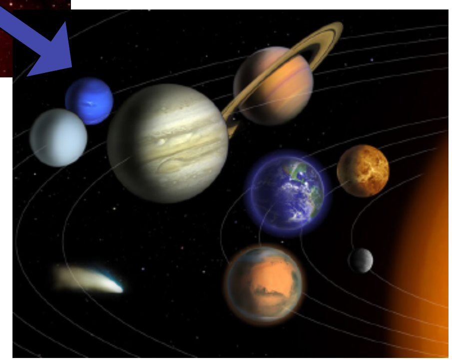
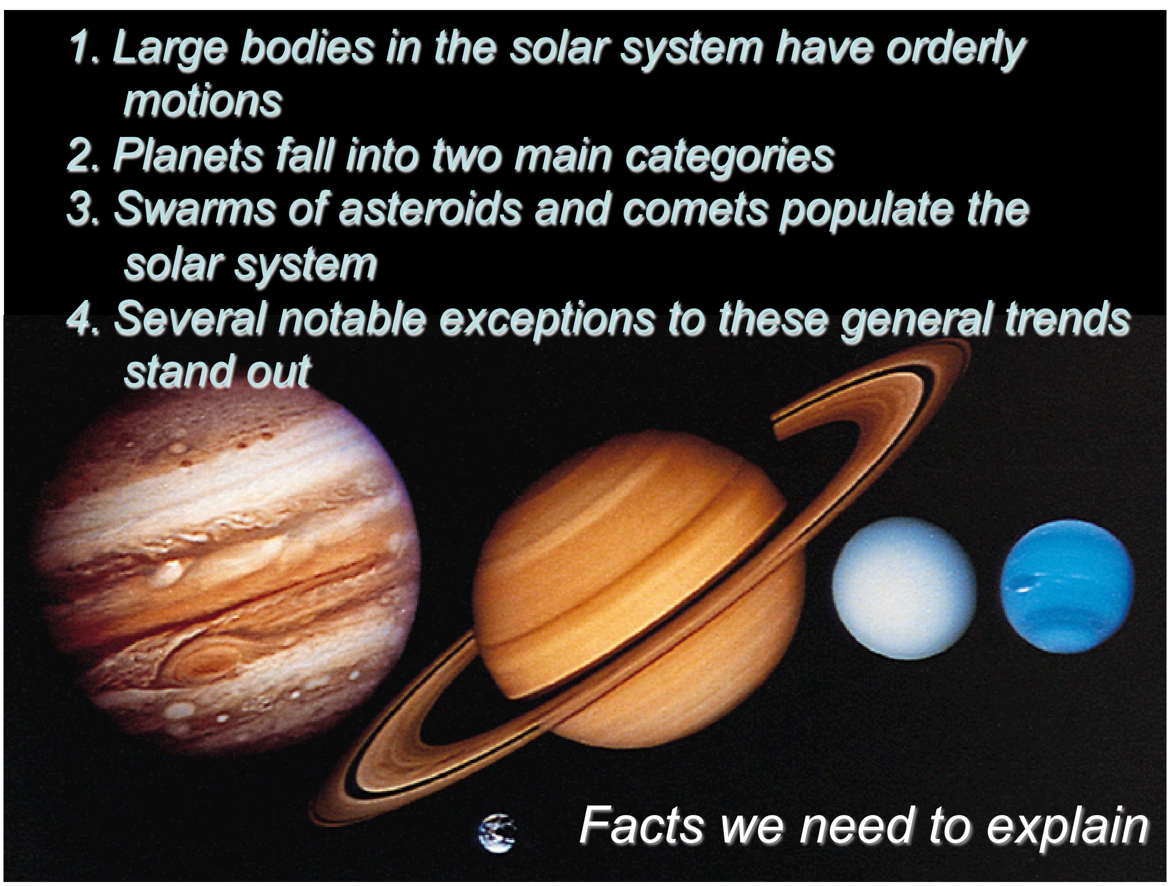
Fran Bagenal

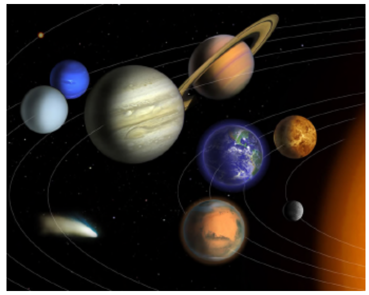


How does a solar system form from a cloud of gas?



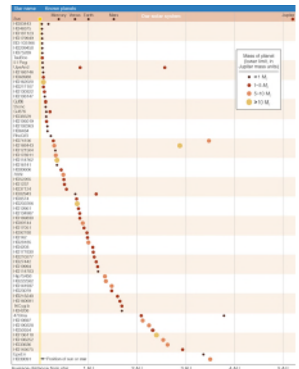
Formation: Sources of Evidence

Star-forming regions
Chemistry of source material



Our solar system

1. Patterns of motions
2. 2 types of planets
3. Asteroids and comets
4. Exceptions



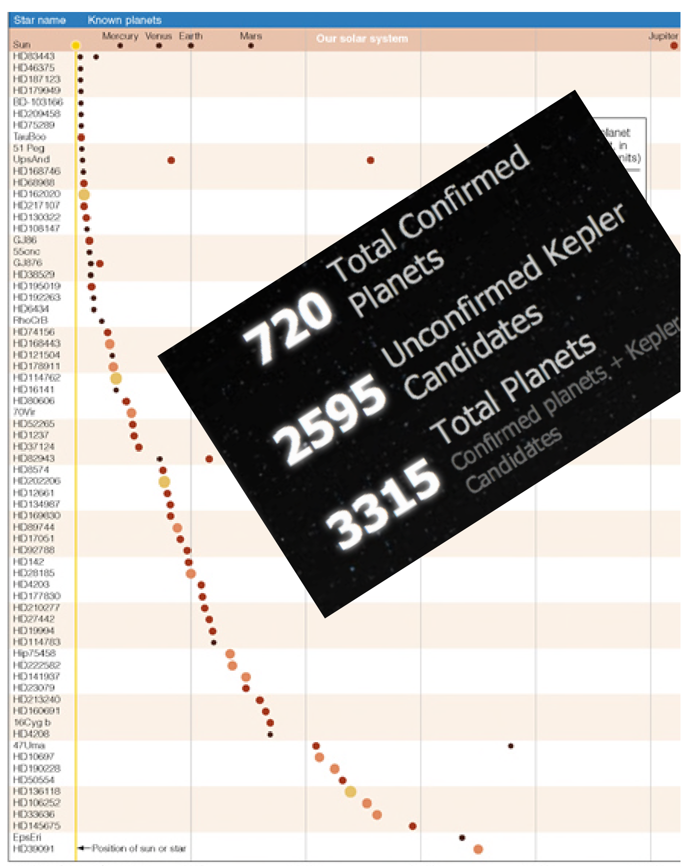
Other solar systems
Similarities and differences

Other Solar Systems

Over 1235 potential planetary systems detected - all very different from ours

- so far

http://www.youtube.com/watch?v=qRJ30fkyiU4



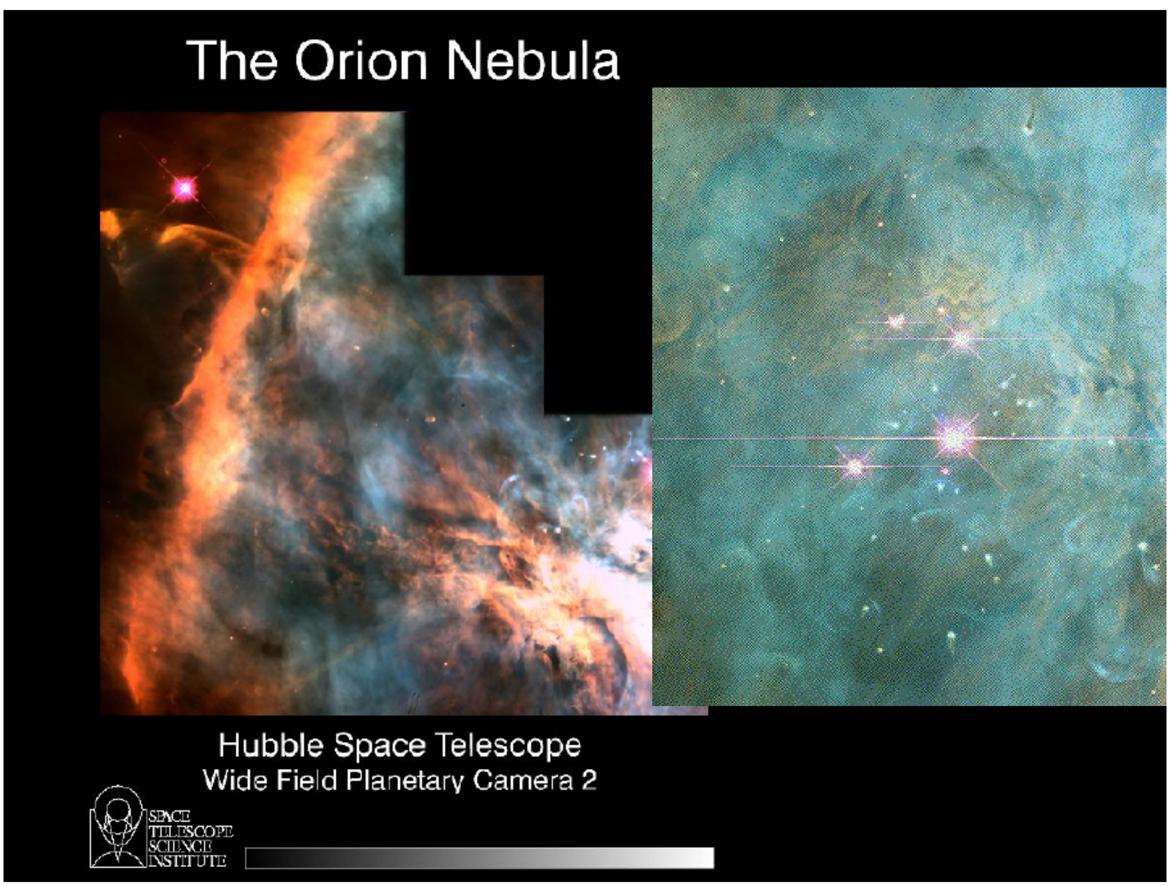
Collapse of the Solar Nebula

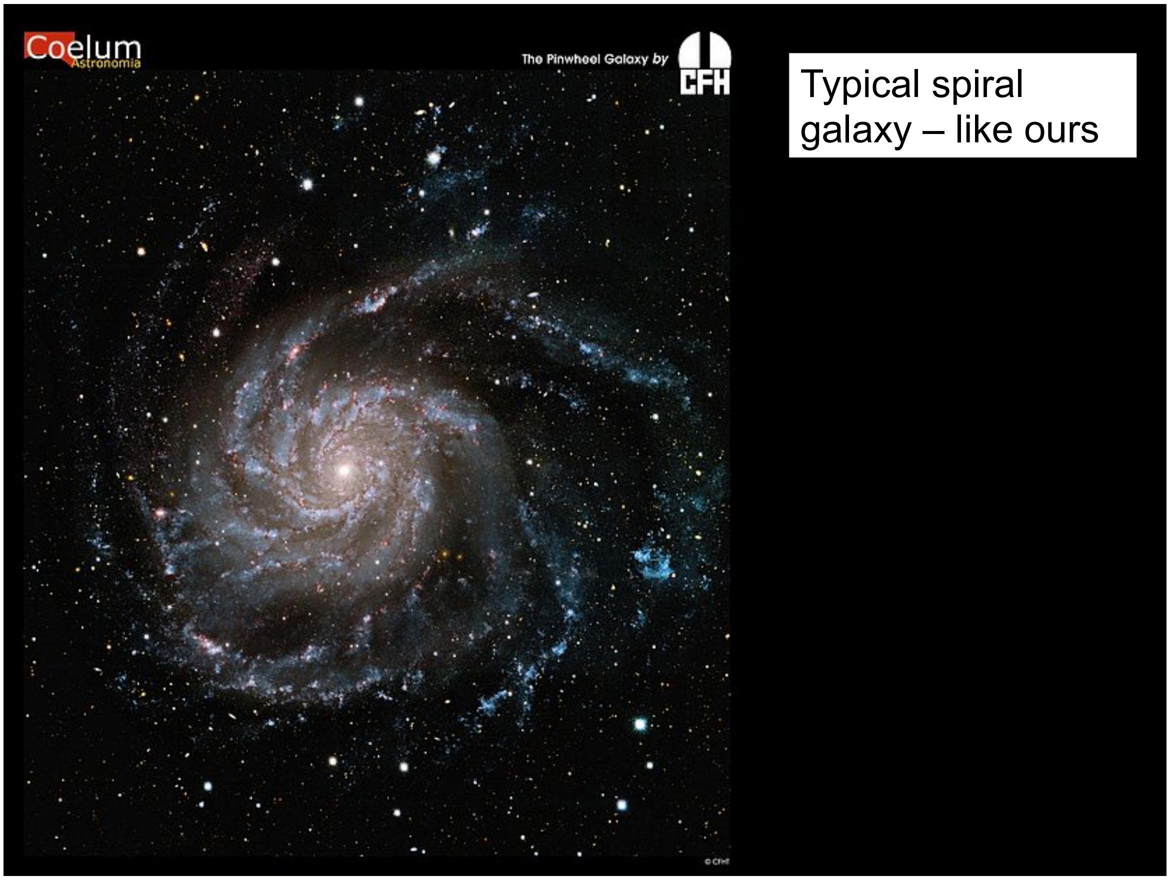
- Formation of the Sun seems a good place to start.
- Theories of star formation are based on observing millions of stars of different ages.

