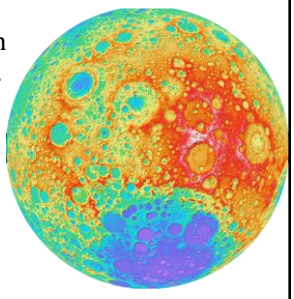
Today's Class: The History & Evolution of the Moon

- Read: Section 14.1-14.2 in Cosmic Perspective on the *Properties of the Sun*.
- Homework #4 due on Oct. 21.



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Class Exercise

What are some of the new opportunities for exploration and science on the Moon that are different from those during Apollo?

2

Origin of the Earth-Moon System

- The Moon itself is fascinating, but it is also a "Rosetta Stone" for telling us about:
  - The unknown nature of the primordial Earth!
  - The critical last stages of planet formation throughout the solar system!

Thanks to Dr. Bill Bottke for slides for this lecture!

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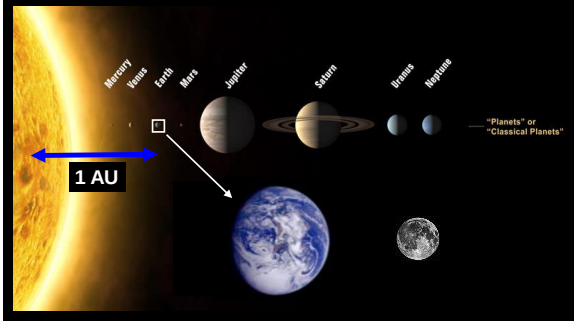
The Known Solar System



- The solar system did not always look this way!

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A Few Interesting Questions…

1. What does the Moon tell us about planet formation?
2. How did the Earth get a large Moon?
3. What does the Moon tell us about bombardment of the early Earth?

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Our Story Begins… The Classical Model of Planet Formation

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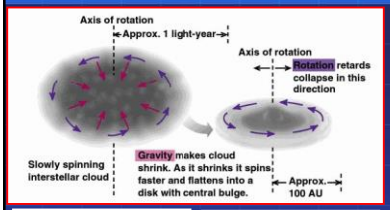
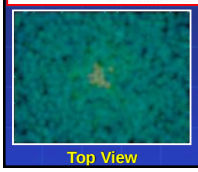
Formation of Protoplanetary Disk



- Gravity causes cloud to flatten.
- Conservation of ang. momentum causes it to spin faster.


Top View


Side View

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Formation of Protoplanetary Disk

- The dominant physical processes controlling the evolution of small bodies in the early solar system are:
  - Collisions
  - Gravitational forces

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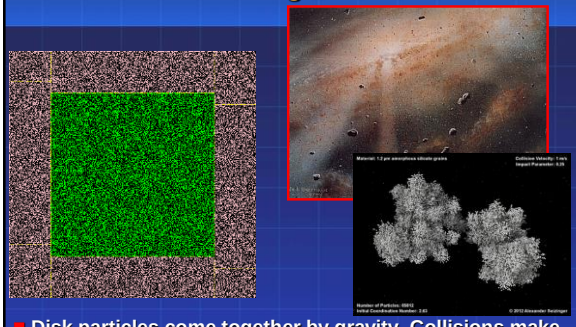
Growing Planets



- Disk particles come together by gravity. Collisions make larger and larger objects by "accretion".

Animation from Tanga et al. (2003)

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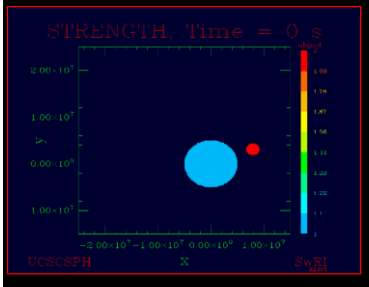
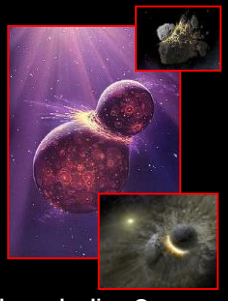
Collisions Make Large Bodies!





