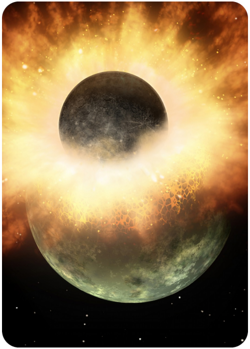
Constructing the Solar System: A Smashing Success

# Constructing the Moon




**Thomas M. Davison**

Department of the Geophysical Sciences

THE UNIVERSITY OF CHICAGO


Compton Lecture Series
Autumn 2012

# Compton Lecture Series Schedule

| | | |
|---|---|---|
| 1 | 10/06/12 | A Star is Born |
| 2 | 10/13/12 | Making Planetesimals: The building blocks of planets |
| 3 | 10/20/12 | *Guest Lecturer: Mac Cathles* |
| 4 | 10/27/12 | Asteroids and Meteorites: Our eyes in the early Solar System |
| 5 | 11/03/12 | Building the Planets |
| 6 | 11/10/12 | When Asteroids Collide |
| 7 | 11/17/12 | Making Things Hot: The thermal effects of collisions |
| | 11/24/12 | No lecture: Thanksgiving weekend |
| 8 | 12/01/12 | Constructing the Moon |
| | 12/08/12 | No lecture: Physics with a Bang! |
| 9 | 12/15/12 | Impact Earth: Chicxulub and other terrestrial impacts |

# Compton Lecture Series Schedule

1. 10/06/12 A Star is Born
2. 10/13/12 Making Planetesimals: The building blocks of planets
3. 10/20/12 *Guest Lecturer: Mac Cathles*
4. 10/27/12 Asteroids and Meteorites:
   Our eyes in the early Solar System
5. 11/03/12 Building the Planets
6. 11/10/12 When Asteroids Collide
7. 11/17/12 Making Things Hot: The thermal effects of collisions

   11/24/12 No lecture: Thanksgiving weekend

8. 12/01/12 Constructing the Moon

   12/08/12 No lecture: Physics with a Bang!

9. 12/15/12 Impact Earth: Chicxulub and other terrestrial impacts

# The Moon

Image courtesy of Gregory H. Revera/ Wikimedia Commons

| | |
|---|---|
| Orbital distance | 238854 miles |
| Average radius | 1079 miles (0.27 × Earth) |
| Mass | $7.34 \times 10^{22}$ kg (0.012 × Earth) |
| Average density | 3346 $kg/m^3$ (0.61 × Earth) |

- Galileo 1609 showed Moon is rocky
  - Observed hills and what he thought were oceans
- Leads to our names for:
  - the bright highlands (**Terra**)
  - and dark basins (**Mare**)

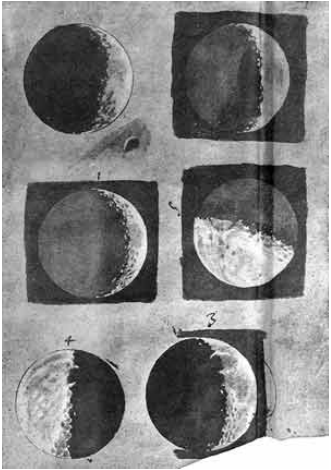


Image courtesy of The Galileo Project

# Features on the Lunar surface

- **Maria** are large, dark, basaltic plain on the Moon
  - Formed by ancient volcanic eruptions
- **Terrae** are the lighter, anorthositic highlands
  - Older than the Mare

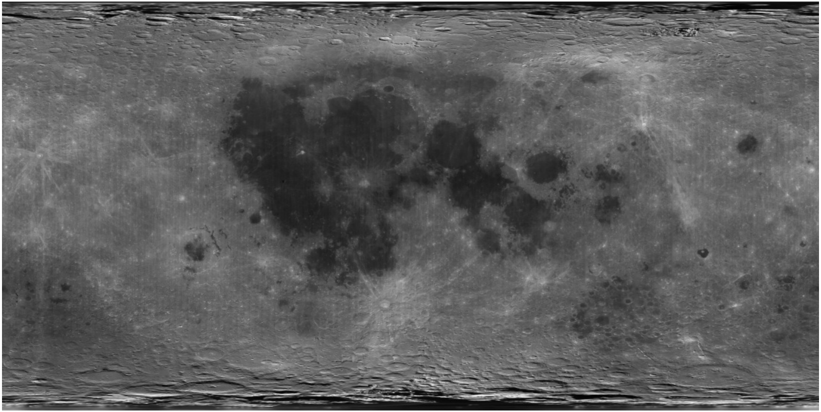
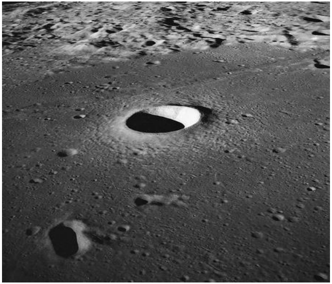
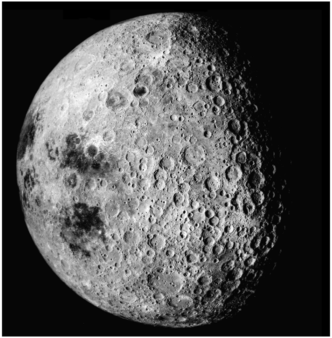