- Start with a **nebula** of gas and dust.
  - ***Nebula = noun = "cloud" (plural = nebulae)***
  - ***Nebular = adjective = "cloud-like"***

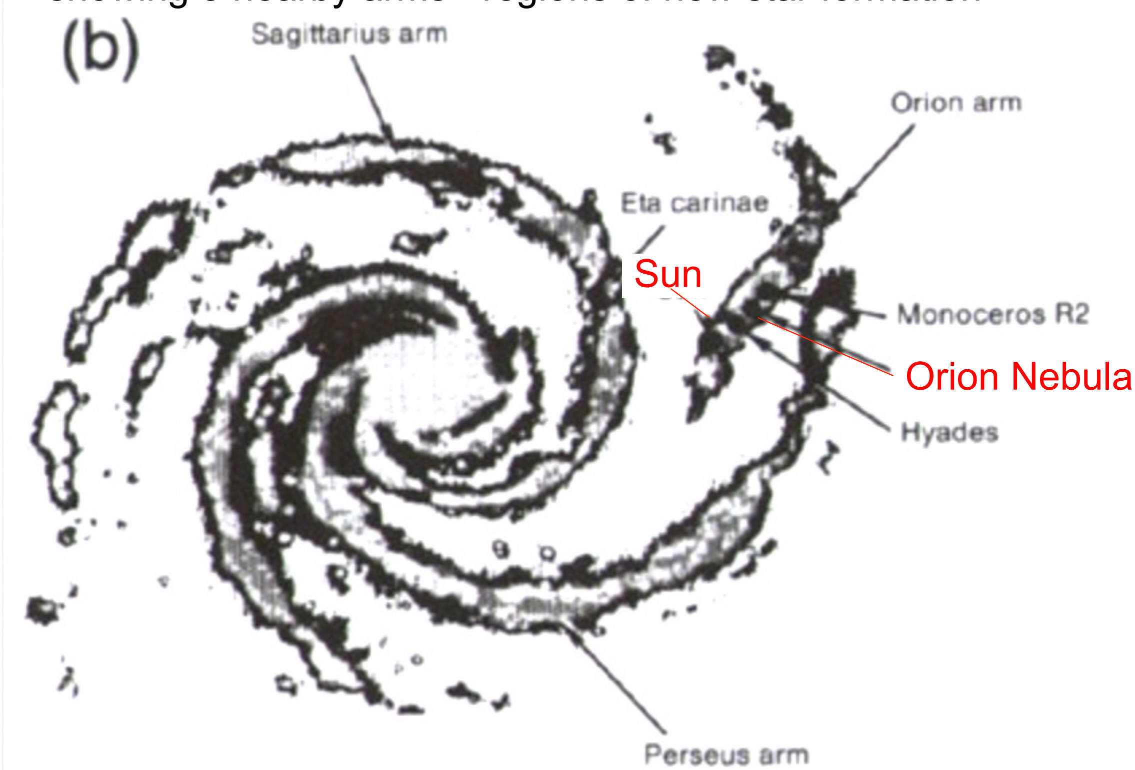
Section could have been called

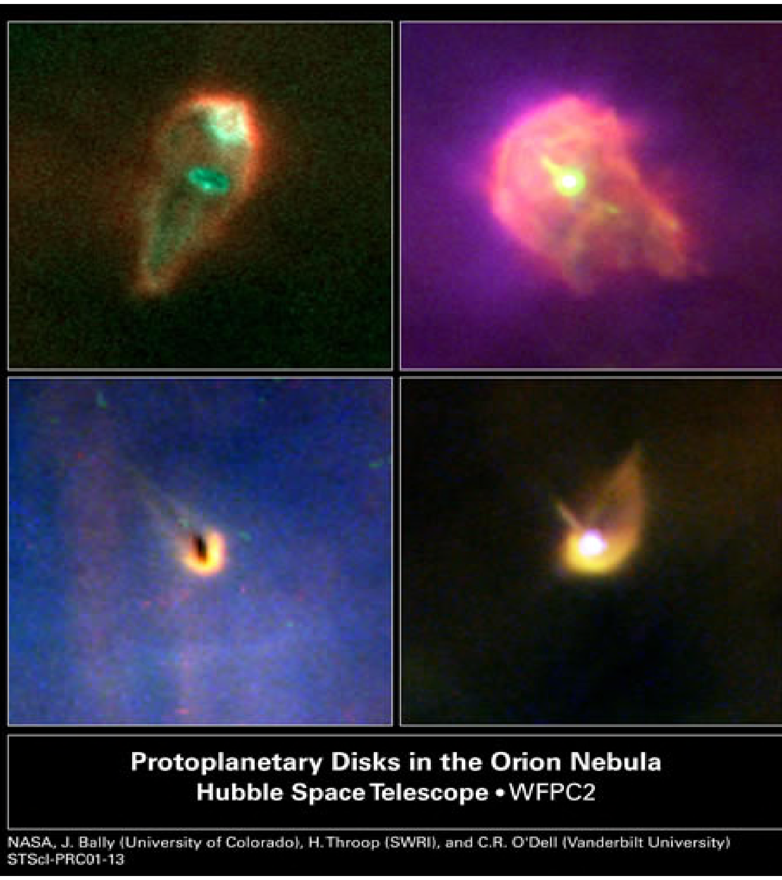
Collapse of Nebular Solar Nebula.



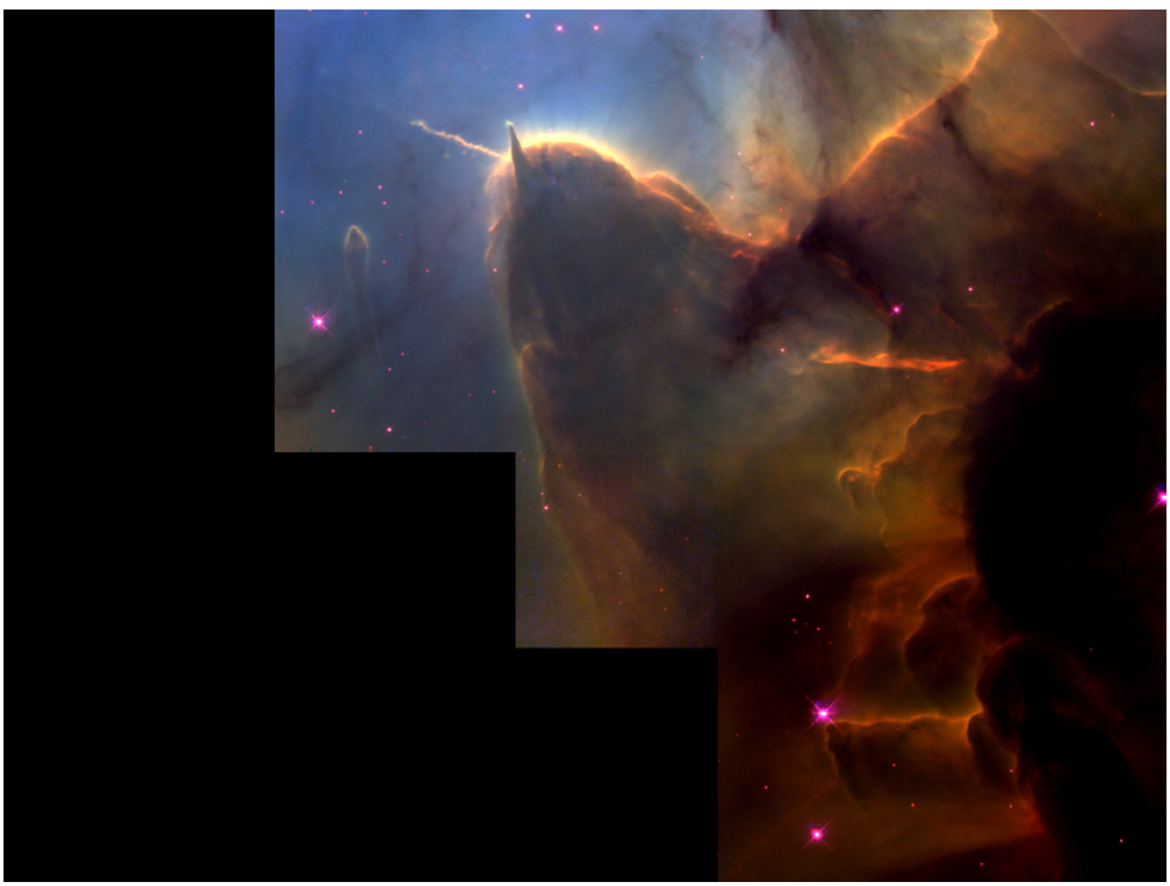


Sketch of probable structure of the **Milky Way – our galaxy**
- showing 3 nearby arms - regions of new star formation



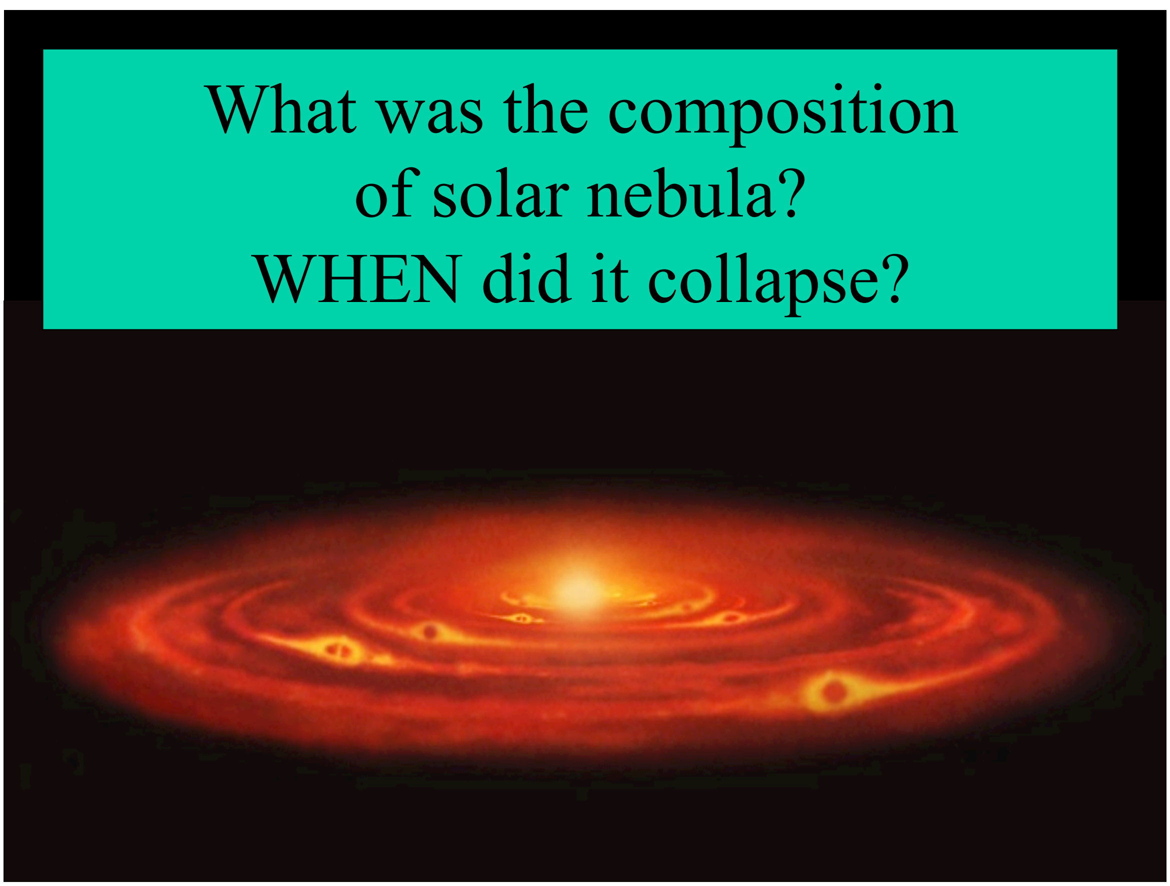


Solar systems being formed



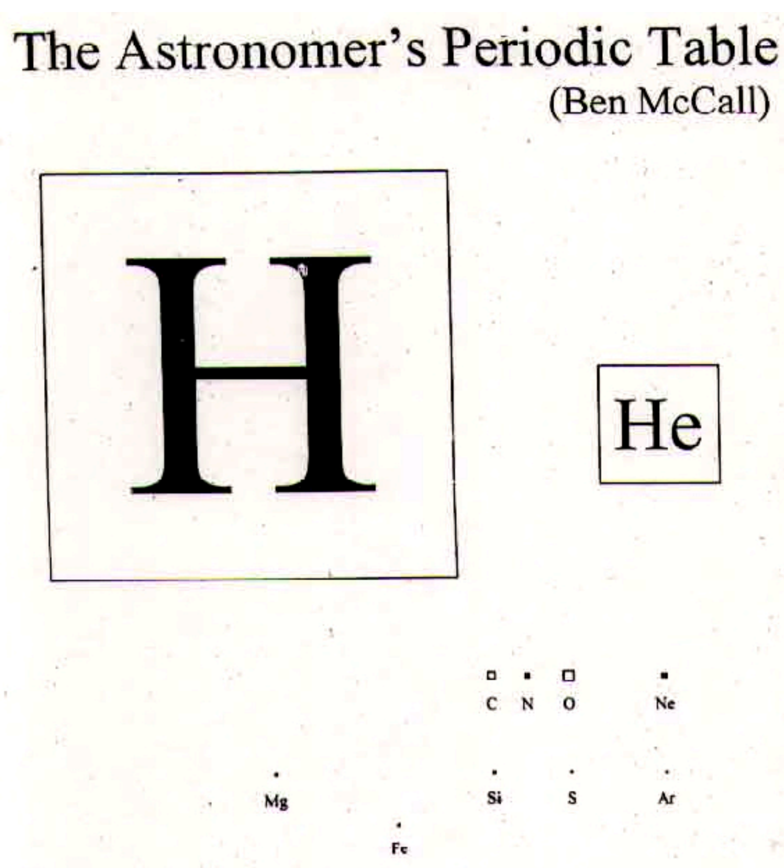
What Caused Nebula to Collapse?

