	Obliquity	Density (g/cm ³)
Sun	0	109	332,800	25.36°	9	---	---	---	1.410
Mercury	0.39	0.38	0.05	58.8	0	7	0.2056	0.1°	5.43
Venus	0.72	0.95	0.89	244	0	3.394	0.0068	177.4°	5.25
Earth	1.0	1.00	1.00	1.00	1	0.000	0.0167	23.45°	5.52
Mars	1.5	0.53	0.11	1.029	2	1.850	0.0934	25.19°	3.95
Jupiter	5.2	11	318	0.411	16	1.308	0.0483	3.12°	1.33
Saturn	9.5	9	95	0.428	18	2.488	0.0560	26.73°	0.69
Uranus	19.2	4	17	0.748	15	0.774	0.0461	97.86°	1.29
Neptune	30.1	4	17	0.802	8	1.774	0.0097	29.56°	1.64
Pluto	39.5	0.18	0.002	0.267	1	17.15	0.2482	119.6°	2.03

The Solar System

- We see that the planets have different
 - ❖ Distances from the Sun
 - ❖ Masses
 - ❖ Eccentricities
 - ❖ Orbital inclinations
 - ❖ Obliquities (tilt angles)
 - ❖ Spin Periods



The Solar System

- They also have different
 - ❖ Atmospheric temperatures
 - ❖ Surface pressures
 - ❖ Surface gravities
 - ❖ Compositions
 - ❖ Formation histories
 - ❖ Satellites (moons)



The Solar System

Planet	Distance	Density	Mass
Mercury	0.4	1.0	0.06
Venus	0.7	0.9	0.8
Earth	1.0	1.0	1.0
Mars	1.5	0.7	0.1
(asteroid)	2.8	0.5	0.0002
Jupiter	5.2	0.2	318
Saturn	9.5	0.1	95
Uranus	19.2	0.2	15
Neptune	30.1	0.3	17
Pluto	39.5	0.3	0.003

The Solar System

- There are two classes of planets in the solar system:
 - ❖ The Terrestrial planets are small and have high densities:
 - Mercury
 - Earth
 - Venus
 - Mars
 - ❖ The Jovian planets are large and have low densities:
 - Jupiter
 - Saturn
 - Uranus
 - Neptune
- Pluto doesn't really fit into either category very well!

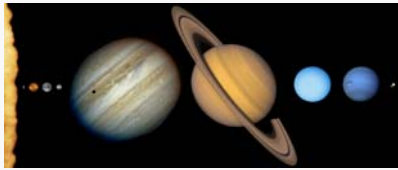
The Solar System

- The general characteristics of planets within the Terrestrial and Jovian groups are quite different:

Terrestrial	Jovian
Close together in inner solar system	Widely spaced in outer solar system
Small, dense, rocky	Large and gaseous
Solid surfaces	No solid surfaces
Weak magnetic fields	Strong magnetic fields
Only three moons	Lots of moons

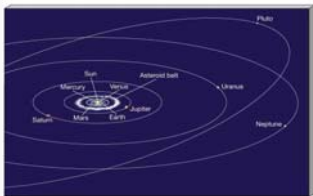
The Formation of the Solar System

- The solar system displays great regularity, combined with amazing exceptions
- We would like to be able to explain the current appearance of the solar system in terms of a simple physical picture
- Any model for the formation and evolution of the solar system must satisfy several requirements



Model Must Explain

- The isolation of the planets, and why their distances from the Sun increase by a factor of 1.5-2 as we work our way outwards through the solar system
- Why most of the planetary orbits are nearly perfect circles
- Why the planetary orbits lie within almost the same plane



Model Must Explain

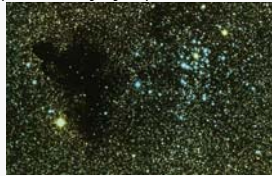
- Why the planets all orbit in the same direction
- Why most of the planets spin in the same direction
- Why most satellites orbit in the same direction as the spin of the host planet
- Why the solar system is differentiated, with terrestrial planets close to the Sun and Jovian planets farther away
- Why asteroids are so different from planets
- Why most comets are in the Oort Cloud, and how it formed



Properties of the Solar System

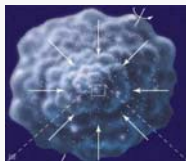
- The great regularity of the solar system suggests that it's not likely the planets were captured by the Sun at random
- The solar system probably formed in a single, drawn-out event about 4.6 billion years ago
- The first attempt at a model to explain the formation of the solar system was the Nebular Theory, suggested by Descartes and later developed quantitatively by Laplace in 1796