Image courtesy of the United States Geological Survey

# Impact craters are a dominant surface feature



Images courtesy of NASA



- Craters cover the surface of the Moon
- Smooth areas are the younger Mare which often infill large craters

# Craters still forming today

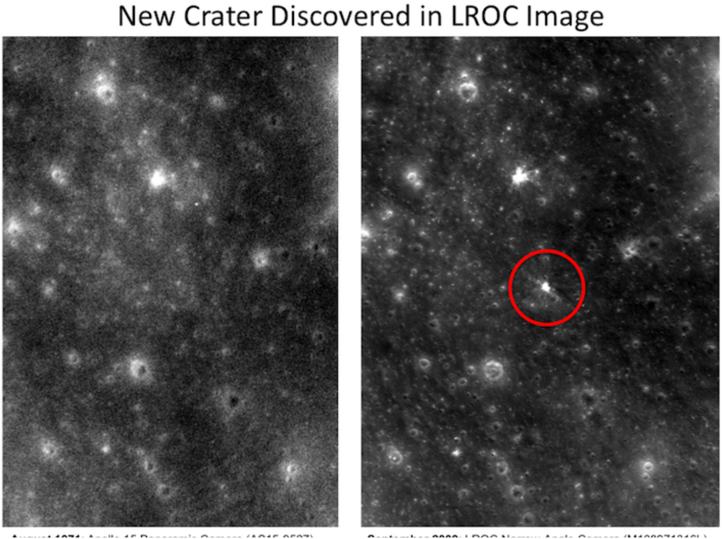



Image courtesy of NASA/GSFC/Arizona State University

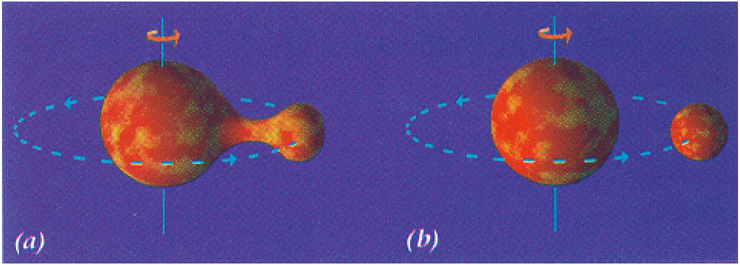
# Part 1:
## Classical formation mechanisms

Image courtesy of NASA

# Fission

- 1878: G.H. Darwin
  - Suggested a large chunk of material split from the Earth
  - Requires fast rotation of Earth
- Four years later: Osmond Fisher
  - Thought that Pacific basin represents the scar left behind


Image courtesy of J. Russell & Sons/ Wikimedia Commons



# Capture

- 1909: Thomas Jefferson Jackson See
  - Moon formed as a planetesimal elsewhere in the Solar System
  - Later captured by Earth's gravity

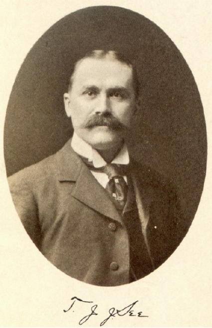


Image courtesy of William Larkin Webb/ Wikimedia Commons

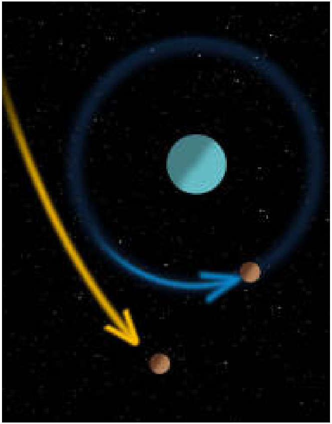
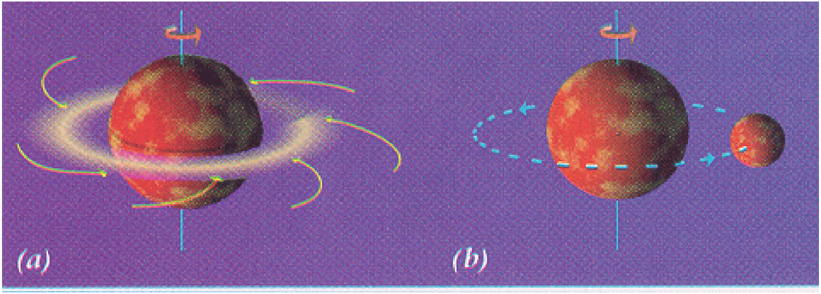


