


ASTR 4800 - Space Science: Practice & Policy
 Today: Guest lecture by Dr. Bill Bottke on the *Origin & Evolution of the Moon*

- **Next Class at the Fiske Planetarium: Forward! To the Moon.**
 - Read articles linked on class website for Sep. 28.
- Exam #1 on Oct. 10.
- Name & brief background of scientist/engineer who you plan to interview needs to be sent to me via email by Oct. 19. Paper is due Oct. 28.



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Exploring the Origin and Bombardment History of the Moon




Dr. William Bottke
 Southwest Research Institute, Boulder, CO

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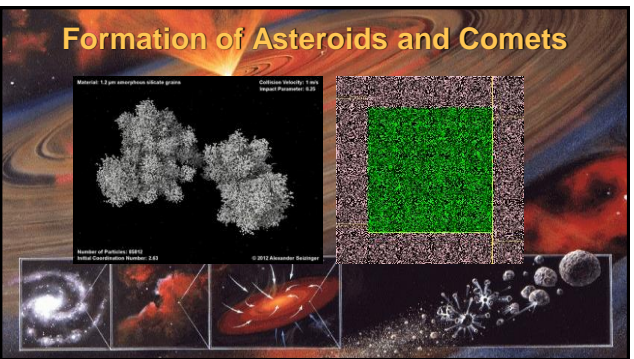
Understanding the Moon

- The ancient lunar surface may give us insights into:
 - Last stages of planet formation
 - The unknown nature of the primordial Earth!
 - Giant planet migration
 - Early lunar evolution
 - ... and much much more!



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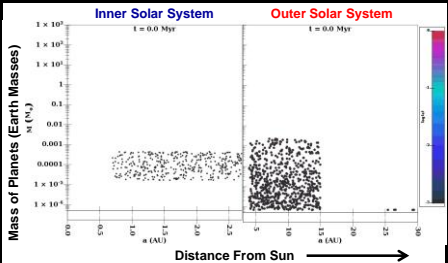
Formation of Asteroids and Comets



Material: 1.2 per centimeter silicate grains
 Collision Velocity: 1 km
 Impact Parameter: 0.5
 Number of Particles: 6892
 Initial Coordinates Number: 245
 © 2012 Alexander Rosengger

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The Beginning



Over 10 to 100 Myr, hundreds of mini-planets collided and merged to yield the four inner planets

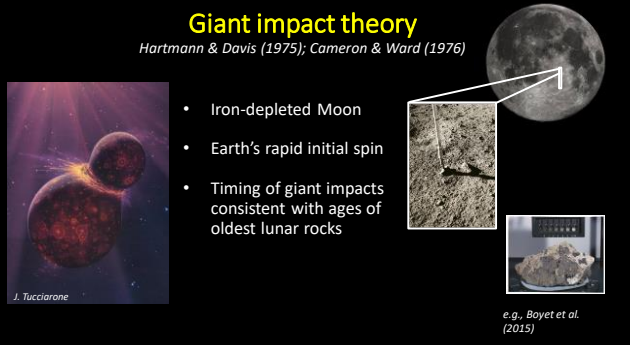
One such collision likely produced our Moon

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Giant impact theory

Hartmann & Davis (1975); Cameron & Ward (1976)

- Iron-depleted Moon
- Earth's rapid initial spin
- Timing of giant impacts consistent with ages of oldest lunar rocks

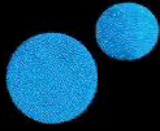


e.g., Bayet et al. (2015)

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Canonical impact by Mars-sized "Theia"

Canup & Asphaug (2001); Canup (2004, 2008)



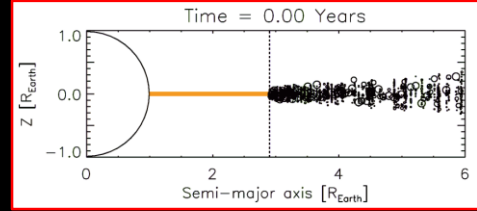
- ✓ Earth and Moon masses
- ✓ Lunar iron depletion
- ✓ Earth-Moon angular momentum
- ✓ Similar impacts predicted for ~ 20% of Earth-analogs

e.g. Jacobsen & Morbidelli (2014), Kaib & Cowen (2014)

