Composition and origin of the Moon

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• Giant impact model ← chemistry and angular momentum
• Giant impact model is questioned.
  – Unexpected observations: “wet” Moon?
  – Very close agreement in isotope composition (+ different FeO content): hard to explain with a classic giant impact model
Outline

• Is there water in the Moon as much as in the Earth?: Geophysical evidence for the “wet” (not-so-dry) Moon

• How to explain the “wet” Moon with a giant impact model?

• How to explain the isotopic and major element chemistry of the Moon simultaneously?
Earth is depleted with volatiles ("dry") relative to the primitive materials (CI).

The Moon is depleted with volatiles relative to Earth. \( \Rightarrow \) very "dry" Moon.

Results with modern technology revised the volatile depletion pattern (to be explained).
Giant impact model and the “dry” Moon paradigm

Giant impact $\rightarrow$ intense heating ($\rightarrow$ condensation)
$\rightarrow$ depletion of volatiles (“dry” Moon paradigm)
$\rightarrow$ How much depletion really?

New technology allows to measure the volatile content more precisely $\rightarrow$ quite different view on the volatile content in the Moon
Inclusions in olivine in some lunar rocks show volatile content similar to Earth. → **Lunar interior** is as wet as Earth’s upper mantle (depleted but not-so-dry (~100 ppm wt water)).
The bulk of the Moon is substantially more depleted in volatile elements than Earth. (strong emphasis on Zn)

→ Not-so-dry rocks are not representative (anomalous samples)?

“Typical” lunar interior is dry (less than 1 ppm wt water).

→ How about the geophysical observations?
How about geophysical observations?

- Geophysical observations = global (indirect)
- Which observations?
  - Seismic wave velocities
  - Electrical conductivity
  - Tidal Q (viscosity)

In addition to affecting the semimajor axis, the frictionally tides on the planet also produce changes in eccentricity, inclination, and nodality. As we are particularly interested in changes of eccentricity, we shall consider the mechanism by which it is reduced.

A torque on a satellite which has an eccentric orbit is larger at apoapse than at apocenter. For this reason, the torque causes the periapse to precess. Although this results in a periodic radial component of the orbital angular momentum, the radial tidal dissipation in these radial tides, provided \( \epsilon \neq 0 \), is sufficient to cause the orbital energy without changing the tidal dissipation.

Electro-magnetic induction

Tidal dissipation
Deep lunar mantle has electrical conductivity as high as Earth’s asthenosphere (hot and “wet” region).
Water (hydrogen) enhances electrical conductivity.

\[
\sigma = \sigma_1 \left( \frac{f_{O_2}}{f_{O_2,0}} \right) q_1 \exp \left( \frac{H_s^*}{RT} \right) + \sigma_2 \left( \frac{C_W}{C_{W_0}} \right)^{q_2} \exp \left( \frac{H_s^*}{RT} \right)
\]

→ Useful water sensor

Karato (2011)
Temperature and water content in the Moon from electrical conductivity

“Dry” Moon predicts very high $T$ $\Rightarrow$ Some water ??

But no unique solution from conductivity alone because of the temperature-water trade-off
Anelasticity ↔ viscosity (temperature, water content)
Q: low Q ↔ “soft” materials

Low tidal Q (37-60 (Williams et al., 2001))
[tidal Q of solid Earth ~290 (Ray et al., 1996)
Seismic Q of the asthenosphere ~80
Seismic Q of the lower mantle ~300 (Dziewonski-Anderson, 1981)]
Water (hydrogen) enhances anelasticity (tidal dissipation).

\[
\frac{Q^{-1}(C_W, T; \cdot)}{Q_o^{-1}(C_{W_0}, T_0; \cdot)} = \left( \frac{Q}{Q_o} \right) \exp \left[ \frac{H_Q^*}{R} \left( \frac{1}{T} - \frac{1}{T_o} \right) \right]
\]

→ Another useful water sensor (needs some models on frequency and depth dependence)
Lunar mantle is cooler than Earth’s mantle, but its water content is similar to the Earth’s asthenosphere (or slightly less).
Volatile depletion in Earth and in the Moon from geochemistry (+ geophysics)

- The Moon and Earth are much depleted with volatiles compared to CI chondrite. (most volatiles were lost during the formation of Earth)

Volatile loss is controlled by the bond energy.

