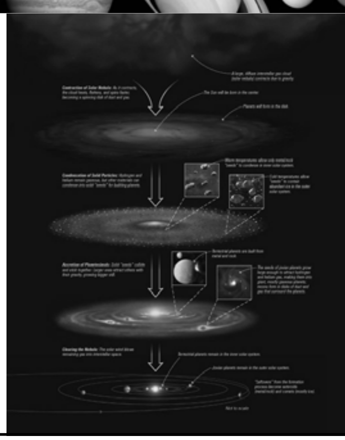
Lecture #34: Solar System Origin II

- How did the solar system form?
  - Chemical Condensation ("Lewis") Model.
  - Formation of the Terrestrial Planets.
  - Formation of the Giant Planets.
  - Planetary Evolution.
- Reading: Chapter 8.

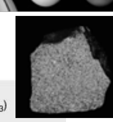
The Main Point

The planets formed (and began evolving) in relation to their original positions in the solar nebula, according to the so-called “Lewis model” that describes the hypothesized distribution of rocky, gaseous, and icy planetary building blocks.

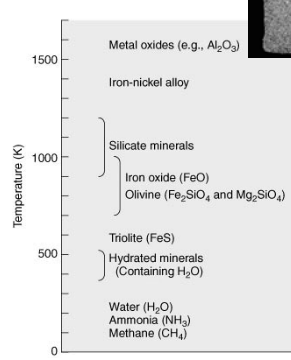
- Contraction of solar nebula. Cloud heats, flattens, and spins faster.
- Condensation of solid particles. Metal/rock seeds condense throughout. Ices only in outer solar system.
- Accretion of planetesimals. Small seeds collide/stick, large seeds accrete by gravity.
- Clearing of the nebula.



Chemical Condensation (“Lewis”) Model



- The solar nebula theory predicts a specific *chemical condensation sequence* as the hot gaseous nebula cooled.
- Model worked out by astronomer John Lewis and others.



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- Close to Sun, rocks and metals condense, hydrogen compounds stay gaseous.
- Farther away, lower temperatures allow condensation of hydrogen compounds.

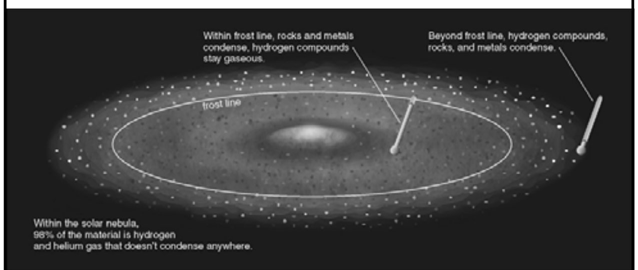

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Table 9.1 Materials in the Solar Nebula A summary of the four types of materials present in the solar nebula, along with examples of each type and their typical condensation temperatures. The squares represent the relative proportions of each type (by mass).

	Metals	*Rock*	*Hydrogen Compounds*	*Hydrogen and Helium Gas*
Examples	iron, nickel, aluminum	various minerals	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%

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Assumptions of the Lewis Model

- Model Pressure, Temperature of the nebula.
- Composition of the nebula:
  - Solar: 98% H & He, 1.4% hydrogen compounds, 0.4% rock, 0.2% metal.
- Phase diagrams of nebula materials:
  - When do which solids condense from the gas?
- *Equilibrium* chemistry:
  - Slow solid/gas reactions; rates, products?

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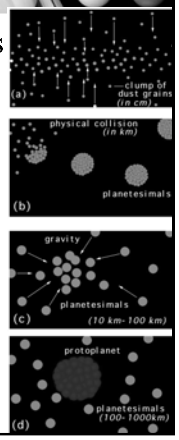
Predictions of the Lewis Model

- Rocky inner planets, icy outer ones. Yes.
- Mercury will have a large metallic core. Yes.
- Bulk H_2O increases from Venus to Earth to Mars.
  - Maybe, but interiors not well understood...
- Volatile-rich materials in the asteroid belt.
  - Consistent with some asteroid spectra & meteorites.
- "Unprocessed" outer satellites half rock, half ice.
  - Consistent with Callisto data.

Formation of the Terrestrial Planets

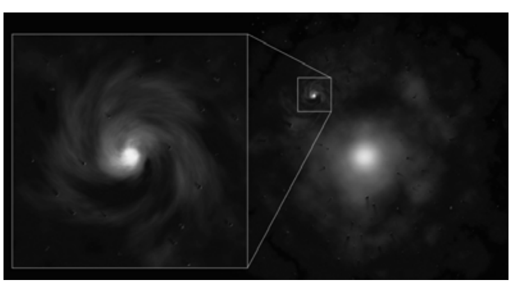
- Grains condense out of the nebula as it cools.
- Condensed grains settle to mid-plane and merge into larger and larger aggregates by sticking, forming 1-10 km size *planetesimals.*
- Planetesimals grow by gravitational *accretion.*
- Small number of *protoplanets* 100-1000 km (Moon, Mars masses) form.
- Continued accretion of planetesimals adds energy and heat, contributing to a rise in the temperature of the growing protoplanets.
- Beyond a certain size, planets melt, *differentiate,* and lose most of their *volatiles* (gases and ices).
- Terrestrial planets are not massive enough to be able to hold on to light Hydrogen & Helium gas.



Formation of the Giant Planets

- Additional supply of ices and other volatiles in the outer solar system allowed the *protoplanets* to grow much larger, perhaps 5-10 times the mass of the Earth.
- Masses large enough to keep Hydrogen and Helium gravitationally bound to the protoplanet.
- Giant protoplanets heated as their cores collapse under more and more mass: same way stars start to form!
- But the giant planets in our solar system are not massive enough to initiate fusion of Hydrogen into Helium, so the cores cooled to their present state.