Data from Canup (2004); rendering by American Museum of Natural History

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Canonical impact by Mars-sized "Theia"

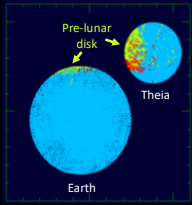


- The Moon could form in as short as a few years or as long as 1,000 years.
- Moon formed ~50-70 Myr after the first solids (4.5 Ga)

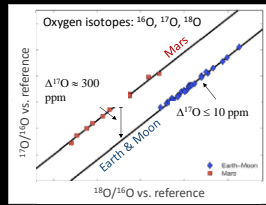
Touboul et al. (2009); Cuk & Stewart (2012); Canup (2012); Salmon and Canup (2013); Bottke et al. (2015)

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Isotopic "crisis" for impact theory



In most collisions, Moon originates primarily from Theia

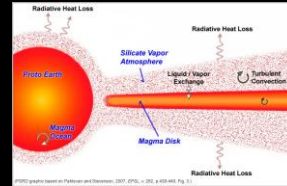


If Theia was Mars-like → Earth-Moon differences. Instead, Earth-Moon are isotopically identical.

Equilibration?

Pahlevan & Stevenson (2007)

Mixing between disk and Earth vapor equilibrates their isotopic compositions before Moon forms



- Would equalize Earth-Moon across many elements, including W
- BUT: Efficiency remains unclear. Might expect Earth-Moon differences in refractory elements. But no difference for Ti & only small difference in Ca (Zhang et al. 2012; Schiller et al. 2018)

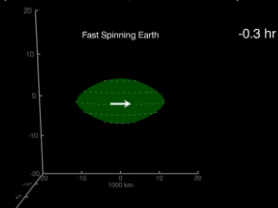
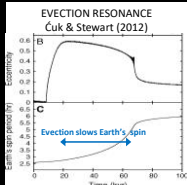
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High-angular momentum impact?

Solar interactions can transfer AM from Earth-Moon to Earth's orbit

Second example: Moon from mostly-Earth (Stewart et al. 2012; Lock et al. 2018)



Cuk & Stewart (2012); Wisdom & Tian (2015); Cuk et al. (2016); Ward et al. (2019)

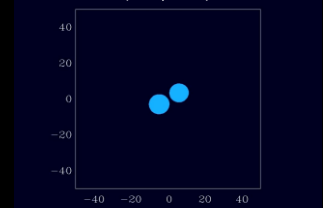
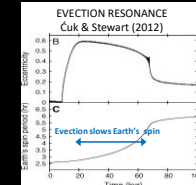
BUT: Needed impact and/or AM-change could be improbable. W match still difficult.

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High-angular momentum impact?

Solar interactions can transfer AM from Earth-Moon to Earth's orbit

One example: Half-Earth impact (Canup 2012)



Cuk & Stewart (2012); Wisdom & Tian (2015); Cuk et al. (2016); Ward et al. (2019)

BUT: Needed impact and/or AM-change could be improbable. W match still difficult.


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What we know now

- Many impacts produce moons → dominant process in planet accretion
- Multiple scenarios for forming Moon, given new discoveries (e.g., AM-modification) and new data (e.g., extensive Earth-Moon isotopic similarities).

What is needed next

- 1) Models relating origin scenarios to observable Moon properties
- 2) New constraints/data
- 3) Evaluation of key aspects of origin scenarios




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Context for Lunar Bombardment: A Brief History of Planet Formation and Giant Planet Migration



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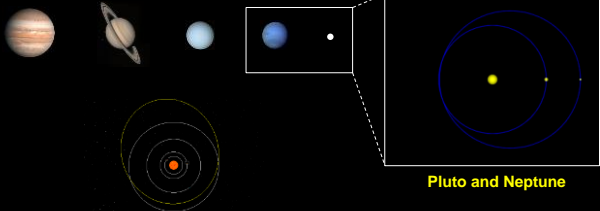
Giant Planet Formation: Pre-1990's View



- Outer planets formed near present locations.