Image courtesy of Black Cat Studios

# Co-accretion

- 1873: Édouard Roche
  - Earth and Moon formed together
  - Formed from swarm of planetesimals as a **double planet**



# Part 2:
## Properties of our Moon

Image courtesy of NASA

# Angular Momentum

Earth and the Moon: the view from Mars

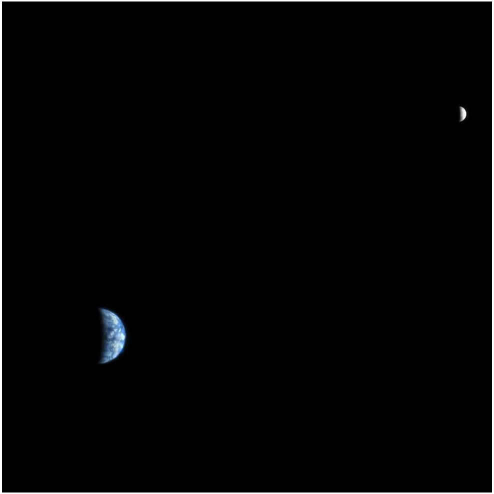
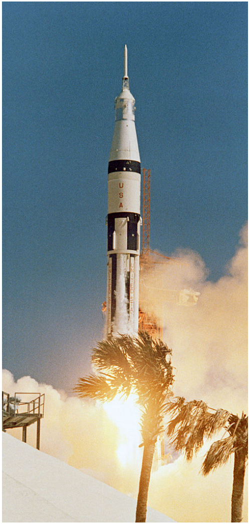


Image courtesy of NASA/JPL-Caltech/University of Arizona

- The Earth–Moon system has a high angular momentum
- The Moon has a greater mass fraction compared with other planet–satellite systems

# We have samples of the Moon

- NASA's Apollo program in the 1960s to 1970s
- Collected samples from the Moon
  - Also have lunar meteorites
- Can measure ages, composition, structure, etc.





Images courtesy of NASA

# The Moon formed late

- The Moon formed relatively late (given its size)
  - Radiometric age of lunar rocks from hafnium/tungsten isotopes
    - → Moon formed > 30 million years after Solar System formation
  - Other objects this size formed in a few hundred thousand years

Harrison H. Schmitt collects lunar rocks during the Apollo 17 misson

Image courtesy of E.A. Cernan/NASA

# The Moon has a small core

- Apollo astronauts left seismometers on the Moon
- Recorded moonquakes from 1969 to 1977
- Using moonquake data, the size of the lunar core is estimated to be $\sim$ 330 km
  - $\sim$ 20% of the Moon's radius
  - Compare to Earth's core ($\sim$ 50% Earth's radius)
- Explains low density of Moon:
  - Moon is depleted in iron

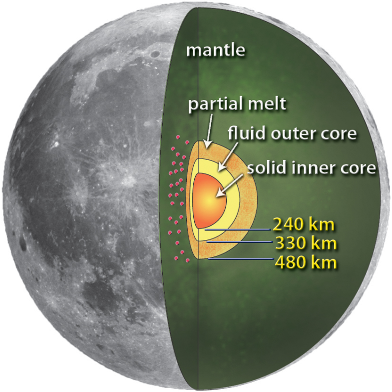



Image courtesy of NASA/MSFC/Renee Weber

# The Moon had an early magma ocean

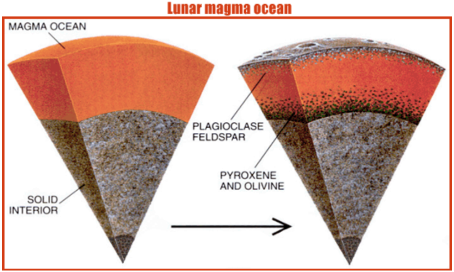



Image courtesy of G.J. Taylor
(*Scientific American/Planetary Science Research Discoveries*)