- The Moon is not much depleted with volatiles compared to Earth, and the degree of volatile depletion is insensitive to species (bond energy). (not much volatile loss during the Moon formation)

Volatile loss during the Moon formation is not controlled by the bond energy.

- Why is the nature of volatile loss so different in these two cases?
How to explain the different degree of volatile loss during planet formation? (back to the basics)

Moon formation (cosmochemistry)

How to explain the different degree of volatile loss during planet formation? (back to the basics)

- geology (petrology)
- [partial melting]
Why do **liquids** play an important role for the **Moon** while **solids** are important for **Earth**?

\[ P_{\text{disk}} = \frac{2}{\pi} \frac{G}{R^4} \left( \frac{2GM}{R^2} \right)^{\frac{3}{2}} \]

- \( \frac{1}{2} \)
- \( G \)
- \( \frac{1}{2} \)
- \( G \)
- \( \frac{M^2}{R^4} \)

Temperature \( \rightarrow \)  liquid; V, vapor; I previously.

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1.5 atm except for a progressive lowering of the equilibria to lower temperatures with decreasing temperature and small changes in the relative temperatures of the infalling solids as the sequence of appearance of solid phases with decreasing temperature changes slightly with decreasing total pressure. The solid phases of the latter at 1 atm are the break in the liquidus of all olivines, while at 1 atm olivines precipitate (\( T \)) at 1824 K, crystallizing in the olivine structures. Liquidus at the temperature at which the liquid first appears, \( T_{\text{liquid}} \) is the complete melting of melilitic (\( T_\text{liquid} \)) at the temperature at which the liquid reappears. At \( P_{\text{tot}} = 0.3 \text{ atm} \), the liquidus for melilitic, rather than spinel, crystallizing. When the Moon-forming disk (high P) is subjected to the absence of liquid at a temperature greater than that at which the liquid reappears. As \( P_{\text{tot}} \) falls, truncation of the increased MgO content of the liquid with falling temperature by another.

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**Solar nebula**

- gas \( \rightarrow \) solid: Solar nebula (low P)
- gas \( \rightarrow \) liquid: Moon-forming disk (high P)

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Not much water loss due to condensation to **liquid** (major water loss due to condensation to solid)

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**model:**

Not much water loss due to condensation to liquid

*only small degree of water depletion by condensation to liquid (amorphous materials can also dissolve a large amount of water)*
Volatiles during the Moon formation after a giant impact

**Moon-forming disk**
High P (high mass density) → condensation to liquids 
and $\tau_{\text{accretion}} \leq \tau_{\text{cooling}}$
($\tau_{\text{cooling}} \approx 100$ y, $\tau_{\text{accretion}} \approx 1-100$ y)
→ a large fraction of materials accrete as liquids
→ little depletion in volatiles

**Proto-solar nebula**
Low P (low mass density) → condensation to solids
[and $\tau_{\text{accretion}} \gg \tau_{\text{cooling}}$]
→ high degree of depletion in volatiles
How can we explain the similarity in isotopic composition and the different major element chemistry?

Very similar Ti isotope composition (Zhang et al., 2012)