- The planetesimals collide and form larger bodies. Over time, they grow into Moon/Mars-sized protoplanets.

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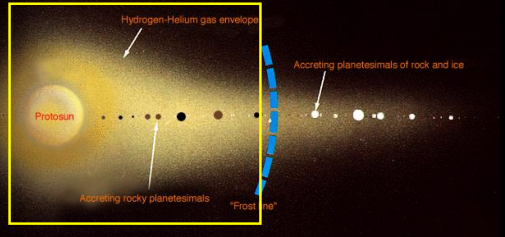
Planet Formation



- The protoplanets closer to the Sun are made of rocky materials. Those farther away are made of icy materials.

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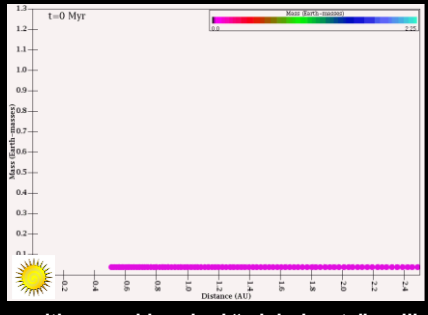
Simulated Planet Growth



- Starting with several hundred "mini-planets", collisions cause bodies to merge and form big planets!

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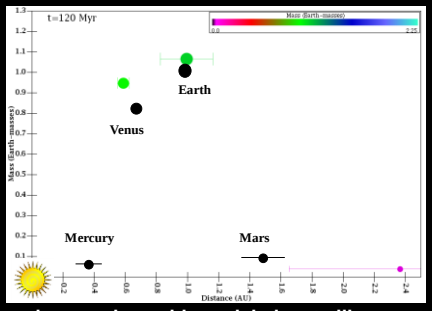
Simulated Planet Growth



- In the end, we end up with model planets like our own.

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Properties of the Moon

- Large, single Moon

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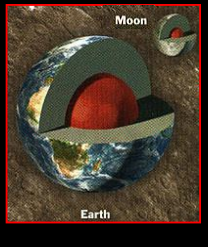
Properties of the Moon

- Large, single Moon
- The Moon is depleted in iron.



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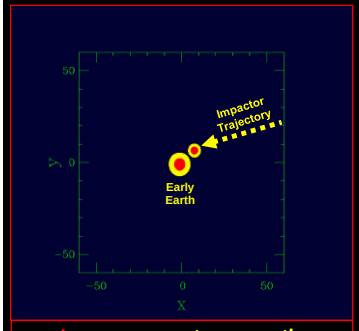
Giant Impact Model of Moon Formation



Iron core vs. stony mantle

Animation from Robin Canup

- Mars-sized body hits Earth and forms Moon from debris disk.
- This model explains:
  - Large Moon!
  - High Earth/Moon angular momentum.
  - Lack of iron in Moon.
  - Large impacts common!

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Properties of the Moon

Ancient lunar distance and apparent size

Lunar distance: 384400 km
(100% of today's distance)

Angular size: 0.5°
(looks 1 times bigger)

Handy astro tip! Stretch your arm out to the sky, and:
1°... is your little-finger's width
10°... is the width of your fist

0 million years ago
Lunar retreat: 1.46 cm/year

Lunar orbit at 60 Earth radii and 24-hour Earth day →
5-hour Earth day when Moon formed near Earth 4.5 billion years ago

- Using conservation of angular momentum, we know the Moon formed near a rapidly-rotating Earth!

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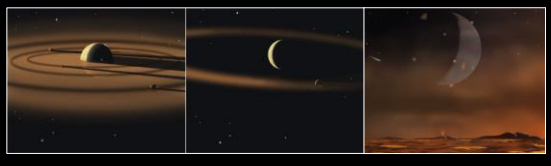
Some Implications



- Planet properties affected by final large impacts
  - Tilt of planet's axis (north pole), its rotation rate, whether it had a moon.
- Earth & Moon resulted from single chance event!
  - A collision between a Mars-size protoplanet and the newly formed Earth 4.5 billion years ago.

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Impact History of the Moon

- The Moon has the most complete and clear impact history available of the last 4.5 billion years of Solar System evolution.