- The crust of the Moon is composed of a rock called **anorthosite**
- Anorthosite is a rock made up of low-density components
- This implies that the Moon had a magma ocean
  - The low-density components floated to the surface, and cooled as the crust

# Summary of Constraints

A model of how the Moon formed should explain each of these

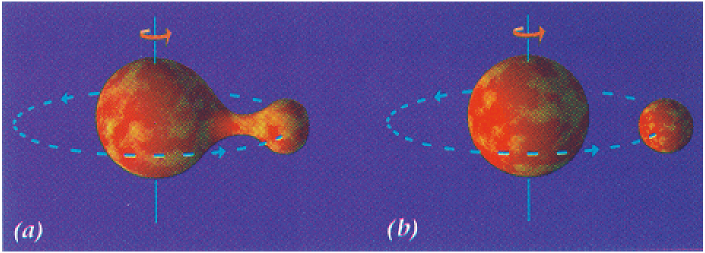
1. High angular momentum
2. Low density/small core
3. Late formation
4. Oldest rocks appear to come from magma ocean
   - Energetic start occurred after decay of short-lived radionuclides
5. Oxygen and titanium isotope data identical to Earth
   - Asteroids and planets differ
   - Common origin

Image courtesy of Gregory H. Revera/ Wikimedia Commons

How do these constraints fit with the classical formation hypotheses?

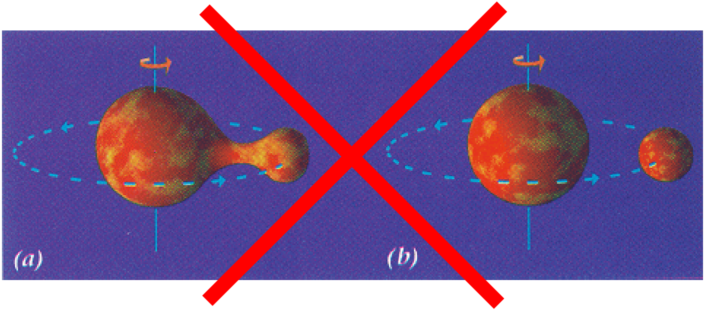
# Fission

- Can explain:
  - Lack of large core
  - Oxygen isotope similarity
- But, problems exist:
  - Earth would have had to spin very fast before fission event
  - Pacific Basin only formed 70 million years ago
  - Moon's orbit and Earth's equator not co-planar
  - Cannot account for lack of volatiles on the Moon



# Fission

- Can explain:
  - Lack of large core
  - Oxygen isotope similarity
- But, problems exist:
  - Earth would have had to spin very fast before fission event
  - Pacific Basin only formed 70 million years ago
  - Moon's orbit and Earth's equator not co-planar
  - Cannot account for lack of volatiles on the Moon



# Capture

- Can explain:
  - Compositional differences
- But, problems:
  - Small core
  - Isotopic similarities
  - Unlikely to be captured:
    - More likely to impact or by hurled back out to space

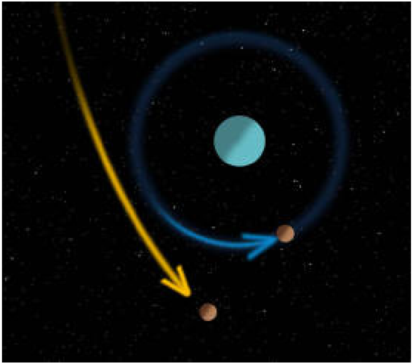


Image courtesy of Black Cat Studios

# Capture

- Can explain:
  - Compositional differences
- But, problems:
  - Small core
  - Isotopic similarities
  - Unlikely to be captured:
    - More likely to impact or by hurled back out to space

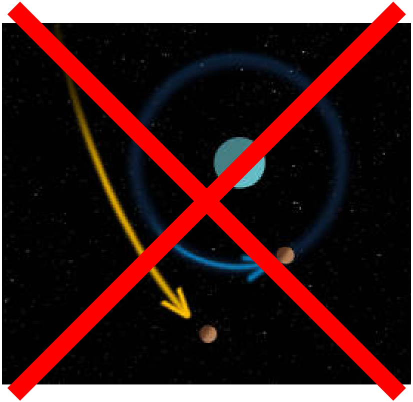
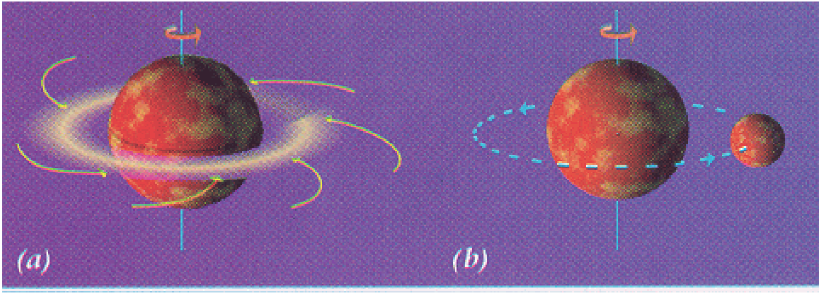