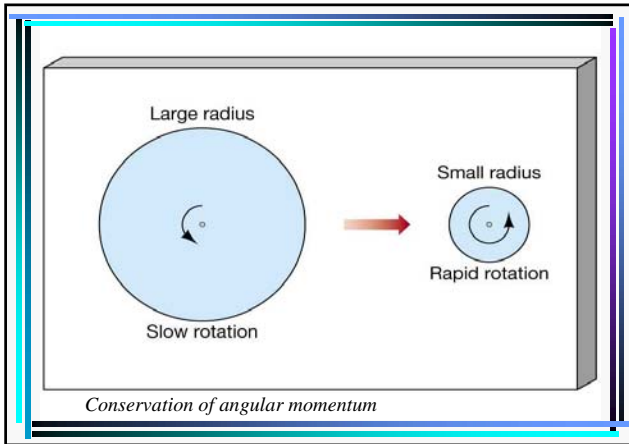
Dark molecular cloud and young stars



The Nebular Model

- The early solar nebula was a large cloud about 1 light-year across (about 6 trillion miles)
- The nebula was spinning slowly
- The nebula began to shrink due to its own self-gravity
- As it shrank, the spinning became faster to conserve angular momentum
- The resulting centripetal force caused it to flatten out into a "pancake" about 100 AU across





The Nebular Model

- The Sun forms at the center of the disk, surrounded by rings of material
- The material in the rings coalesces to form the planets
- HOWEVER – there is a *problem* with the Nebular Model!
- The problem is that any rings would tend to disperse due to high pressure because the matter was very warm

The Condensation Theory

- The Condensation Theory takes the old Nebular Model and adds dust
- The dust has two benefits:
- Dust cools the nebula by emitting infrared radiation, which reduces the pressure
- Dust particles also act as condensation nuclei that help atoms to stick together
- These two effects help the collapse of the disk proceed, forming the planets
- In the Condensation Theory, rings do not form before planets

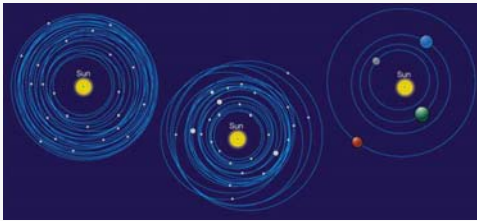
Formation of the Planets

- The planets grew by the process of accretion, with small objects sticking together to form larger objects
- There were millions of large objects, called "planetesimals"
- These were probably about the size of Pluto
- The planetesimals were large enough to attract each other gravitationally, causing them to collide and merge



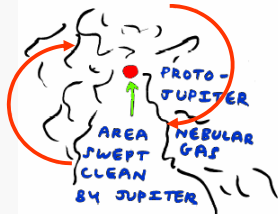
Formation of the Planets

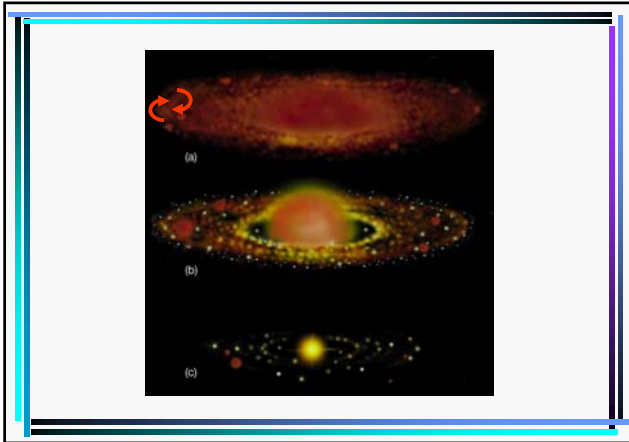
- The planetesimals had highly eccentric orbits that tended to average out, yielding nearly circular planetary orbits
- This eventually led to the nine planets we see today
- Leftover material formed the comets in the Oort cloud and the Kuiper belt, as well as the asteroids



Formation of the Planets

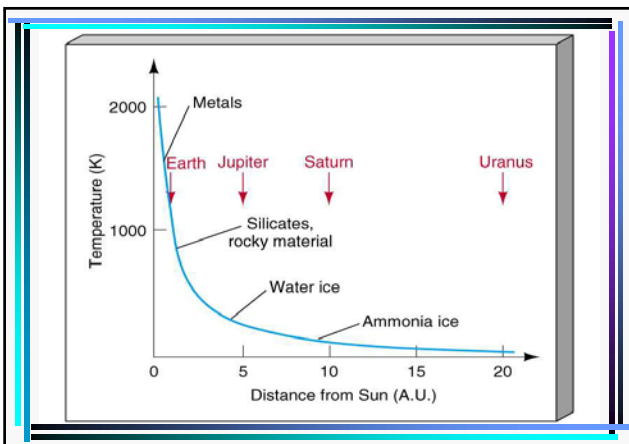
- The four largest objects in the cool, outer solar system swept up lots of hydrogen from the solar nebula, becoming the Jovian planets
- Large turbulent eddies may have helped to give the Jovian planets a head start, without requiring a very large core:





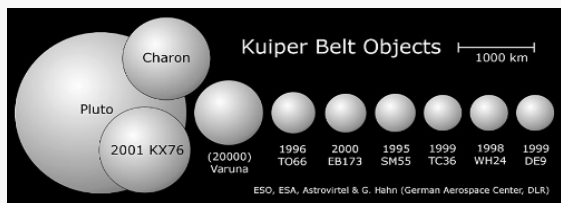
Formation of the Solar System

- Fragmentation also occurred due to millions of high-speed collisions
- This process broke up smaller objects, producing a huge number of meteors
- Most matter became part of a planet or moon, but some survived to remain in the form of asteroids and comets
- The regular spacing of the planets we observe today is roughly reproduced in modern computer simulations, although the precise spacing is not recovered
- The formation of the solar system took about 100 million years, followed by about 10^9 years of bombardment by leftover material
- The variation of the temperature with distance from the Sun caused differentiation of the early solar system



Formation of the Jovian Planets

- The temperature was only about 200 K or less in the outer solar system, beyond about 5 AU
- This allowed water vapor, ammonia, and methane to freeze out, forming the "iceberg" cores of the Jovian planets
- When massive enough, these planetesimals accreted hydrogen and helium gas, probably helped by the turbulent eddies
- Some leftover, icy planetesimals and fragments interacted with Jupiter and were flung outward, forming the Oort cloud
- Other icy leftovers remained in place to form the Kuiper Belt
- Some of the icy objects were probably flung by Jupiter into the inner solar system, perhaps supplying Earth with water during its formation



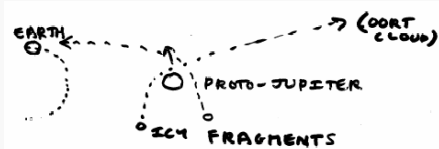
Relative Sizes of Large Kuiper Belt Objects

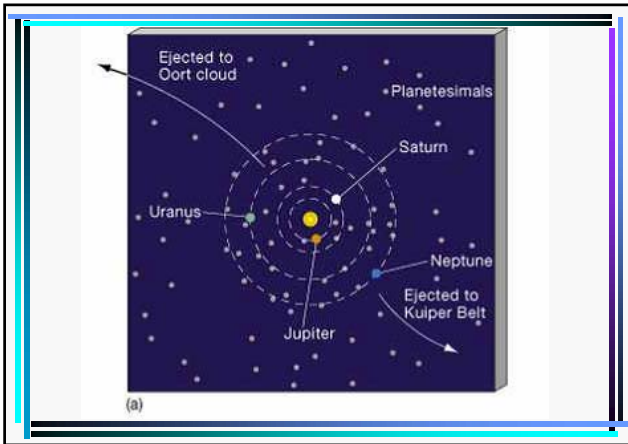
ESO 78 Photo 27b01 (23 August 2001) © European Southern Observatory

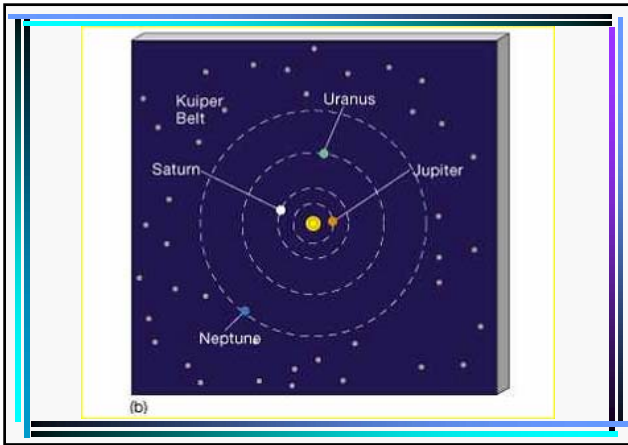
The New Horizons mission will investigate the Kuiper belt and beyond... <http://pluto.jhuapl.edu/>

Formation of the Terrestrial Planets

- The temperature in the inner solar system was about 1,000 K, so no ices formed there
- Instead, heavy elements such as iron combined with oxygen and silicon to form rocky planetesimals
- Light elements such as hydrogen did not condense to become part of the terrestrial planets, and escaped from their primary atmospheres