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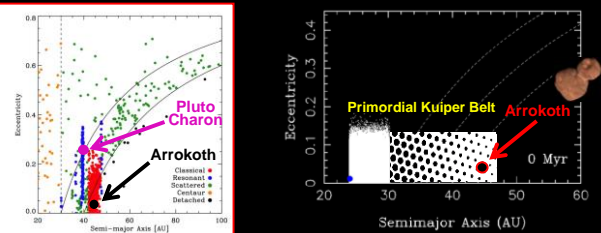
Giant Planet Formation: Pre-1990's View



- Outer planets formed near present locations.
- Pluto in Neptune's 2:3 resonance at high inclination. Why?

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Kuiper Belt Provides Proof of Migration

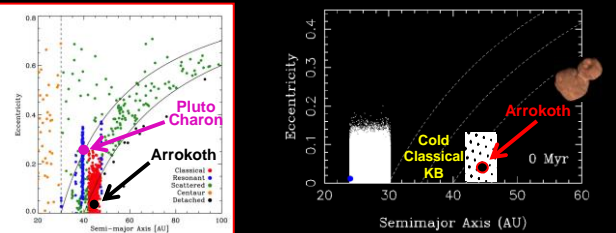


- Neptune migration needed to capture objects in resonance.
- To get right Kuiper Belt structure, need disk 1000x larger.

Sample references: Malhotra (1993); Nesvorný and Vokrouhlický (2017)

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Kuiper Belt Provides Proof of Migration



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Giant Planets Form in Different Configuration

- Gas giants form between 5 to ~20 AU. Massive comet population existed beyond Neptune out to ~50 AU.
- It has to lead to the current giant planet system and Kuiper belt.

Background/new papers: Fernandez & Ip (1986); Malholtra (1995); Thommes et al. (1999; 2003); Tsiganis et al. (2005); Brasser et al. (2011); Nesvorny & Morbidelli (2013); Roig & Nesvorny (2014)

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Giant Planet Instability (GPI)

- “Nice model” describes how Jupiter-Neptune migrated to their orbits after a possible delay of a few Myr to many hundreds of My.

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

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Early GPI and a Lost Neptune

- Most successful simulations come from 5 giant planets, with an extra Neptune ejected.
- But... KBO constraints suggest instability occurred early.
- **Terrestrial planet formation must include effects of giant planet migration.**

Nesvorny & Morbidelli (2013); Nesvorny et al. (2018; 2020); Clement et al. (2018)

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Terrestrial Planet Formation with GPI

time = 0 Myr

- Moon forms when two half-Earths hit at 43 yr
- Early bombardment should come from
 - Leftover planetesimals
 - Comets
 - Asteroids

Nesvorny et al. (2020)

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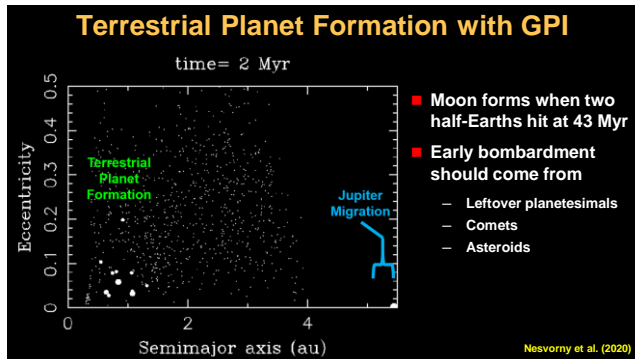
Terrestrial Planet Formation with GPI

time = 1 Myr

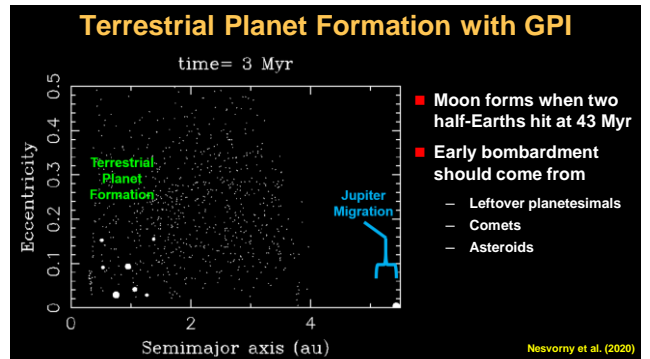
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Nesvorny et al. (2020)