Image courtesy of Black Cat Studios

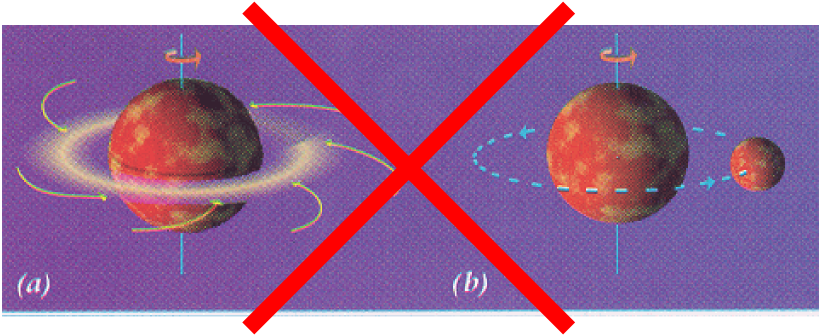
# Co-accretion

- Most popular theory until 1970s
  - Doesn't require low frequency event like capture
- But, cannot explain:
  - Difference in iron content
  - Large angular momentum of Earth–Moon system

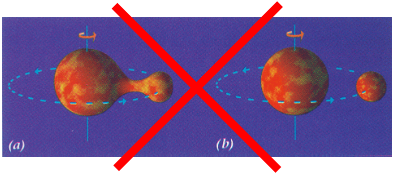


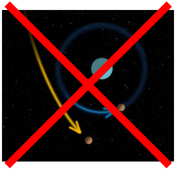
# Co-accretion

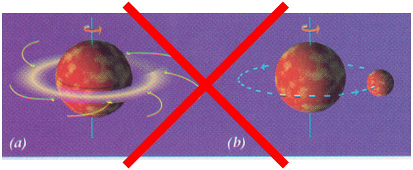
- Most popular theory until 1970s
  - Doesn't require low frequency event like capture
- But, cannot explain:
  - Difference in iron content
  - Large angular momentum of Earth–Moon system



# New theory required






- Not fission, capture or co-accretion
- After Apollo, we needed a new theory to explain the origin of the Moon

# Part 3:
## Giant Impact Hypothesis

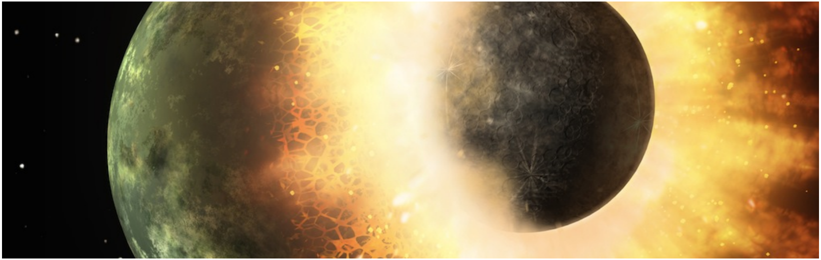


Image courtesy of NASA

# Giant impact hypothesis

- Mid 1970's to 1980's: New theory
- First suggested by Hartmann & Davis

- Giant impact with Earth
  - Debris disk
  - Coalesced to form the Moon

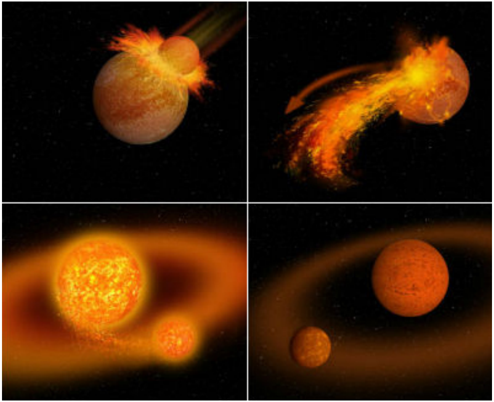
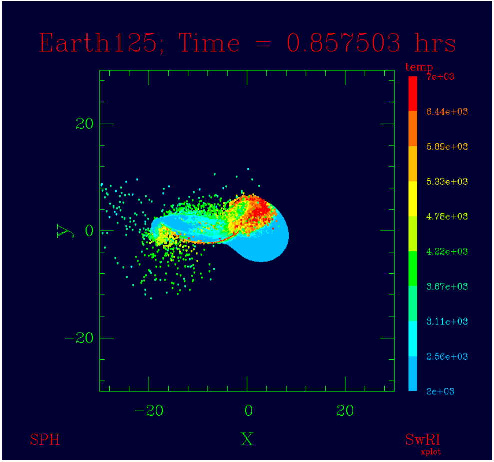