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Rocks Tell a Story

"A rock is the most efficient way to encode information about a planet."

– Bruce Banerdt (as paraphrased by Bob Grimm)

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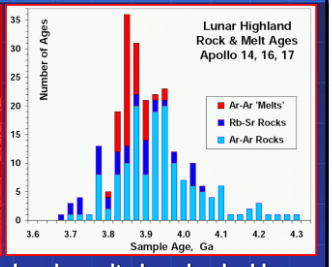
Apollo Insights: Ages of Lunar Samples



- Apollo astronauts returned rocks melted or shocked by impacts that were 3.7-4.1 billion years old.
- Lots of big impacts about 3.9 billion years ago?

Bogard (2006); Norman et al. (2010)

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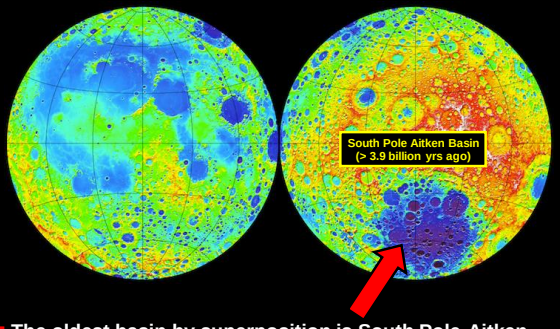
Lunar Basins



- The oldest basin by superposition is South Pole-Aitken basin (~2400 km). SPA's absolute age is unknown.

Wilhelms (1987); Topography from LOLA on LRO

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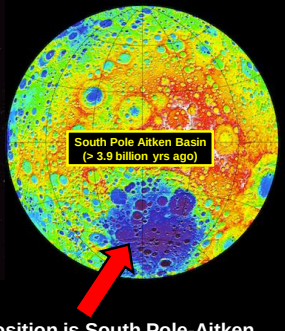
Lunar Basins



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New Solar System Formation Model

- **Old view.** Gas giants/comets formed near present locations (5-30 AU) and reached current orbits ~4.5 Gy ago.

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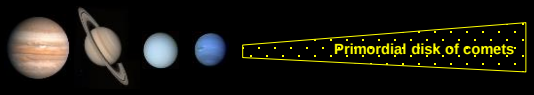
New Solar System Formation Model

- **Old view.** Gas giants/comets formed near present locations (5-30 AU) and reached current orbits ~4.5 Gy ago.



- **New view.** Gas giants formed in more compact configuration (5-15 AU). Massive comet population existed between 15-30 AU.

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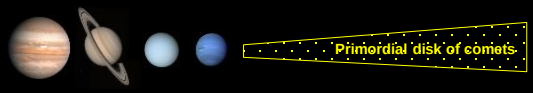
New Solar System Formation Model



- Why is this a good thing? Objects closer to Sun can grow faster!
  - We can make Uranus and Neptune!
  - We can make dwarf planets like Pluto and Eris!
- But…
  - The planets are in the wrong places!
  - The disk of comets is much bigger than we see today!

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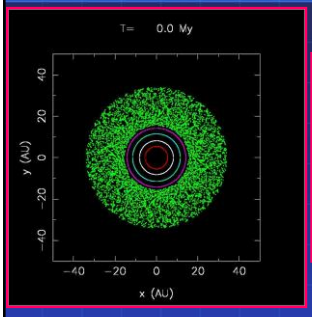
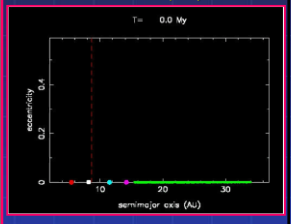
Destabilizing the Outer Solar System



Tsiganis et al. (2005); Morbidelli et al. (2005); Gomes et al. (2005)



Watch what happens after 850 My!

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"Late" Bombardment of the Solar System

- Huge lunar craters made ~4 billion years ago by impacting comets/asteroids scattered by giant planet migration.

Animation from Goddard Space Flight Center

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Why Go Back to the Moon?

- Lunar samples from the right places may tell us about the very last stages of planet formation!

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