A. Gravity
B. Rapid rotation
C. Magic
D. Laughter



What is the 3rd most abundant element in the Universe?

A. Iron
B. Carbon
C. Water
D. Oxygen
E. Nitrogen



- Mostly H, H and more Hydrogen
- Some Helium
- Tiny amount of other elements

Cosmic abundance of elements - in stars, universe

Element	Symbol	Atomic Number	Number of Atoms per Million Hydrogen Atoms
Hydrogen	H	1	1,000,000
Helium	He	2	68,000
Carbon	C	6	420
Nitrogen	N	7	87
Oxygen	O	8	690
Neon	Ne	10	98
Sodium	Na	11	2
Magnesium	Mg	12	40
Aluminum	Al	13	3
Silicon	Si	14	38
Sulfur	S	16	19
Argon	Ar	18	4
Calcium	Ca	20	2
Iron	Fe	26	34
Nickel	Ni	28	2

Inert
= non-reactive

Cosmic Abundances

Element	Symbol	Atomic Number	Number of Atoms per Million Hydrogen Atoms
Hydrogen	H	1	1,000,000
Helium	He	2	68,000
Carbon	C	6	420
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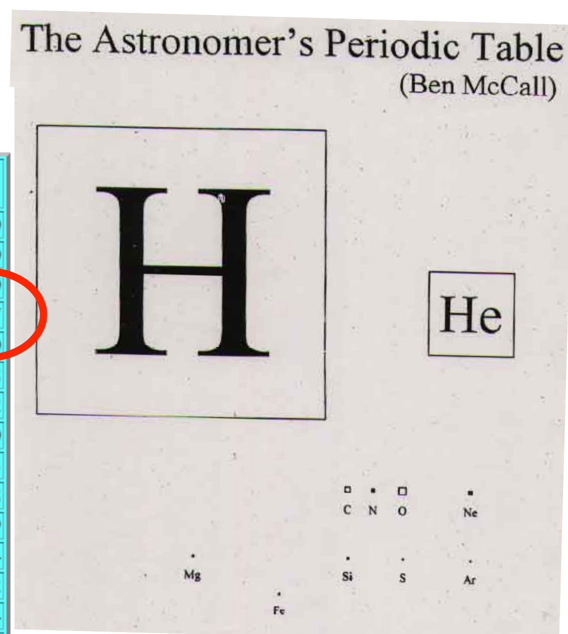
Neon	Ne	10	98
Sodium	Na	11	2
Magnesium	Mg	12	40
Aluminum	Al	13	3
Silicon	Si	14	38
Sulfur	S	16	19
Argon	Ar	18	4
Calcium	Ca	20	2
Iron	Fe	26	34
Nickel	Ni	28	2



Ignore inert gases
He, Ne, Ar

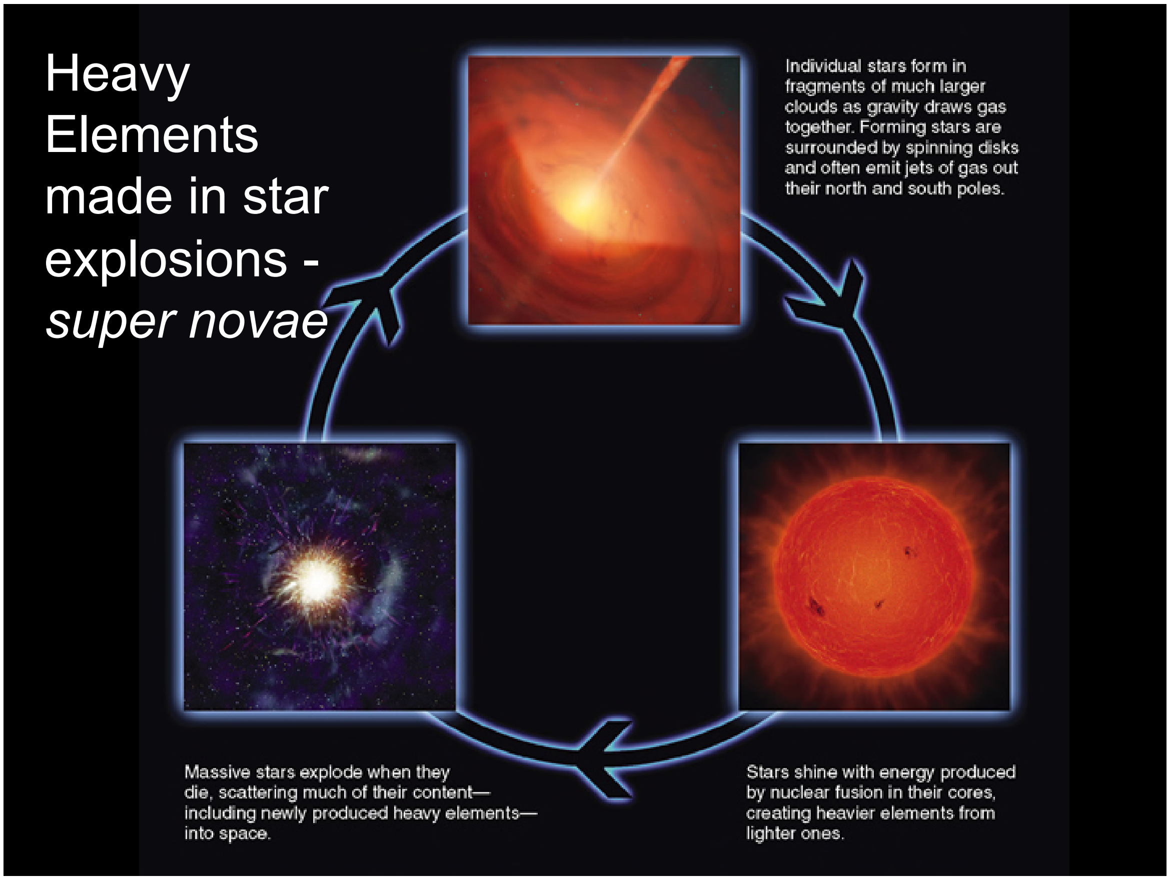
H_2O, NH_3, CH_4

Water, **A**mmonia, **M**ethane

Hydrogen compounds

WAM!

(for Nitrogen – N_2 more likely)



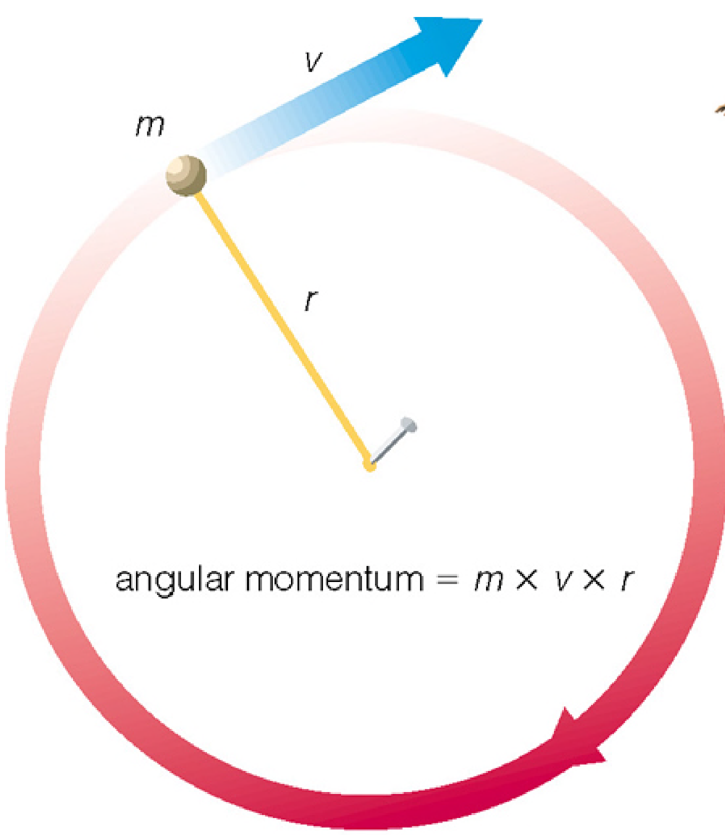
Interstellar Organic Molecules - lots of them!

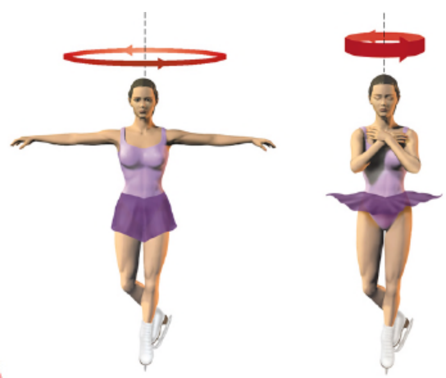
Simple Hydrides, Oxides, Sulfides, Halides, and Related Molecules				
H_2	CO	NH_3	CS	NaCl
HCl	SiO	SiH_4	SiS	AlCl
H_2O	SO_2	CC	H_2S	KCl
	OCS	CH_4	PN	AlF
Nitriles, Acetylene Derivatives, and Related Molecules				
HCN	$HC{\equiv}C{-}CN$	$H_3C{-}C{\equiv}C{-}CN$	$H_3C{-}CH_2{-}CN$	$H_2C{=}CH_2$
H_3CCN	$H(C{\equiv}C)_2{-}CN$	$H_3C{-}C{\equiv}CH$	$H_2C{=}CH{-}CN$	$HC{\equiv}CH$
CCCO	$H(C{\equiv}C)_3{-}CN$	$H_3C{-}(C{\equiv}C)_2{-}H$	HNC	
CCCS	$H(C{\equiv}C)_4{-}CN$		$HN{=}C{=}O$	
$HC{\equiv}CCHO$	$H(C{\equiv}C)_5{-}CN$		$HN{=}C{=}S$	
H_3CNC				
Aldehydes, Alcohols, Ethers, Ketones, Amides, and Related Molecules				
$H_2C{=}O$	H_3COH	$HO{-}CH{=}O$	H_2CNH	
$H_2C{=}S$	$H_3C{-}CH_2{-}OH$	$H_3C{-}O{-}CH{=}O$	H_3CNH_2	
$H_3C{-}CH{=}O$	H_3CSH	$H_3C{-}O{-}CH_3$	H_2NCN	
$NH_2{-}CH{=}O$	$(CH_3)_2CO$?	$H_2C{=}C{=}O$		
Cyclic Molecules				
C_3H_2	SiC_2	C_3H		
Ions				
CH^+	HCO^+	$HCNH^+$		
HN_2^+	$HOCO^+$	SO^+		
	HCS^+			
Radicals				
OH	C_3H	CN	HCO	C_2S
CH	C_4H	C_3N	NO	NS
C_2H	C_5H	H_2CCN	SO	
	C_6H			

C H O N...

Collapse of the Solar Nebula

- Spins up
- Forms a disk
- Heats up





Conservation of Angular Momentum

MVR = Constant

Where did the angular momentum come from???

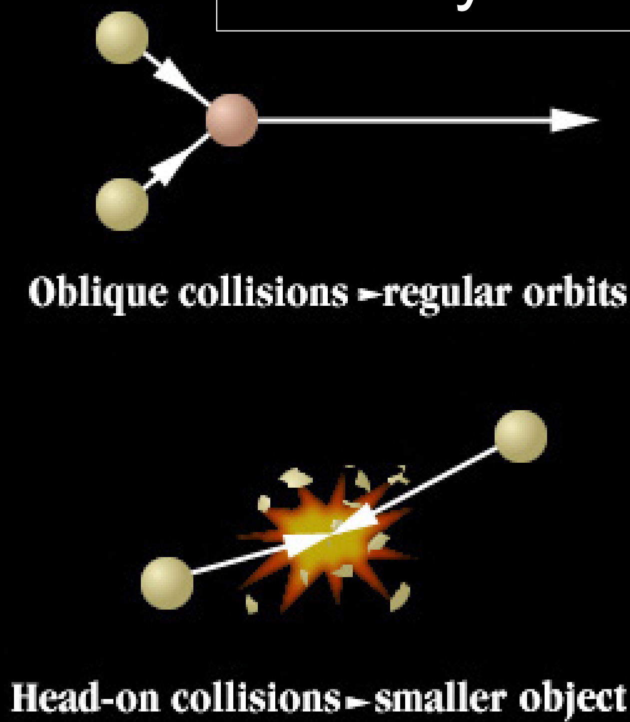
Small random motions averaging out to a tiny bulk motion

- this bulk motion is then “amplified” (due to conservation of angular momentum) as the cloud collapses

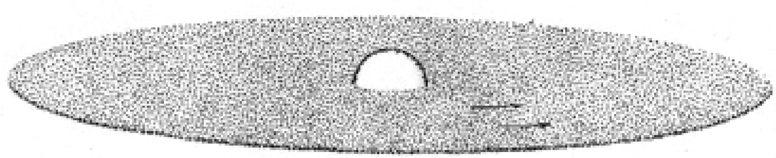
Collapse of the Solar Nebula

Why a disk?