Image courtesy of Black Cat Studios

# Giant impact

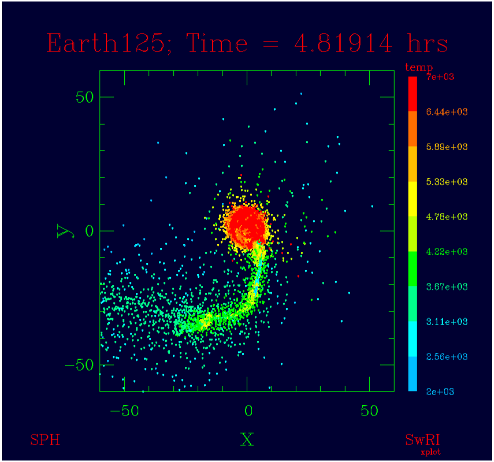
- 2004: Robin Canup's model of the giant impact
- Impact of a $\sim$ Mars–sized body with Earth
  - **Theia**
- Impact angle 42–50°
- Moon is composed of $>$ 60% impactor material




Images courtesy of Canup (2004) *Icarus*

# Giant impact

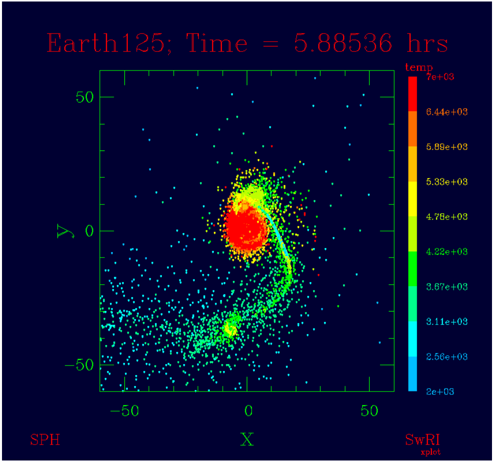
- 2004: Robin Canup's model of the giant impact
- Impact of a $\sim$ Mars–sized body with Earth
  - **Theia**
- Impact angle 42–50°
- Moon is composed of $>$ 60% impactor material




Images courtesy of Canup (2004) *Icarus*

# Giant impact

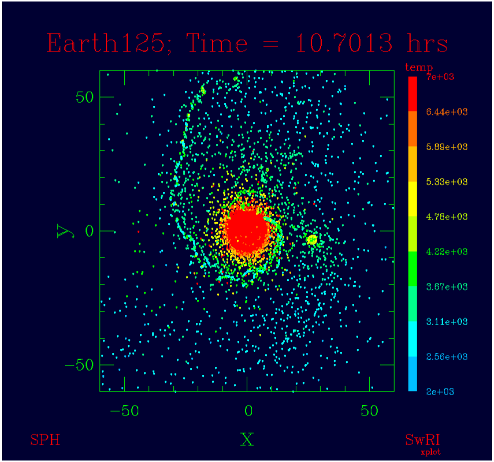
- 2004: Robin Canup's model of the giant impact
- Impact of a $\sim$ Mars–sized body with Earth
  - **Theia**
- Impact angle 42–50°
- Moon is composed of $>$ 60% impactor material




Images courtesy of Canup (2004) *Icarus*

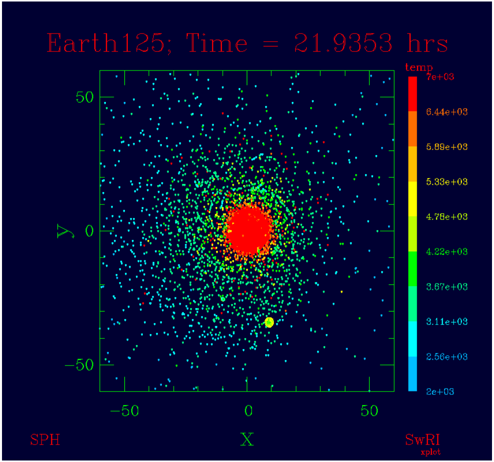
# Giant impact

- 2004: Robin Canup's model of the giant impact
- Impact of a $\sim$ Mars–sized body with Earth
  - **Theia**
- Impact angle 42–50°
- Moon is composed of $>$ 60% impactor material