Different Fe/(Fe+Mg) (higher FeO content in the Moon) (Khan et al., 2006; Kuskov-Kronrod, 1998)
<table>
<thead>
<tr>
<th>source</th>
<th>CaO</th>
<th>FeO</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
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<tbody>
<tr>
<td>Ringwood [3]</td>
<td>3.7</td>
<td>14.1</td>
<td>32.9</td>
<td>4.2</td>
<td>45.1</td>
</tr>
<tr>
<td>Taylor [4]</td>
<td>4.6</td>
<td>13.1</td>
<td>32.3</td>
<td>6.1</td>
<td>43.9</td>
</tr>
<tr>
<td>Wänke &amp; Dreibus [5]</td>
<td>3.8</td>
<td>13.1</td>
<td>32.6</td>
<td>4.6</td>
<td>45.9</td>
</tr>
<tr>
<td>O’Neill [6]</td>
<td>3.3</td>
<td>12.4</td>
<td>35.1</td>
<td>3.9</td>
<td>44.6</td>
</tr>
<tr>
<td>Kushov &amp; Kronrod I [7]</td>
<td>4.8</td>
<td>10.4</td>
<td>28.5</td>
<td>6.3</td>
<td>50.0</td>
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<tr>
<td>Kushov &amp; Kronrod II [7]</td>
<td>4.3</td>
<td>11.7</td>
<td>29.6</td>
<td>5.9</td>
<td>48.5</td>
</tr>
</tbody>
</table>

bulk silicate Earth; McDonough & Sun [8] 3.6 8.2 38.2 4.5 45.5

Melosh (2014)

Sakai et al. (2014)
Challenges in developing a model to explain the chemistry of the Moon

- **Isotope** → the Moon and Earth have very similar composition
- **FeO** → major element chemistry is different
  - How could the Moon be formed mostly from the proto-Earth materials?
  - If the Moon was formed from proto-Earth, then why FeO composition is so different between the Moon and Earth?
A standard model: oblique collision (large angular momentum) → shearing the impactor → a majority (~70%) of the Moon is made of the impactor materials (inconsistent with the chemistry)

Canup (2004)
How to explain the similar isotopic compositions and dissimilar FeO?

  → angular momentum?, how good is the mixing?
- A majority of Moon is from Earth (and the impactor mass was not large): Cuk-Stewart (2012)
- Same size bodies collided and mixed completely: Canup (2012)

→ All previous models do not explain dissimilar FeO content. Problems in explaining the large angular momentum.

→ A new model: magma-ocean origin of the Moon
Giant impact and the composition of the Moon

A crisis?

“classic” model
Benz et al. (1986)
Canup (2004)
→ different composition

Cuk-Stewart (2012)

Canup (2012)

Clery (2013)
Problems with the Cuk-Stewart model

1. Only in a small parameter space one can have composition similar to Earth (*by chance?).
2. Predicts a major element composition inconsistent with the observation.
Problems with the Canup, Cuk-Stewart models

1. Only in a small parameter space, one can obtain composition similar to Earth *(by chance?)*.
2. Predicts a major element composition (FeO) that is inconsistent with the observation.
3. Difficult to explain the large angular momentum.
A mixing model
(Melosh, 2014)

→ Very extensive mixing must occur to explain a similar composition.
→ Hard to explain the angular momentum (large mass exchange → large momentum exchange → reduce the angular momentum of the Moon → a serious problem!?)

Also this model does not explain the difference in FeO.
Terrestrial magma ocean origin of the Moon

- Similarity in the isotope composition but higher FeO than Earth $\rightarrow$ the Moon from the magma ocean of the proto-Earth?

- Is this a physically plausible model?
  
  - Physics of shock heating
    
    Proto-Earth likely had a magma ocean, an impactor was likely a solid planet $\rightarrow$ heating differently?

  - Physics of collision/ejection
Collision $\rightarrow$ pressure, volumetric strain
liquid-solid collision leads to a large compression of liquid

Karato (2014)
Liquid is more heated than solid

\[
dT = \left\{ \frac{r}{V} + \frac{1}{2C} \left[ (P - P_o) + (V_o - V) \frac{dP}{dV} \right] \right\} dV
\]

Compressional properties of **liquids** are very different from those of **solids** → heating of liquids >> heating of solids → the Moon mainly from the magma ocean of the proto-Earth

Karato (2014)
If a magma ocean is present in the proto-Earth, a large amount of vaporized materials upon a giant impact (the Moon) is from the magma ocean.

→ **How much materials exchange** (between the proto-Earth and the impactor) do we need to explain the observed chemical composition?