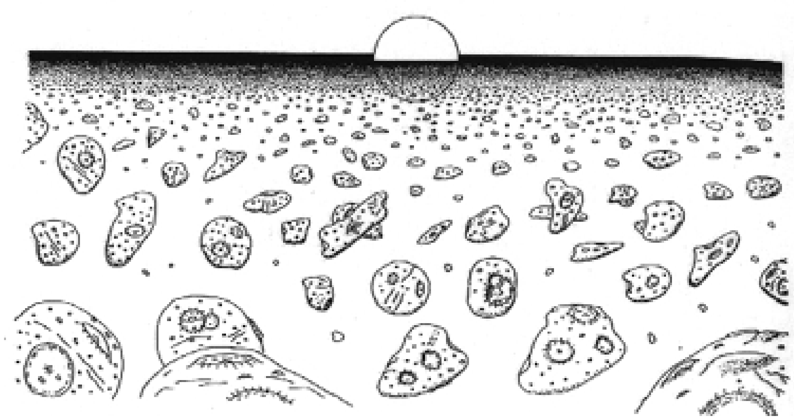
Why a Disk?

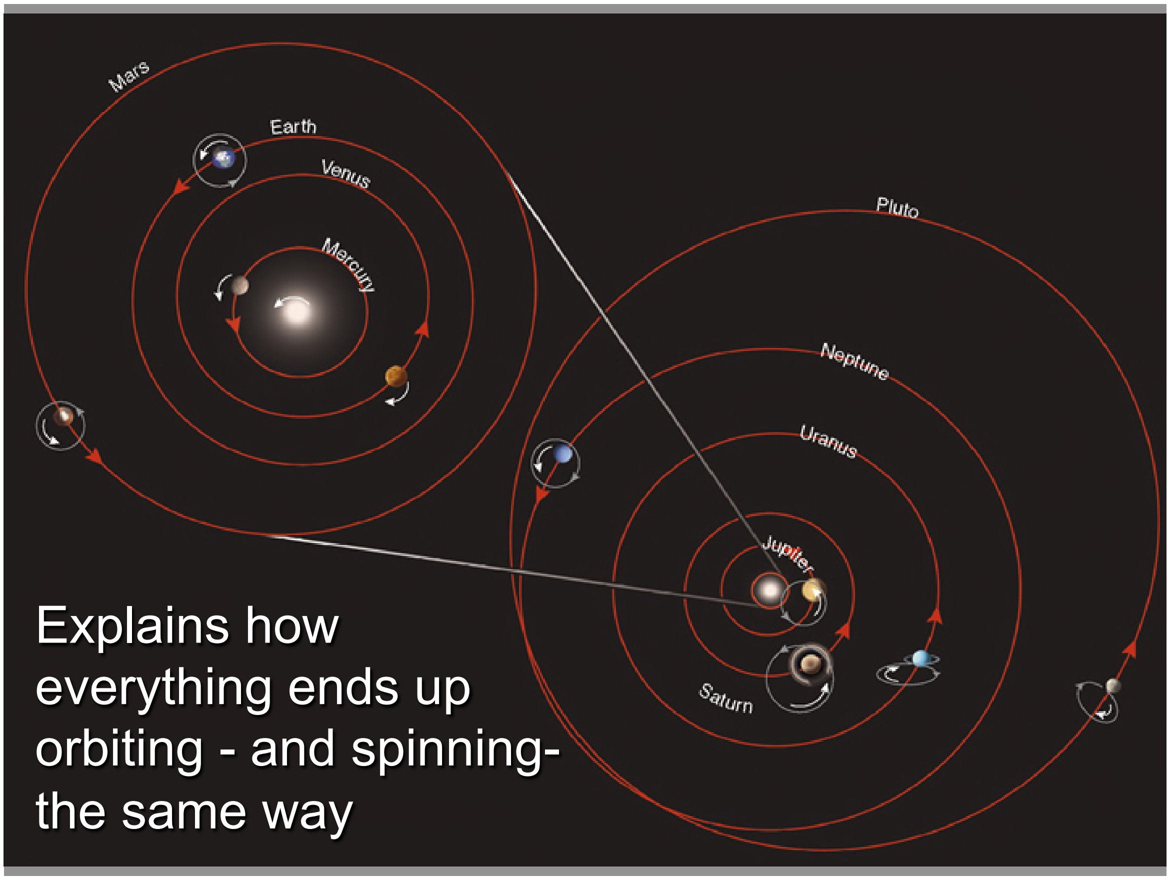


As the cloud collapses (due to gravity) the gases, dust and stuff orbit the central mass -
On the timescale of an orbit gravity still balances the centrifugal force - the disk is not formed by being “flung out into a disk”. Nor does gravity “pull the material into a disk”. These are common misconceptions.



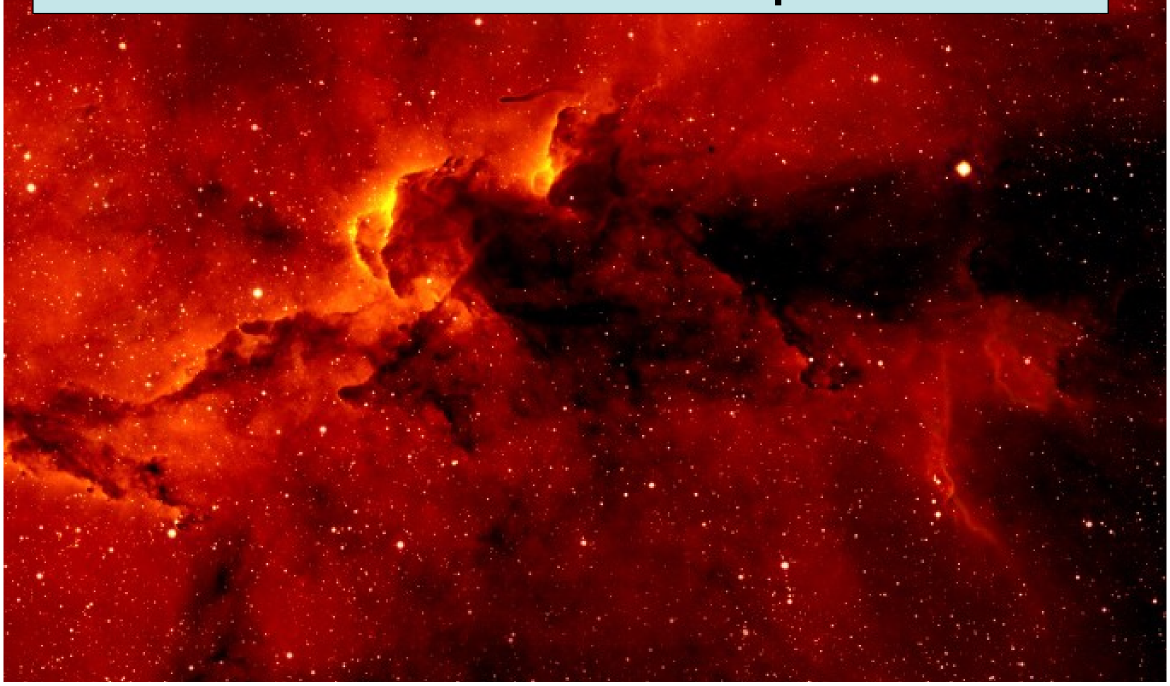
Go with the flow or crash to oblivion - Extreme Conformism!





Explains how everything ends up orbiting - and spinning- the same way

WHEN did the solar nebula collapse?

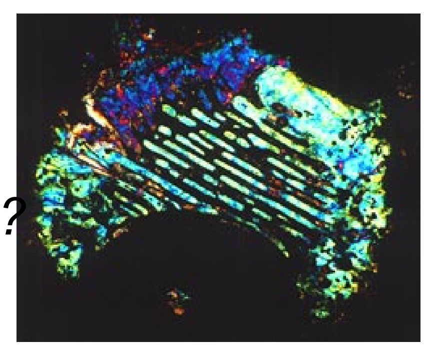


The Age of Our Solar System

A. ~4,500 years
B. ~4.5 million years
C. ~450 million years
D. ~4.5 billion years
E. ~450 billion years

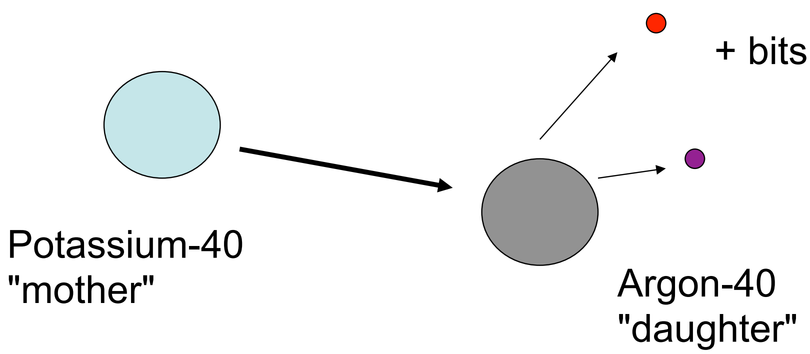
Oldest Meteorite

Allende - fell to Earth near Chihuahua, Mexico at 1:05am on February 8, 1969.
Age: 4.5 BY old

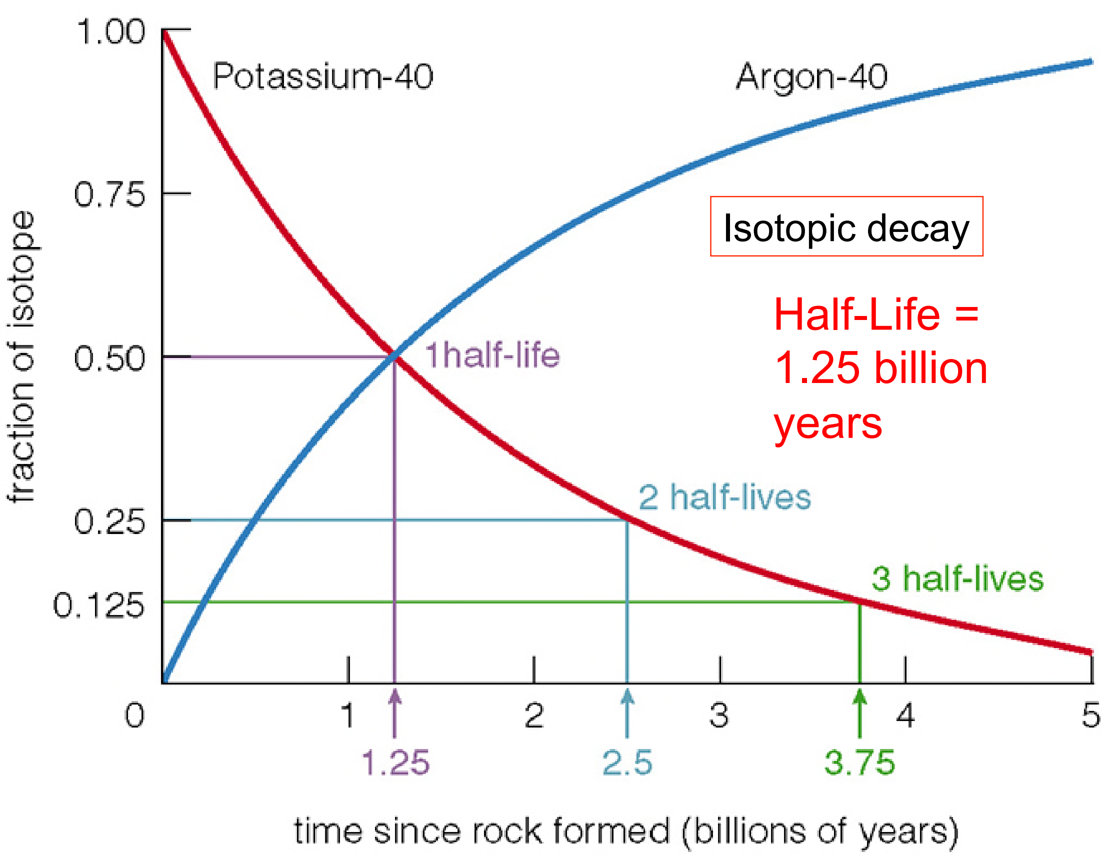


How do we know it's that old?

Fission of atomic nucleus

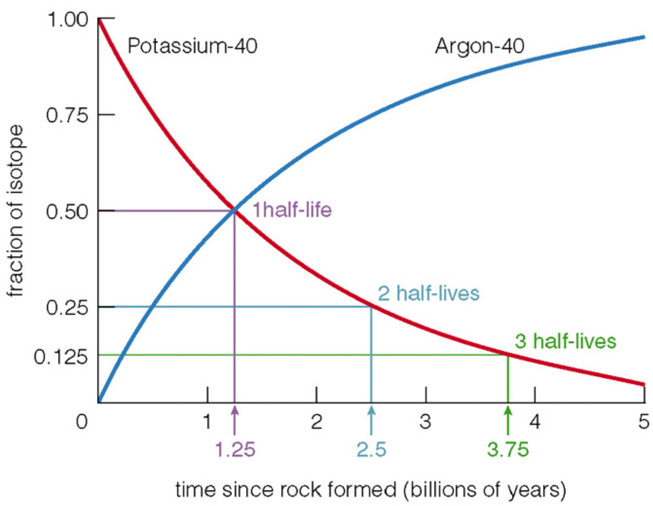


Probability of "splitting up":
Expect half the material to decay in 1.25 billion years
Half-Life = 1.25 billion years



How do we date rocks?!