Images courtesy of Canup (2004) *Icarus*

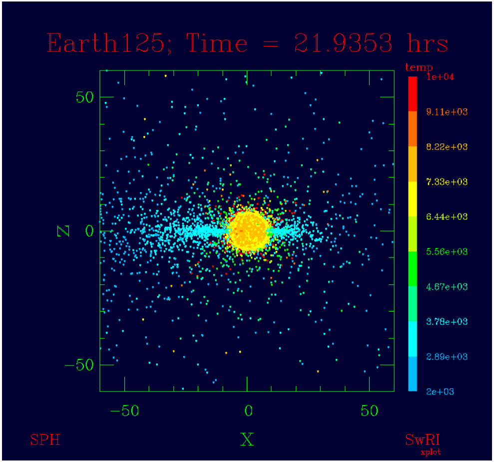
- 2004: Robin Canup's model of the giant impact
- Impact of a $\sim$ Mars–sized body with Earth
  - **Theia**
- Impact angle 42–50°
- Moon is composed of $>$ 60% impactor material




Images courtesy of Canup (2004) *Icarus*

# Giant impact

- 2004: Robin Canup's model of the giant impact
- Impact of a $\sim$ Mars–sized body with Earth
    - **Theia**
- Impact angle 42–50°
- Moon is composed of $>$ 60% impactor material




Images courtesy of Canup (2004) *Icarus*

# Giant impact

- 2004: Robin Canup's model of the giant impact
- Impact of a $\sim$ Mars–sized body with Earth
  - **Theia**
- Impact angle 42–50$^\circ$
- Moon is composed of $>$ 60% impactor material

In the lecture, I showed a movie of this collision. That movie, and other resources from Canup (2004), can be found at:
http://www.boulder.swri.edu/~robin/moonimpact/

# Success?

## Does this model match the observational constraints?

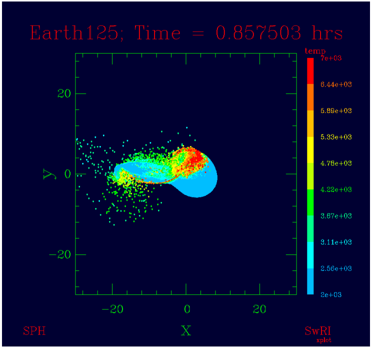



Image courtesy of Canup (2004) *Icarus*

- Explains a lot of the constraints on Moon formation
  1. Angular momentum ✓
  2. Low iron content/small core ✓
  3. Late formation time ✓
  4. Magma ocean ✓

# One constraint cannot be easily explained by this model

- Measurements of oxygen and titanium isotopes — now a lot more accurate
- As the error bars on the measurements shrunk, isotopic composition of the Moon and Earth became indistinguishable
- This means that:
  - They must come from a single body, or
  - They were well mixed during/after the impact

Titanium

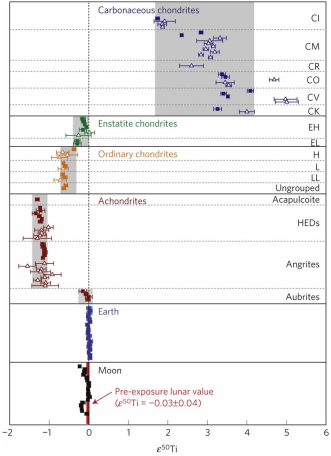



Image courtesy of Zhang et al. (2012) *Nature Geoscience*

# Can we save the Giant Impact Hypothesis?

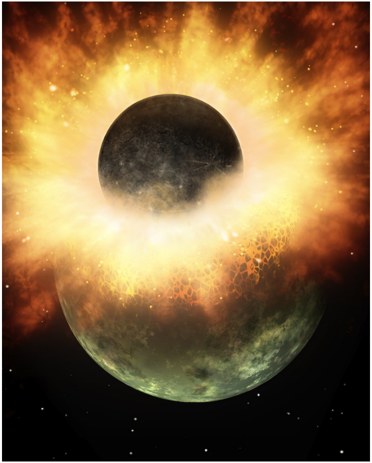


Image courtesy of NASA

1. Earth and Theia came from the same orbital distance
   - Explains similar isotopic composition
   - But, can't account for late formation time
2. Material stayed hot for a long time, allowing exchange in the vapor phase
   - Could reach isotopic equilibrium for volatile elements like oxygen
   - However, refractory elements like tungsten and titanium and silicon are not readily explained