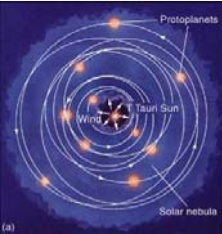
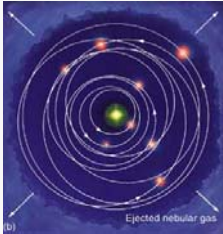






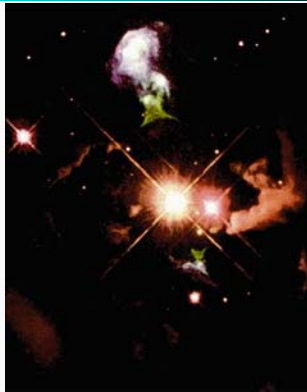
Formation of the Solar System

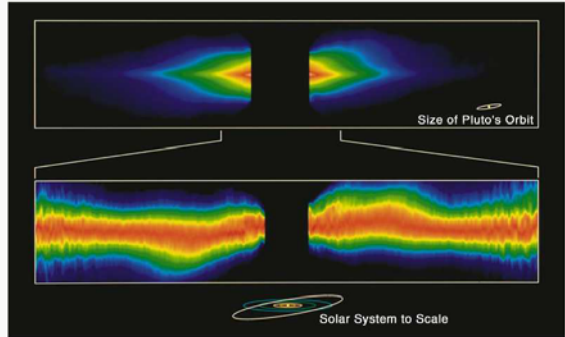
- Leftover gas was blown away into interstellar space by the intense stellar wind of the young Sun

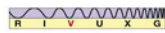
• We see the same process occurring now around other young stars...

*Herbig-Haro 32,
a young star system
where planets may
be forming now*



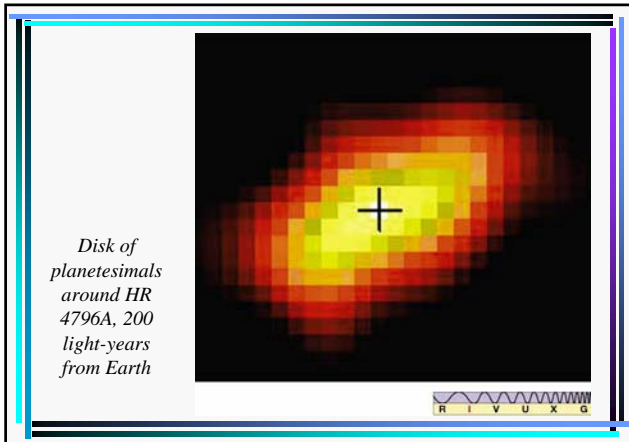


(a) *Disk around Beta Pictoris*





(b) *Disk around Beta Pictoris*



Formation of the Terrestrial Planets

- Our theory for the formation of the solar system accounts for the general regularity that is observed:
 - ❖ Isolation of planets
 - ❖ Circular planetary orbits
 - ❖ Orbits in nearly the same plane
 - ❖ Orbits in same direction as Solar spin
 - ❖ Planets spin in the same direction that they orbit
 - ❖ Moons orbit in the same direction as the spin of the planet
 - ❖ Differentiation of the solar system
 - ❖ Differences between asteroid and planetary properties
 - ❖ Properties of comets and formation of Kuiper Belt and Oort Cloud

Formation of the Terrestrial Planets

- Unusual catastrophes are required to explain the exceptions, for example:
 - ❖ Retrograde spin of Venus
 - ❖ Formation of Earth-Moon system
 - ❖ Tilt of the orbit of Uranus
 - ❖ Strange surface of the moon Miranda
 - ❖ Spin-orbit resonance of Mercury
- All of these seem to imply violent collisions in the distant past...
- Although the Sun contains 99.9% of the matter in the solar system, it contains only 0.3% of the angular momentum
- Jupiter contains about 60% of the angular momentum
- Early in its life, the Sun was probably spinning much faster – was the angular momentum lost via the Solar Wind, or due to a jet of matter?

Other Solar Systems

- One technique that we can use to understand the formation and evolution of our solar system is the study of other systems
- 110 planets are now known outside our own solar system
- These are too small to image directly, and therefore they are detected using two indirect techniques
 - ❖ Doppler shifts of host star
 - ❖ Photometric studies of planetary transits
- The planets that are detected using these methods tend to be large and close to their star
- Eventually, NASA plans to be able to detect Earth-class planets around Solar-type stars...

<http://planetquest.jpl.nasa.gov/>

<http://exoplanets.org/index.html>