Measure the ratio: $\dfrac{\text{Mother Isotope}}{\text{Daughter Isotope}}$

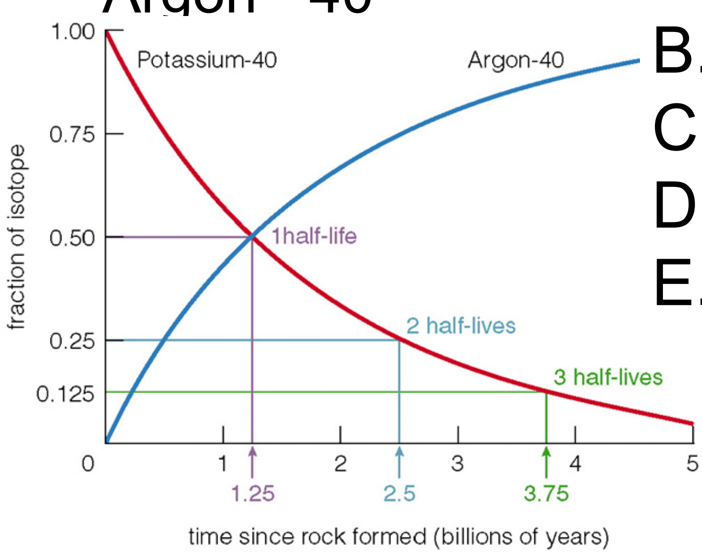


$\dfrac{\text{Potassium - 40}}{\text{Argon - 40}}$

Half-Life = 1.25 billion years

We measure a ratio of 0.25 - what age is the rock?

$\dfrac{\text{Potassium - 40}}{\text{Argon - 40}}$



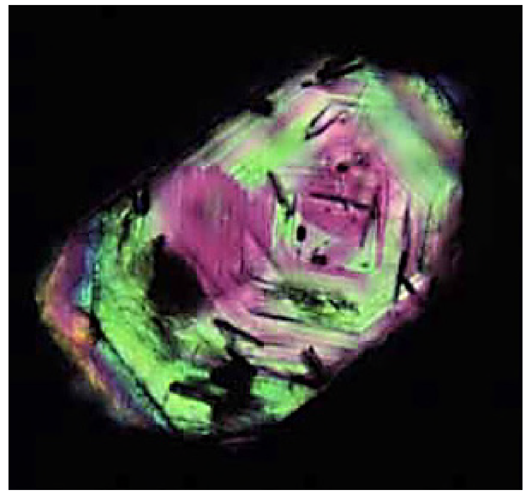
A. 0.25 billion yrs
B. 0.65 billion yrs
C. 1.25 billion yrs
D. 2.50 billion yrs
E. 3.75 billion yrs

Half-Life = 1.25 billion years

- Mineral grains (zircon)
- Uranium/Lead (U/Pb) ratios suggest
- age ~4.4 billion years
- sedimentary rocks in west-central Australia.

4.4 Billion Years Old

Oldest Earth Rocks



Oldest Solar System Rocks

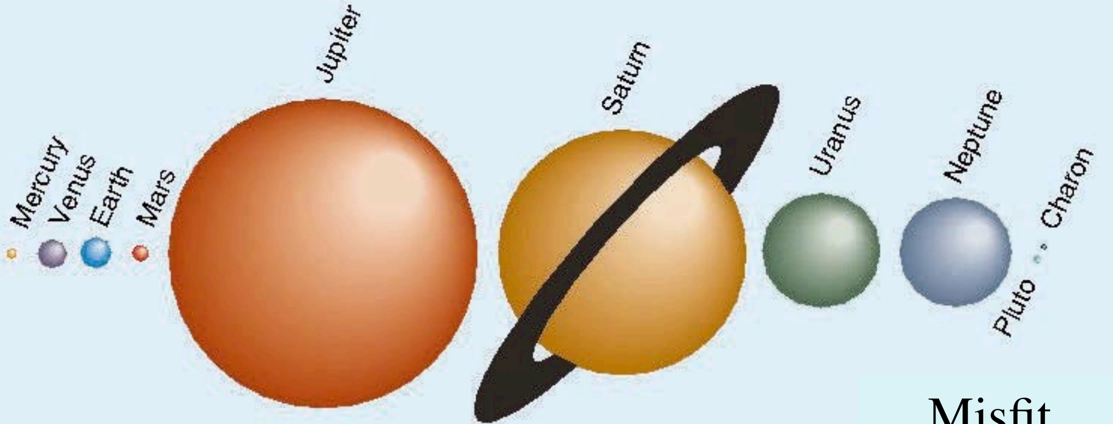
- The oldest dated **moon rocks**, however, have ages between **4.4 - 4.5 billion years** and provide a minimum age for the formation of Moon

- **Meteorites** – closest to Solar System formation - 4.53 and 4.58 billion years ago

4.54 BY to <1% accuracy

- http://pubs.usgs.gov/gip/geotime/radiometric.html#table

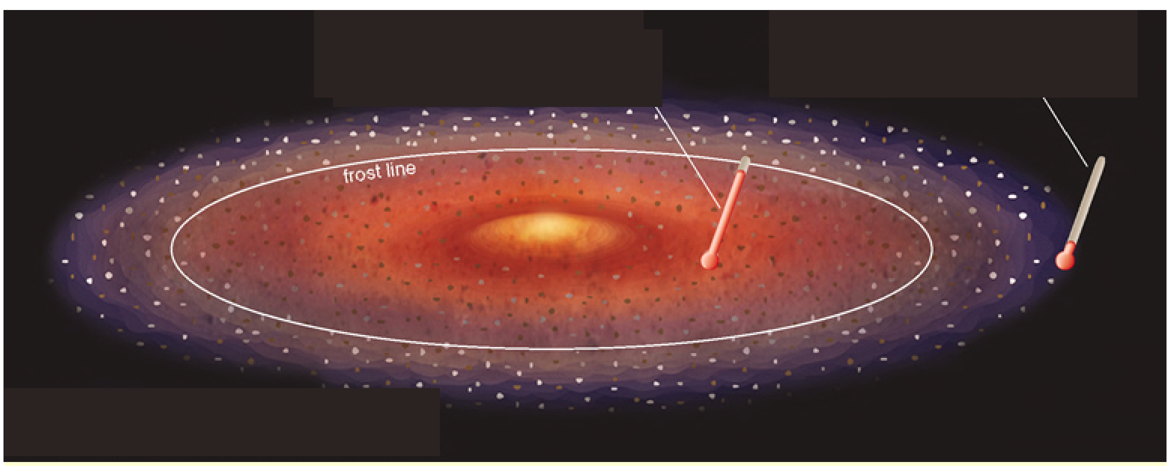
Why Only 2 Types of Planets?



Small Inner Rocky Planets

Giant Outer Gas Planets

Misfit Planets - Ice Dwarves

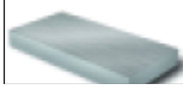


Which materials will condense in the innermost part of the disk?

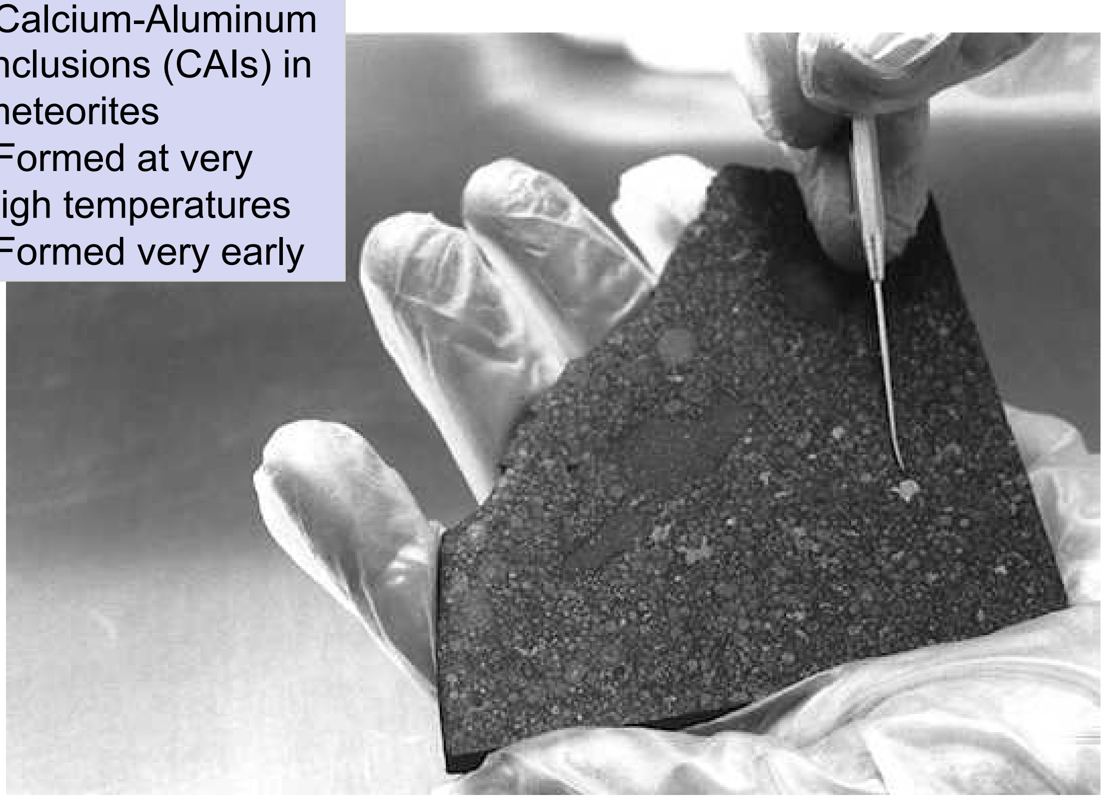
A. Hydrogen and helium - they are so abundant
B. Water, Ammonia and Methane - they are big, heavy molecules
C. Rocks and metals - they condense at high temperatures

***Refractory* =** melts/ evaporates at higher temperatures, tends to be a solid at reasonable temperatures

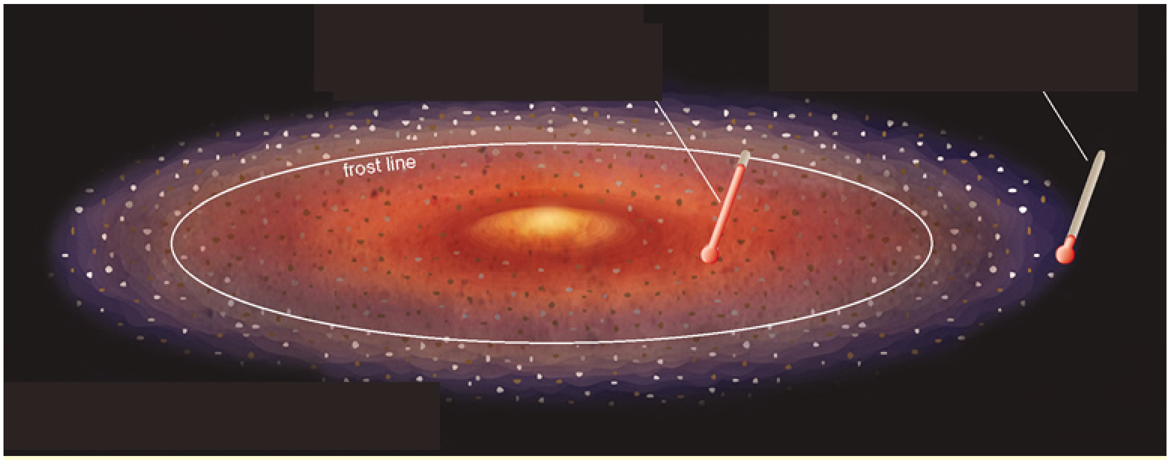
***Volatile* =** melts/ evaporates at lower temperatures, tends to be a gas at reasonable temperatures

	Examples	*Typical Condensation Temperature*	*Relative Abundance (by mass)*
Hydrogen and Helium Gas 	hydrogen, helium	do not condense in nebula	98%
Hydrogen Compounds 	water (H_2O) methane (CH_4) ammonia (NH_3)	<150 K	1.4%
Rock 	various minerals	500–1,300 K	0.4%
Metals 	iron, nickel, aluminum	1,000–1,600 K	0.2%

- Calcium-Aluminum Inclusions (CAIs) in meteorites
- Formed at very high temperatures
- Formed very early