This is where things stood, up to around a month ago

# Part 4:

## Giant Impact Hypothesis: *Updated*

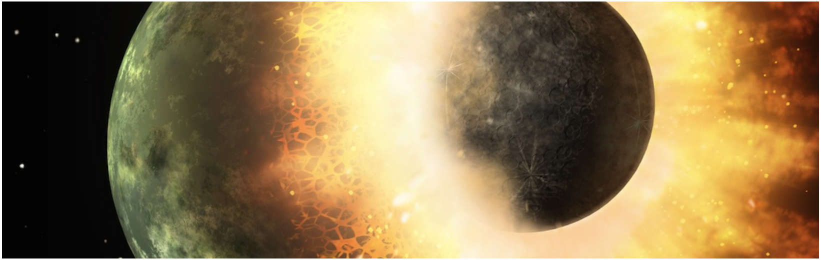


Image courtesy of NASA

# Moving the goalposts

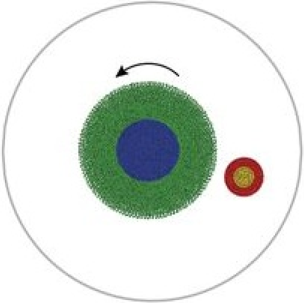


Image courtesy of Ćuk & Stewart (2012) *Science*

- In the original scenario, the angular momentum of the Earth–Moon system was generated by the impact
  - This limited the types of impact that could be studied
- A month ago, two papers removed this limitation
- They assumed that the Earth was spinning rapidly *before* the impact
  - A **resonance** with the Sun after the impact was able to remove the excess angular momentum

# Ćuk and Stewart's rapidly spinning model

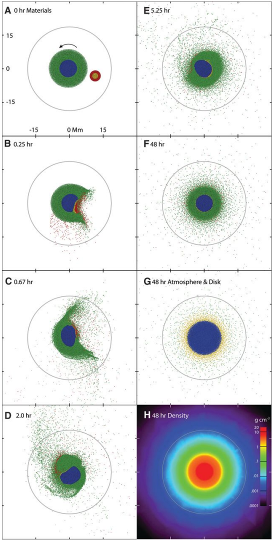



Image courtesy of Ćuk & Stewart (2012) *Science*

- In one of the new models, a smaller impactor is invoked
  - It doesn't need to generate angular momentum
- Small mass — lower fraction of Moon's composition
- Helps explain isotopic similarities
- Think of it as a hybrid of the Giant Impact hypothesis and Darwin's Fission hypothesis

# Canup's new model

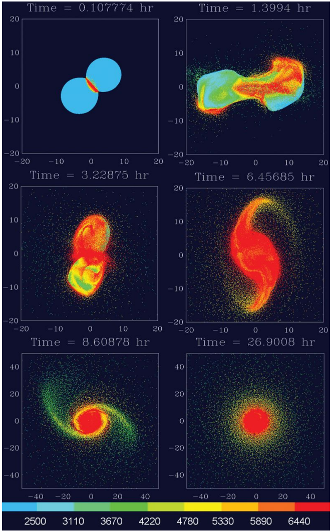



Image courtesy of Canup (2012) *Science*

- In another updated model, Canup also invokes a fast spinning Earth
- But, rather than a smaller impactor, uses an impactor more similar in size to proto-Earth
- Assumption is that the resultant bodies are a mixture of Earth and Theia
- Works well for Theia of $\sim$ 40% the size of Earth

# A hit-and-run collision

- One final alternative doesn't need to invoke resonance with the Sun to slow down the Earth's spin
- Instead, it assumes a **hit-and-run** type collision
  - High velocity, low incidence angle
- Most of the impactor mass continues downrange
- Moon forms from debris disk that is composed primarily of Earth material

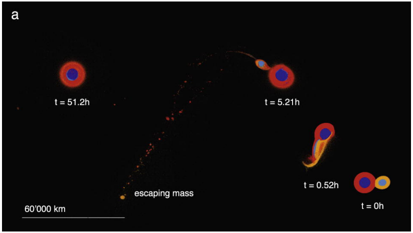



Image courtesy of Reufer et al. (2012) *Icarus*

# Summary

- Impacts, once again, played a key role in shaping the Solar System
- The full details of the impact that formed our Moon are still not resolved
- Exciting work to come in the next few years
    - Which of the possible models best fits our observations?

Image courtesy of Gregory H. Revera/ Wikimedia Commons

Thank you

**Questions?**