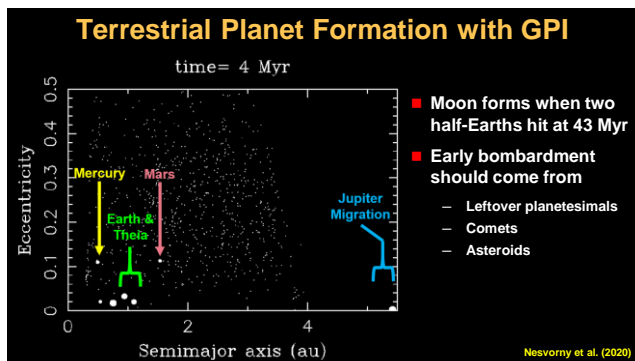
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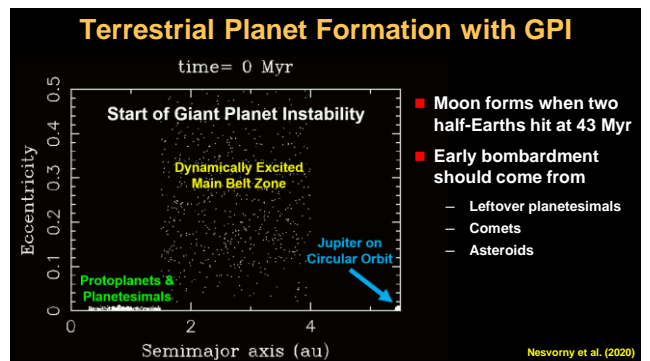
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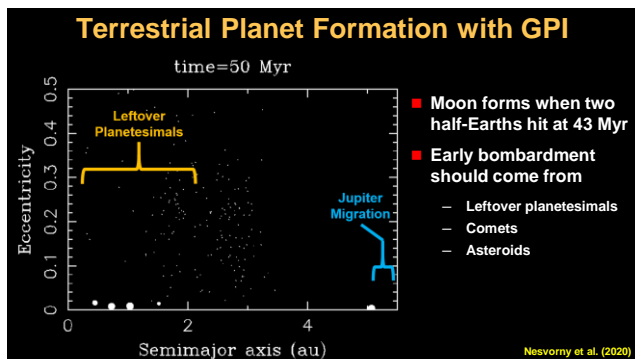
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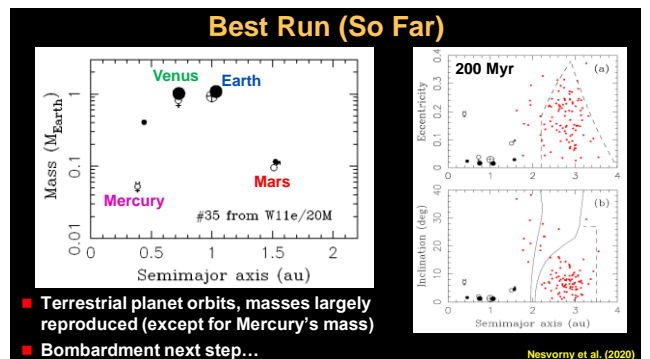
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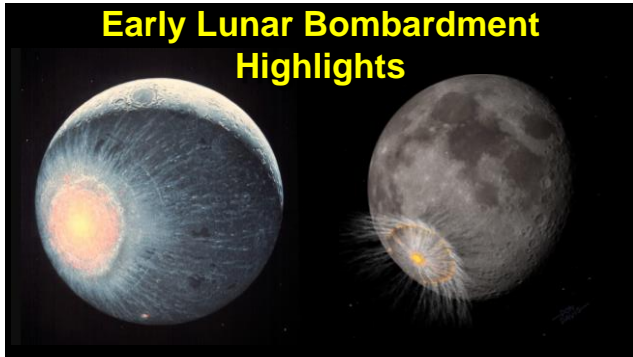
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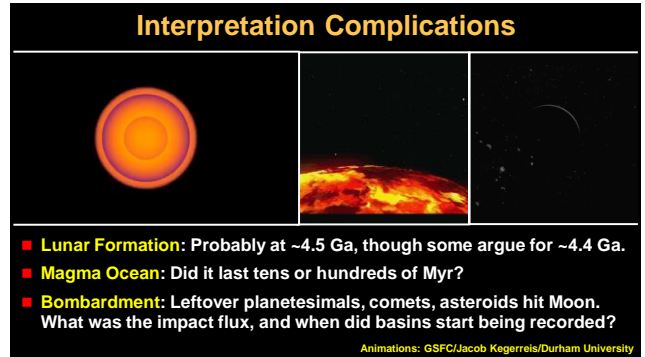
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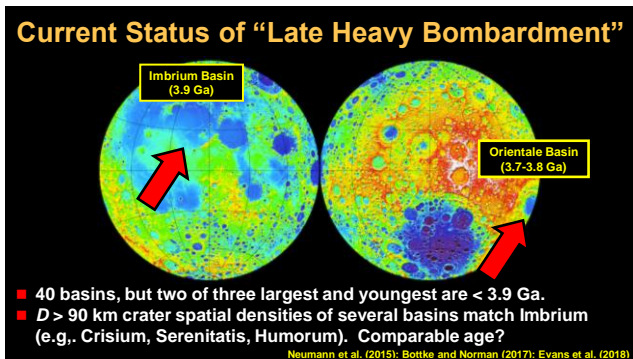