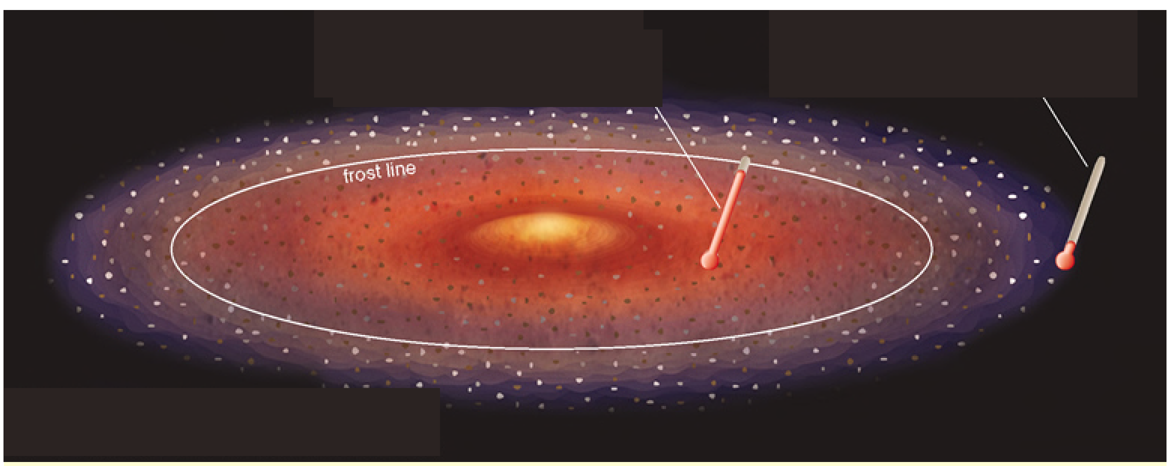


Allende meteorite – fell in Mexico in 1969



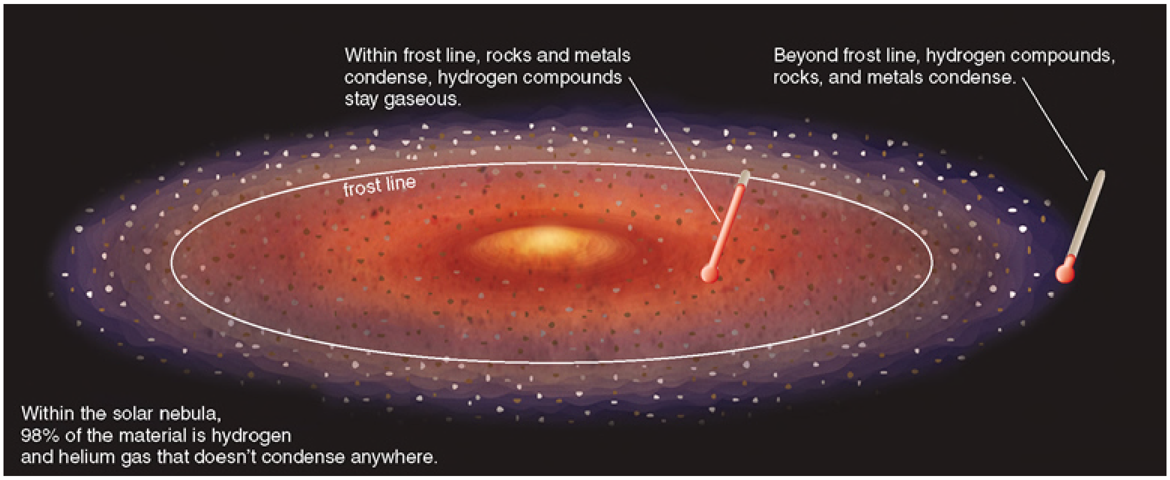
Where do Water, Ammonia and Methane condense?

A. Throughout the solar nebula as it cools
B. The inner region of the solar nebula
C. The outer region of the solar nebula
D. They do not condense anywhere in the solar nebula

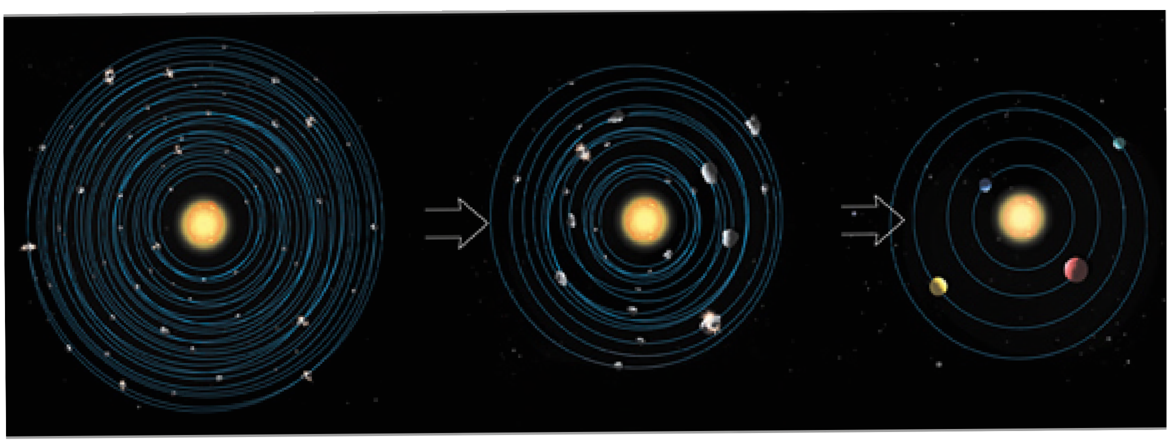


Where do Hydrogen & Helium condense?

A. Throughout the solar nebula as it cools
B. Only in the inner region of the solar nebula
C. Only in the outer region of the solar nebula
D. They do not condense anywhere in the solar nebula



• 98% of material - hydrogen & helium - does not condense - anywhere - stay as gases.
• Inside frostline only refractory materials condense - rocks & metals
• Outside frostline volatiles also condense - WAM - AND rocks & metals too.



Accretion of Planetesimals

- Many smaller objects collected into just a few large ones
- The bigger get bigger - *Oligarchic growth*

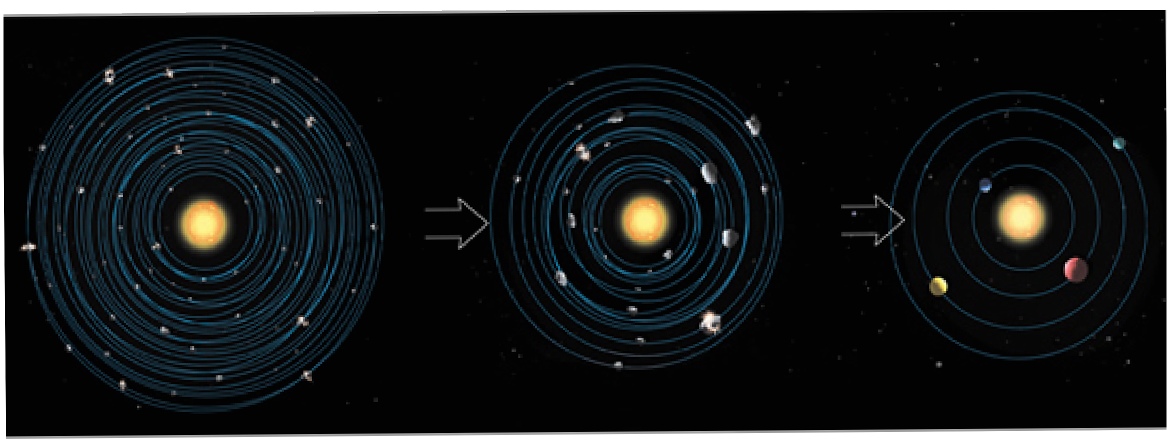
Hyperion

- Moon of Saturn
- Size: 180 x 140 x 112 km

Typical planetestimal??

Core material for giant planet?

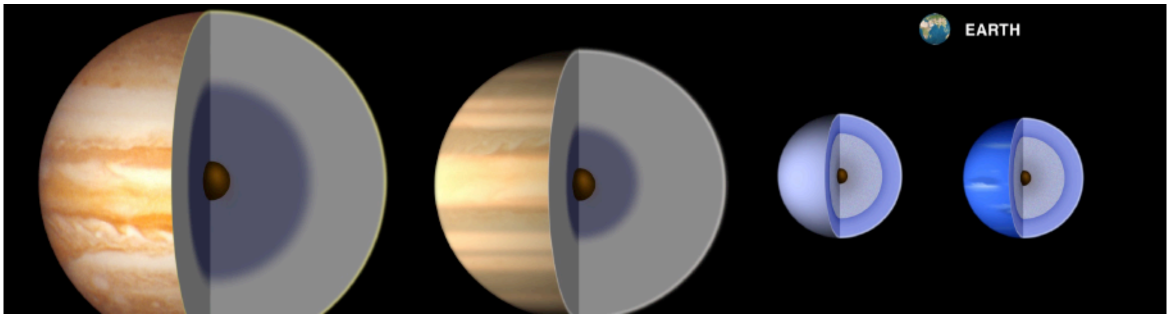
http://ciclops.org/view_event.php?id=37
http://saturn.jpl.nasa.gov



Accretion of Planetesimals

- Many smaller objects collected into just a few large ones
- REALLY big planetesimals (~20 Mearth) gravitationally pull in hydrogen - the most abundant gas - and become GIANT.

The Giant Planets



Hydrogen envelopes over cores of rock, metals and **W**ater, **A**mmonia, **M**ethane

- ***WAM!***

Why Only 2 Types of Planets?

1. Cosmic Abundance of Elements - H, O, N, C
2. Temperature Colder Farther from Sun
   - Abundance ices condense beyond frost line
   - Snowballs -> bigger snowballs
   - Giant snowballs have enough gravity to hold H - most abundant element - > giant planets
   - Small amounts of rock & metal-> terrestrial planets
   - Ice dwarfs, comets, asteroids = leftovers

Issues addressed:

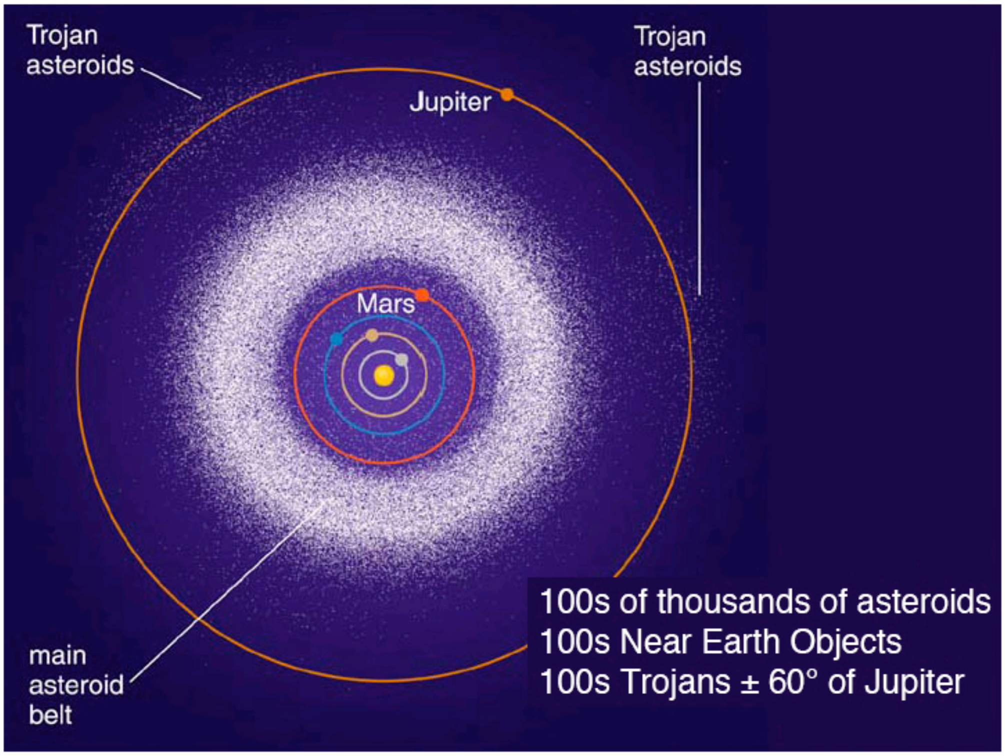
1. Angular momentum distribution
2. Orderly motion of planetary spins and orbits
3. 2 types of planets - small, rocky inner planets vs. giant gas outer planets

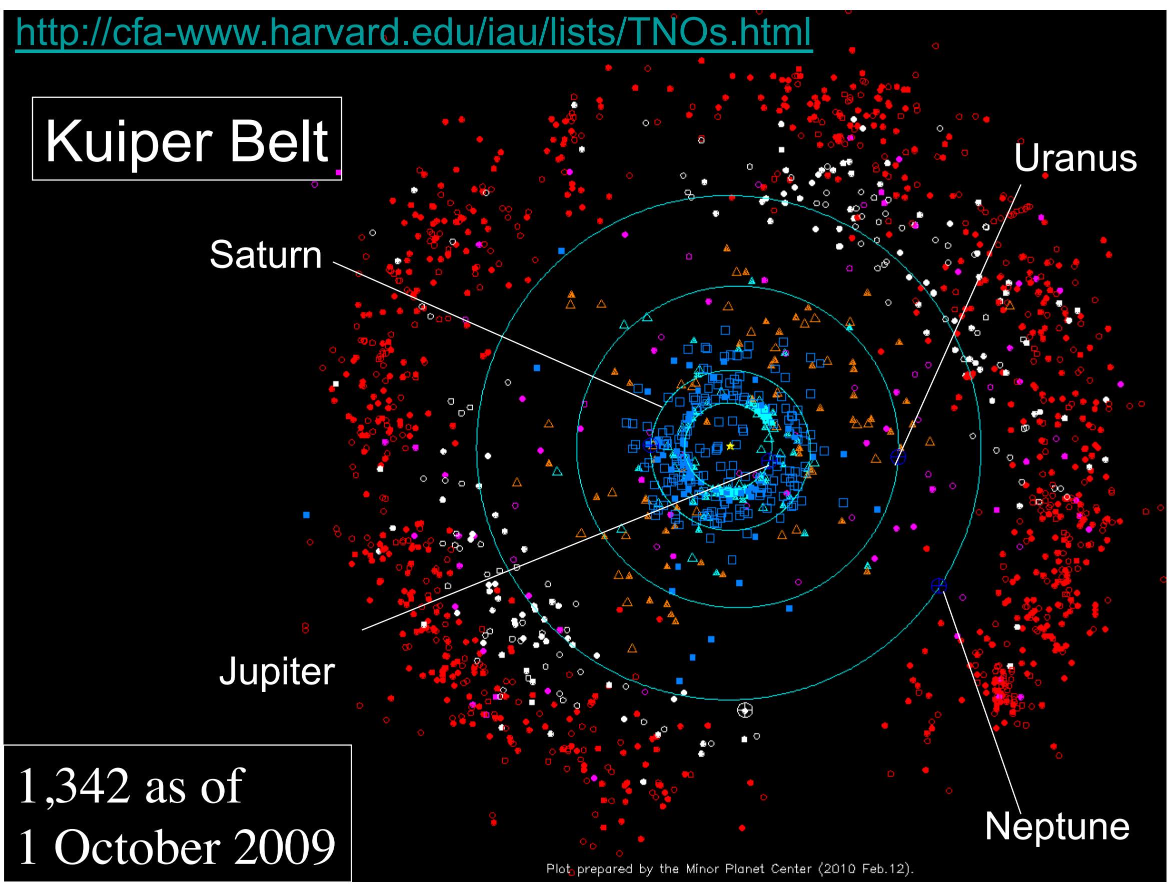
But there's still (a) gas and (b) junk between planets