Solar Systems within Solar Systems



Putative Jovian Nebula   Solar Nebula

Explains presence of satellites and rings in outer planets.

Giant Planets vs. Terrestrial Planets

- An obvious question: Why did proto-Jupiter and proto-Saturn grow to 5-10 Earth masses but proto-Earth did not?
- Leading hypothesis:
  - At lower temperatures beyond the frost line, the more abundant icy materials could condense out of the nebula.
  - More solid material could condense near Jupiter/Saturn orbit than near Earth.

Jupiter/Saturn vs. Uranus/Neptune

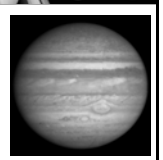
There appear to have been several possible paths for the formation of the giant planets in our solar system:

- If the protoplanet grew big enough (5-10 Earth masses) very early when there was still lots of nebular gas:
  - accretes a lot of gas, has a solar-like composition.
  - Jupiter and Saturn!
- If the protoplanet grew big enough (5-10 Earth masses) but not until later, when there was less nebular gas:
  - accretes only a little gas, less Sun-like composition.
  - Uranus and Neptune!

Jupiter/Saturn vs. Uranus/Neptune

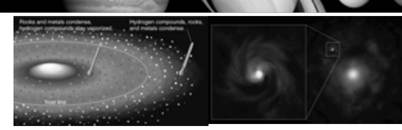
- An obvious question: Why didn't proto-Uranus and proto-Neptune grow as fast as proto-Jupiter and proto-Saturn?
- Leading hypothesis:
  - Farther out in the nebula, the timescales between planetesimal collisions were much longer.
  - Longer orbital periods, larger volume, lower number of planetesimals per unit volume.

Jupiter's Dominant Role



- If Jupiter formed early enough, it could have prevented the formation of a planet in the asteroid belt. Why?
- Jupiter's gravity influences nearby planetesimals (recall Lecture 22 about asteroids…)
  - Nearby planetesimal orbits made more eccentric.
  - Higher eccentricity means higher impact velocities.
  - Higher impact velocities mean disruptive collisions instead of gentle collisions that favor accretion.
  - Planetesimals cannot accrete and grow very well.

Caveats...



- The Chemical Condensation Model is an approximation of a complex process!
  - Was chemical equilibrium reached everywhere?
  - Many of the "leftovers" that we see today from solar system formation have undergone complex evolutionary histories.
- Emphasizes importance of studies of the most primitive solar system bodies (asteroids, comets).

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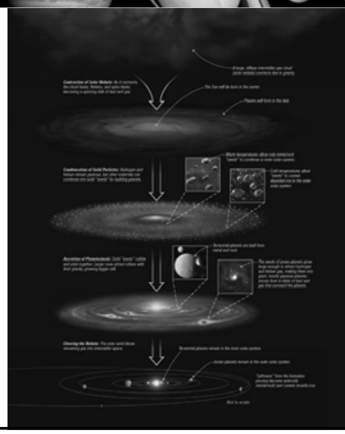

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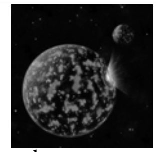
Planetary Evolution



- After only 100 to 500 million years, most of the "debris" in the solar system was either swept up by the planets or ejected.
- The planets started to cool and assume their present appearances.
- Each planet or moon has followed it own *evolutionary course*, governed by its size, composition, solar distance, and the occasional random catastrophic impact...

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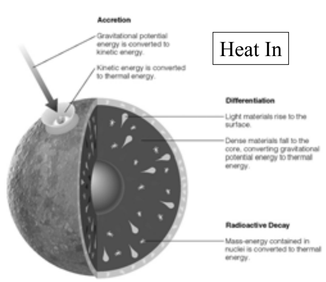
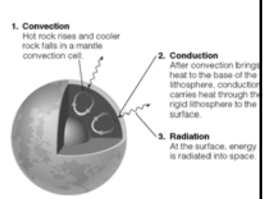
Thermal evolution

Heat In



Heat Out



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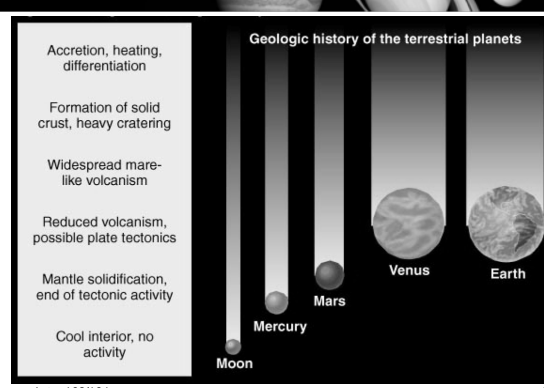
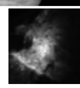
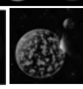


Initial "inventory" of internal heat, radiogenic elements, and size govern a planet's evolution.

Summary





- The solar system formed ~4.6 billion years ago.
- The leading theory is that it formed rapidly from a spinning cloud (nebula) of gas and dust.
- *Condensation* and *accretion* of solids occurred quickly: much of the "action" over in $\leq 10^8 - 10^7$ years.
- The outer planets were massive enough (especially Jupiter and Saturn) to accrete gases from the nebula.
- But the inner planets were not.
- Jupiter may have prevented the formation of another terrestrial planet in the asteroid belt.

Next Lecture...

- The Sun:
  - General Properties.
  - The Sun's Influence on the Earth.
  - Fusion: The Sun's Interior Engine.
  - The Sun as a Star.
- Reading: Chapter 15.