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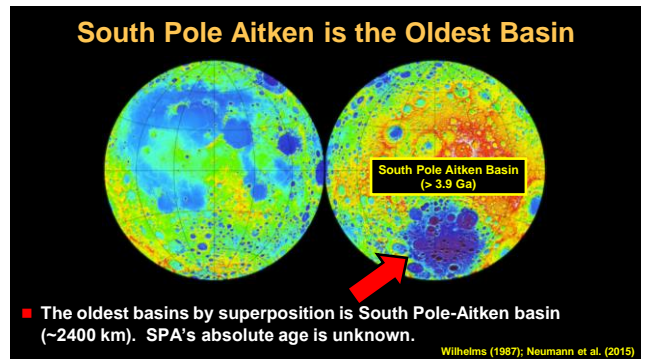
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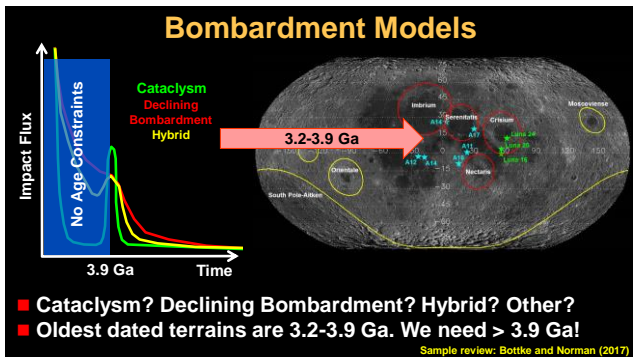
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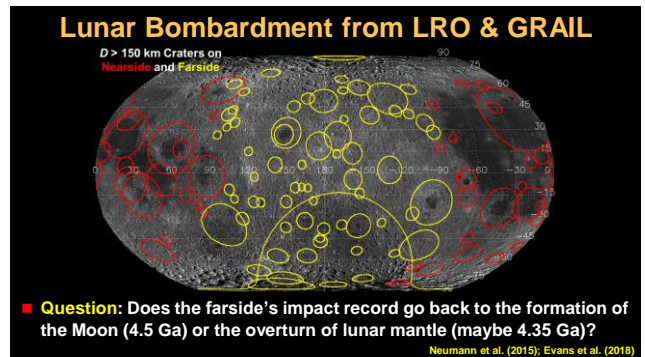
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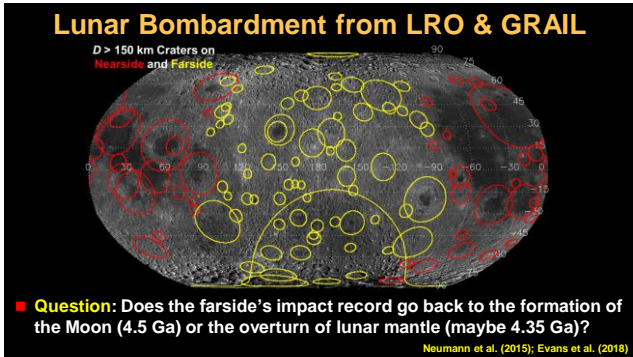
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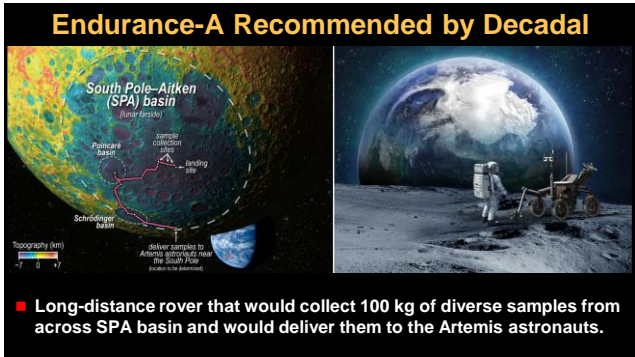
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Endurance-A Recommended by Decadal