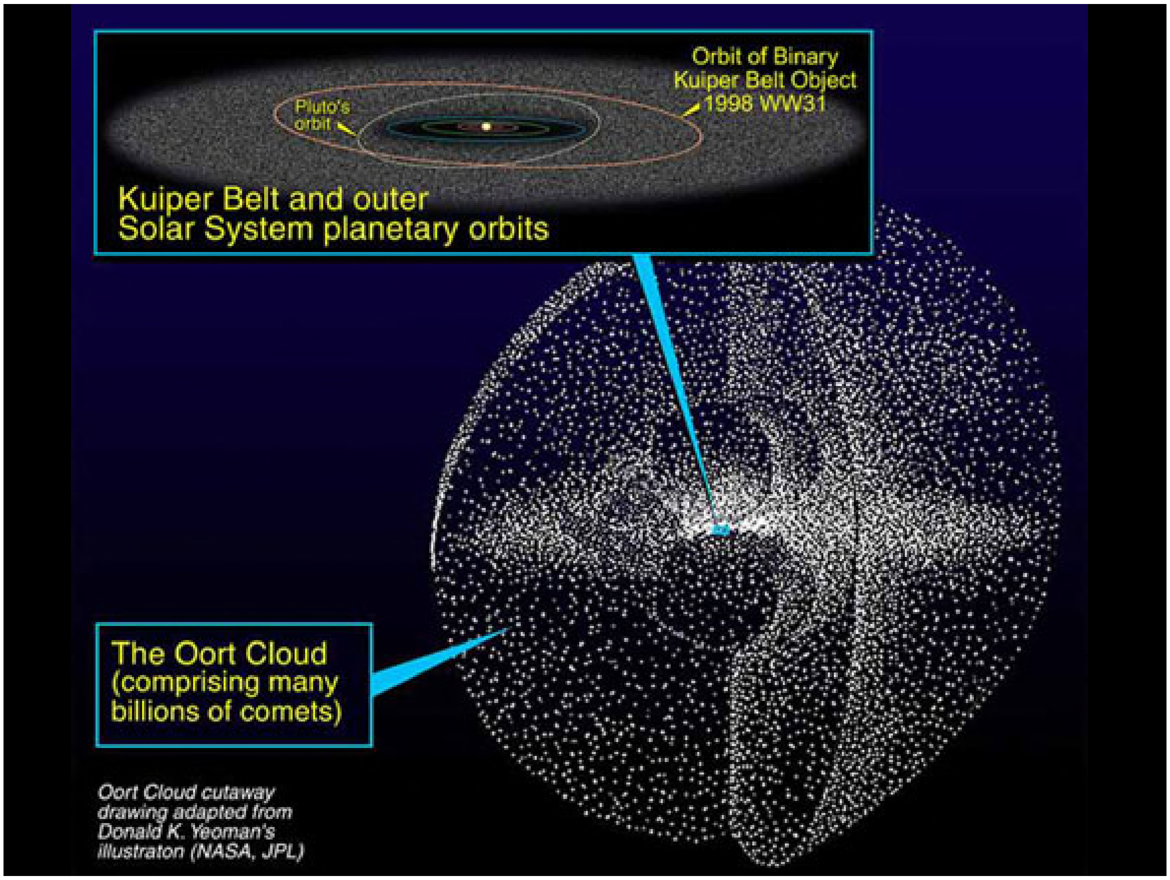
What happens to the junk?

- Gets kicked about - mostly by JSUN
- Kicked out of solar system - Oort Cloud
- Herded - asteroid belt, Kuiper Belt
- Captured as moons
- Bashed into young planets -> Moon, Charon, others?

3 swarms of small bodies: Asteroid Belt, Kuiper Belt, Oort Cloud of comets


Trojan asteroids
Trojan asteroids
Jupiter
Mars
main asteroid belt
100s of thousands of asteroids
100s Near Earth Objects
100s Trojans ± 60° of Jupiter


http://cfa-www.harvard.edu/iau/lists/TNOs.html
Kuiper Belt
Uranus
Saturn
Jupiter
Neptune
1,342 as of
1 October 2009
Plot prepared by the Minor Planet Center (2010 Feb.12).



What's the main reason there are two types of planet (TP vs JP)?

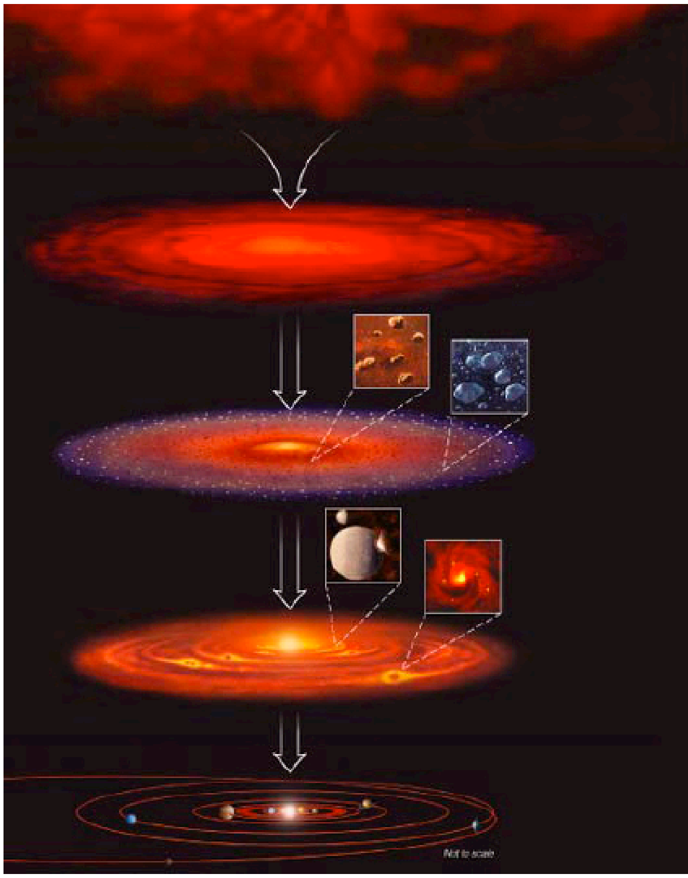
A. Denser particles were drawn closer to the Sun by the Sun's strong gravity where they could form TP's

B. Volatile materials (ice) condensed at lower temperatures of the outer solar nebula, & attract more gas

C. The solar wind pushed lower-density materials into the outer solar system where they formed JP's

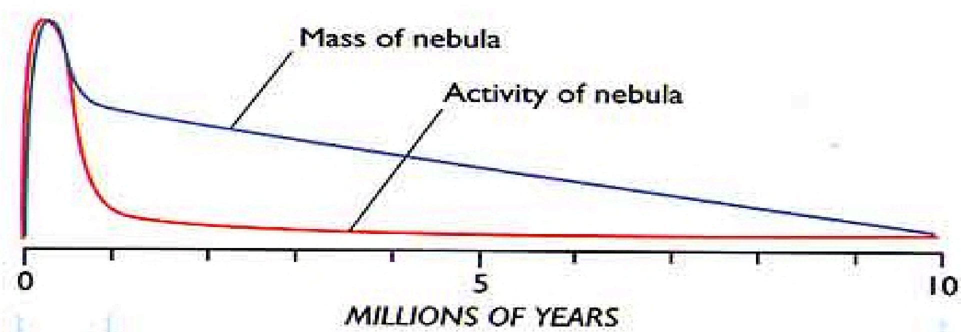
D. Planets of different density formed throughout the solar system, but denser planets fell inwards

E. The solar nebula never had much hydrogen & helium or hydrogen compounds in any form in the inner solar system



Summary of Solar System Formation
Fig 8.13

How long does this whole solar system formation process take?



- Nebula collapse <1 MY
- planetesimal formation in 1MY
- Jupiter, Saturn form < 2 MY
- Terrestrial planets <4 MY
- Uranus & Neptune?
  - •Motions are slow in the outer solar system
  - •Accretion is very slow….

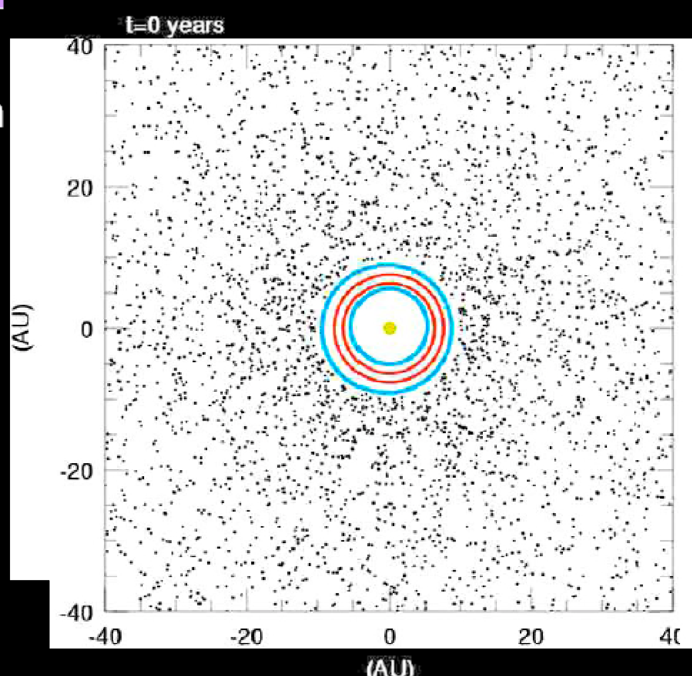
- Nebula collapse <1 Million Years - *fast!!*
- Planetesimal formation < 1MY
- Jupiter, Saturn <2 MY
- Terrestrial Planets <4 MY
- Uranus & Neptune??
  - Accretion is SLOW in the outer solar system
    - Less material
    - Material orbits the sun slowly
    - Few collisions, slower accretion

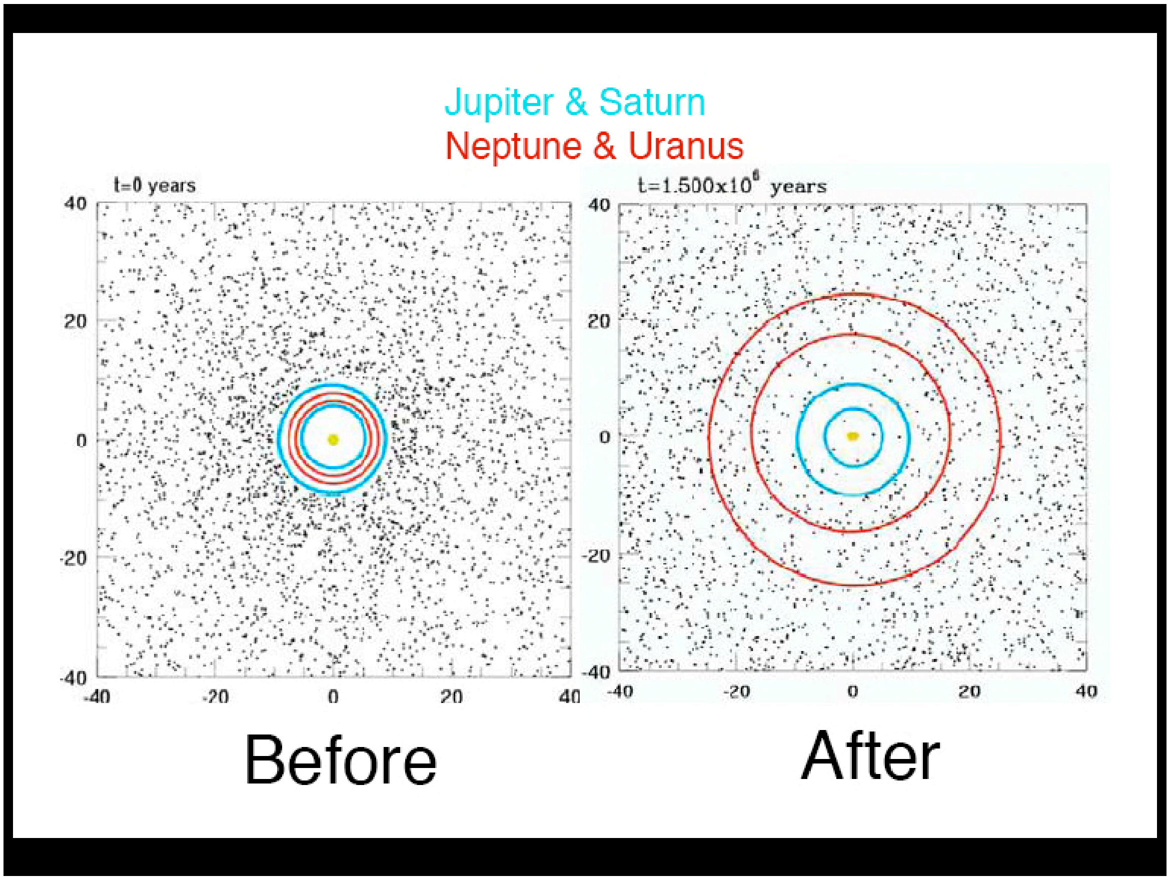
Too slow for Uranus & Neptune to have formed in their current locations

But it's not so simple…

- Hard to make U & N at presen orbits
- Where did Earth's oceans come from?
- How to make Kuiper Belt?

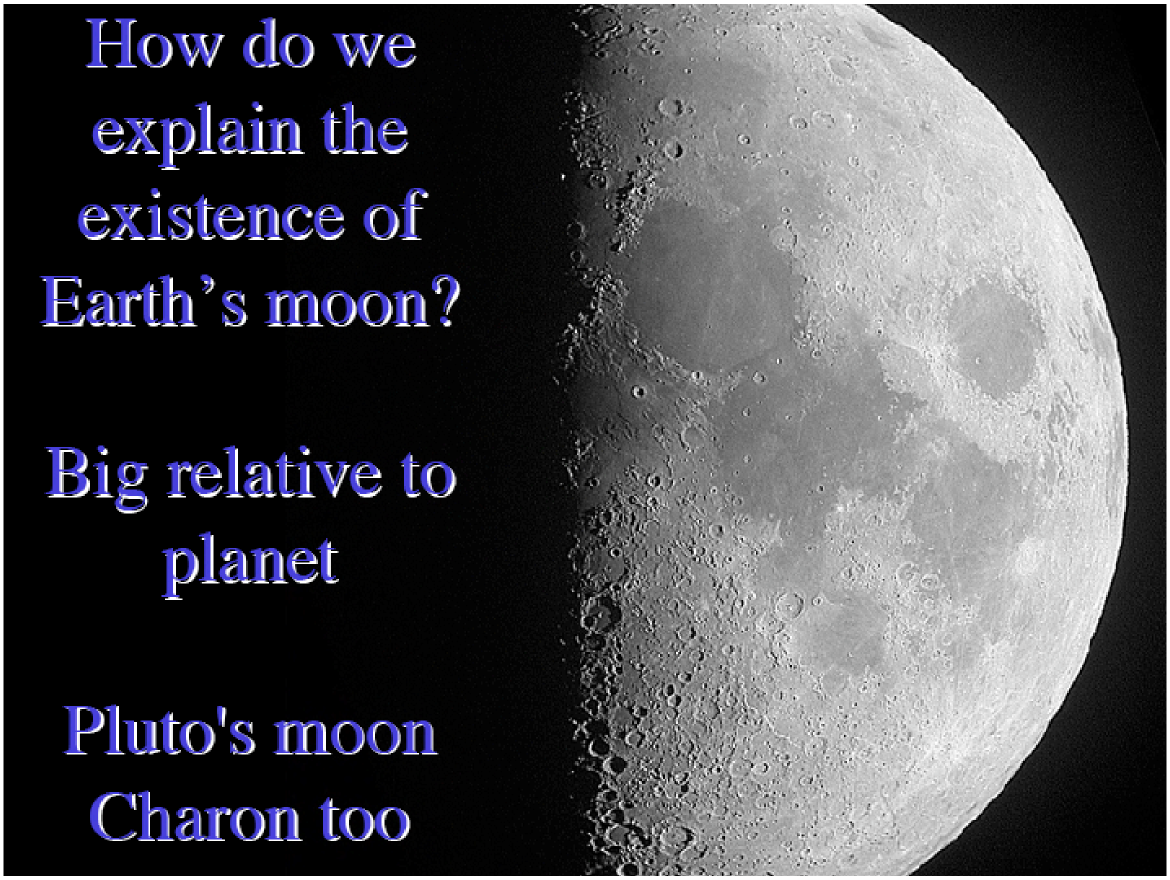
=> Migration?





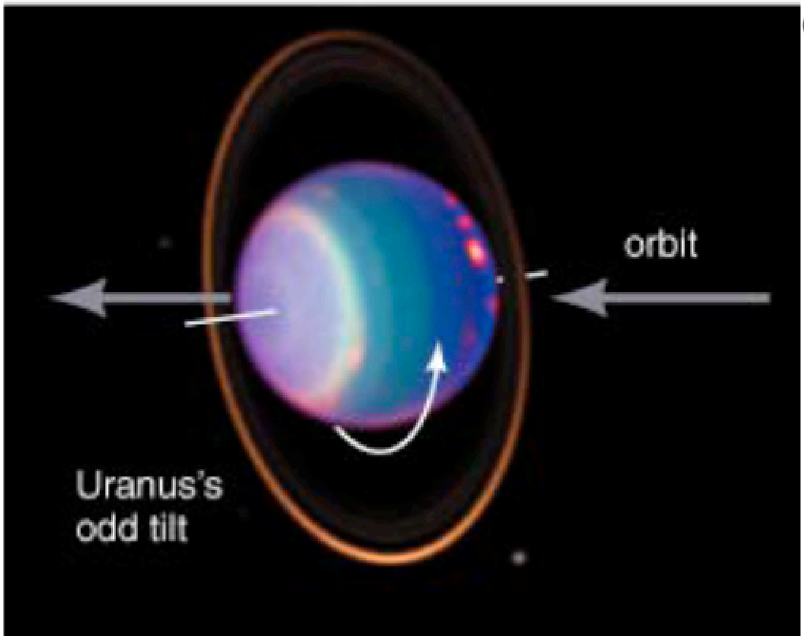
Issues addressed:

1. Angular momentum distribution
2. Orderly motion
3. 2 types of planets
4. Time scale of formation
5. Asteroids, comets, Kuiper Belt
6. How Earth got oceans
7. Anomalies? Uranus tipped on side?
   Formation of Moon & Charon?
   Collisions can explain anything!



Formation of Moon by Giant Impact

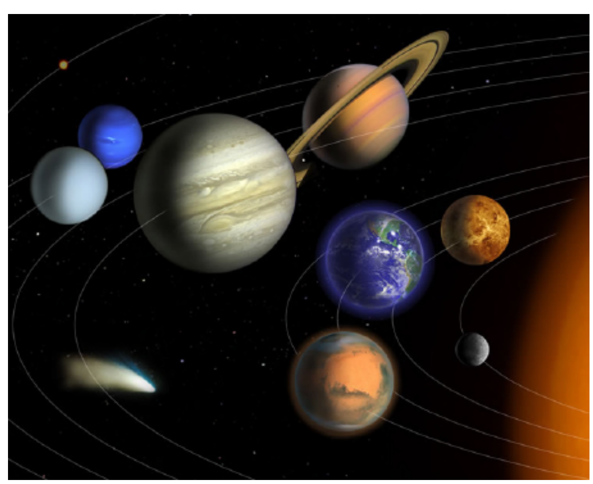
Odd Rotation



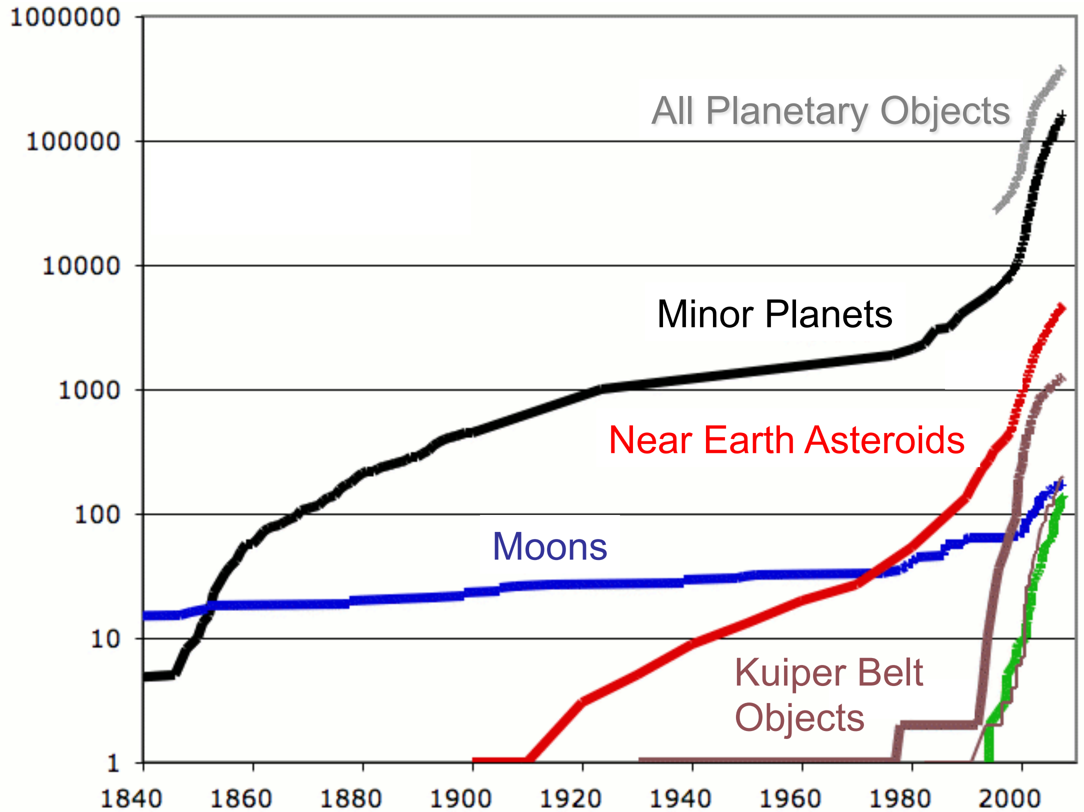
Giant impacts might also explain the different rotation axes of some planets

How Many Planets Are There?

A. Probably thousands
B. Definition is scientifically meaningless
C. 10 - so far, could be hundreds
D. 9.
E. 8.



New Technology has allowed rapid acceleration of discoveries



A Planet (according to IAU)

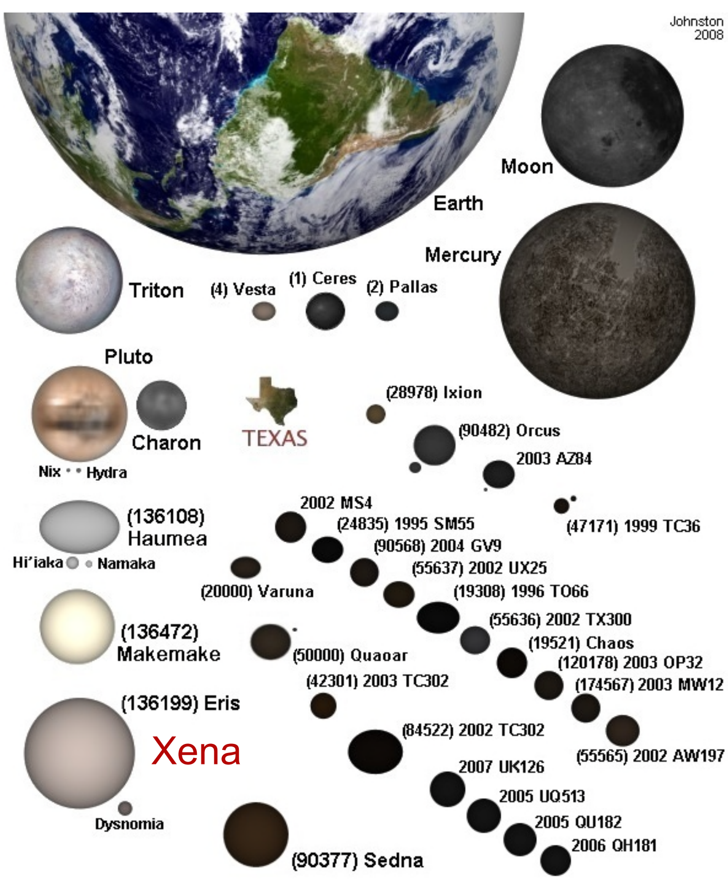
1. orbits the Sun (rather than a moon that orbits a planet)
2. Is big - but *how* big?
3. is big enough so that its own gravity pulls it together into a sphere - but *how* round?
4. Needs to clear out its neighborhood – ie. not be in a crowd – but *how* separate from neighbors?

Definition of Rocks

Particle Name	Minimum Size	Maximum Size
Clay	--	1/256 mm
Dust/Silt	1/256 mm	1/16 mm
Sand	1/16 mm	2 mm
Granule	2 mm	4 mm
Pebble	4 mm	64 mm
Cobble	64 mm	256 mm
Boulder	256 mm	--

Is this science ??

Note: Definition of a planet will not be on the test.



Since anything bigger than TEXAS is certainly not minor, not small, and not a dwarf…. Therefore, a planet must be any star-orbiting body larger than the smallest sphere containing TEXAS.