Endurance is the best* approach for accomplishing the highest priority planetary science at the Moon.

*and cheapest, and fastest, while also maximizing science return and capitalizing on the strengths of NASA's robotic and human exploration capabilities and emerging commercial partners.

Decadal Survey - "The committee concluded that the Endurance-A rover mission is a superior approach for acquiring abundant samples across diverse terrains to address multiple top-level science questions for the Moon and the solar system. The committee recommends that NASA pursue Endurance-A as a strategic medium-class mission within LDEP."

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SPA is geologically and geochemically diverse.

There is no single location on the Moon that can **definitively** and **conclusively** answer all of the priority SPA science questions—necessitating a sample return campaign.

Endurance is a sample return campaign in one mission.

Endurance Science Objectives (as defined in the Decadal Survey, 22-46)	Sample Site Requirements (as defined in the Endurance concept study report)
Determine the age of the largest and oldest impact basin on the Moon, South Pole-Aitken (SPA) to anchor the earliest impact history of the Solar System.	≥1 sample from the SPA impact melt sheet, as supported by geochemical and/or geochronological data.
Determine when post-SPA basins formed to test the giant planet migration and terrestrial core formation models, and to constrain the inner solar system impact chronology used to date the surfaces of other planetary bodies.	≥1 sample from the impact melt sheet and/or peak ring of a basin, pre-titanic, farside impact basin, other planetary bodies.
Determine the age and mineralogical and geochemical composition of older and younger basins beyond SPA to understand the bulk composition of the Moon, its compositional differentiation and geologic evolution, and the significance of chronologic measurements conducted on mare basalts for timing lunar evolution.	≥1 sample from a Thorian hot spot (>2 ppm) on the lunar farside.
Determine the age and nature of volcanic features and compositional anomalies on the lunar farside to constrain the thermochronological evolution of basaltic rocks and constrain the origin of the Moon's nearside-farside asymmetry.	≥2 samples from different basaltic volcanic deposits, including mare basalt, picritic, or other volcanic units.
Determine the geologic diversity of the SPA terrain to provide geologic context for returned samples, ground truth for orbital measurements, and characterize the surface processes that shape planetary bodies.	≥1 sample from each of the three SPA: (1) SPA-A, (2) Pyroclastic Breccia Zone, (3) Heterogeneous Breccia.

Threshold Requirement: 6 samples
Baseline Requirement: 12 samples
1 sample is defined as 200g

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Why Go Back to the Moon?

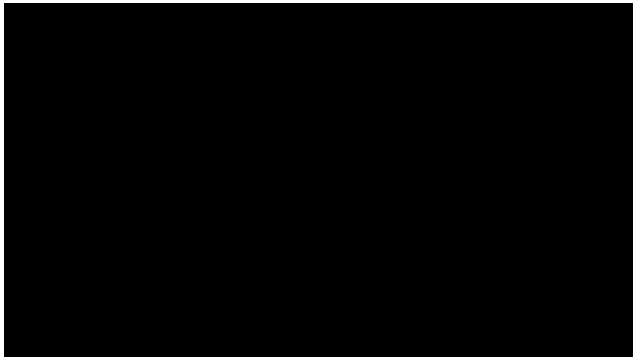
Earth-Moon Formation Early Lunar Bombardment

■ **Lunar samples from the right places may tell us about the origins of the Earth and the last stages of planet formation.**

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Backup Slides

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Big Issues to Explore

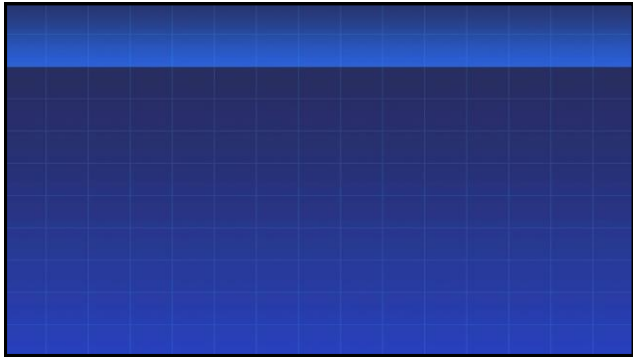
New Early Instability Models

GRAIL Data: Ancient Relaxed Basins

- Early giant planet instability -- What hit the Moon early?
- When did recorded time start for basins? Basin relaxation?

Sample references: Nesvorný (2018); Conrad et al. (2018); Evans et al. (2018); Nimmo (2019)

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Isotopically Earth-like Theia?

- Probability of Earth-like Theia in lithophile elements ~ 5 to 20%

Kaib & Cowen 2014, 2015; Mastrobuono-Battisti et al. 2015; Dauphas 2017

- **BUT:** Inferred equal Earth-Moon tungsten isotopic compositions much more constraining

Low probability of Earth-Moon W match, even if disk was Earth-like in other elements:

Probability distribution for initial Earth-Moon W isotopic difference from Kruijer & Kleine (2017)

Kruijer et al. 2015, Touboul et al. 2015

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Moon origin by multiple impacts?

Rufu et al. (2017):

- Likelihood of Earth-Moon compositional similarity increased
- Requires ≥ 20 sub-Mars sized impactors, if moonlets produced by all impacts merge

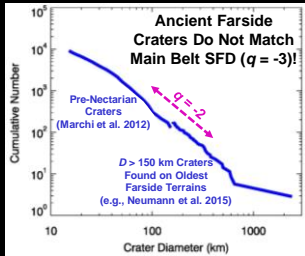
BUT: Moonlets do not always merge (Citron et al. 2018). Moon could accrete too much Fe-rich material as it grows alongside Earth.

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Early Moon orbited close to a rapidly spinning Earth

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Oldest Craters/Basins on Lunar Farside

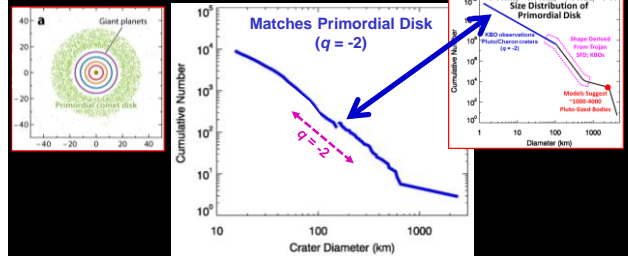


- Shallow size distribution ($q = -2$). Asteroid belt is wavy with $q = -3$.

Marchi et al. (2012); Neumann et al. (2015); Bottke and Norman (2017); Bottke et al. (2018)

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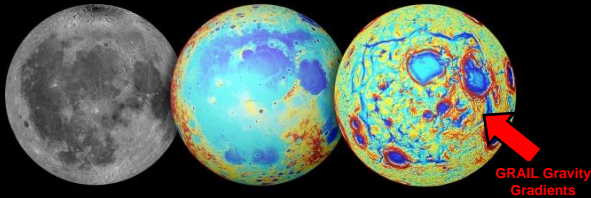
Ancient Lunar Bombardment



- Power law slope of farside craters/basins may match impactors from the primordial comet disk. Evidence for early giant planet instability?

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Nearside Dominated by Magmatic Feature



- **GRAIL:** Lunar nearside is a “square” magmatic region with giant rifts.
 - Heated by high concentrations of radioactive elements; Most older terrains have been erased. Possible formation by an impact?
 - Basins produced in this hotter region are naturally larger.

Miljković et al. (2013); Andrews-Hanna et al. (2014); Zhu et al. (2019)

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