→ **Mass balance calculation**
Mass balance and the isotope ratio upon a giant impact

\[ m = \left( \frac{x}{y} \right)_m \quad I = \frac{1}{2} \left( \begin{array}{cc} 1 & 2 \\ \frac{1}{M} & \frac{1}{M} \end{array} \right) + \frac{1}{2} \left( \begin{array}{cc} 1 & 2 \\ \frac{1}{M} & \frac{1}{M} \end{array} \right) \] = \left( \begin{array}{cc} 1 & 2 \\ \frac{1}{M} & \frac{1}{M} \end{array} \right) \]

\[ 1,2 = \left( \frac{x_{1,2}}{y_{1,2}} \right) \]

→ If a large amount of the Moon is from the \textbf{proto-Earth}, the correction factor will be small enough to explain the isotope and FeO composition. [Without magma ocean, \( \sim 70\% \) of the Moon would be from the \textbf{impactor}]
Terrestrial magma ocean origin of the Moon

- Magma ocean (melting)
  - different major element chemistry
  - no or little change in (the heavy) isotope composition
  - Similarity in the isotopic composition
  - Dissimilarity in the major element chemistry
- Explains the chemistry of the Moon as a "natural" consequence of planetary formation
Conclusions

Not only geochemistry, mineral physics (+ geophysics) helps understand the composition and the origin of the Moon.

• Water content in the lunar mantle
  – Geophysical obs. + mineral physics
  → the Moon is as “wet” as (or slightly less wet than) Earth
  → Condensation of liquid phases + quick accretion compared to cooling time-scale (due to the small space in which the Moon was formed)

• Collisional heating
  – Mineral physics + thermodynamics → heating the pre-existing magma ocean, not much heating on the solid part
  → the Moon from the magma ocean of the proto-Earth?
  both isotope obs. and FeO content can be explained.
  [if more than ~70% of mass is from Earth, isotope obs. can be explained]
  → Need numerical modeling is needed: work in progress in collaboration with Hosono and Makino at Riken, Kobe, Japan)
Liquids and solids have different thermodynamic properties.

Condensation temperature $T_c$:

$$\left[ \frac{\text{gas}}{i} = \frac{\text{gas}}{i,o} + RT_c \log(1 - \left(\frac{f_i}{P_0}\right)) \right] = \frac{\text{solid, liquid}}{i}$$

Gas $\rightarrow$ solid
- **Internal energy** dominates
- Strong effect of chemical bonding
- Sensitive to species

Gas $\rightarrow$ liquid
- **Configurational entropy** dominates (Jing-Karato, 2011)
  - **Hard sphere model** (~van der Waals model)
- Little effect of chemical bonding
-Insensitive to species

Liquid $\leftrightarrow$ solid contrast explains the difference in the abundance pattern of volatiles between Earth and Moon.
Many questions are unanswerable. Many answers are questionable.
Shearing versus vapor jets

(impactor versus magma ocean)

\[
shear: \quad f_{\text{shear}} \approx \frac{\Delta(\rho v)}{\Delta t}, \quad \text{jets:} \quad f_{\text{jet}} \approx \frac{\Delta P}{\Delta L}
\]

\[
\frac{f_{\text{jet}}}{f_{\text{shear}}} \approx \frac{\Delta P}{\Delta L} \frac{\Delta t}{\Delta(\rho v)} \approx 10^{-2} \Delta t
\]

\[
\Delta t \approx 10^3 \text{ (sec): Canup (2004) } \rightarrow \text{ jet dominates?}
\]
Outline/Summary

• **The Moon is not-so-dry.**

Water content of the Moon can be inferred not only from the direct *geochemical method* but also indirectly from the *geophysical method*. → slightly less water than Earth

• **Not-so-dry Moon can be explained by a model of Moon formation in the small space (giant impact).**

*Liquids* play a key role.

→ conventional *volatility scaling* (based on the gas to *solid* condensation) does not work for the Moon.
Problems with the Canup (2012) model

1. Only in a small parameter space one can have composition similar to Earth (*by chance*).
2. Predicts a major element composition inconsistent with the observation.
3. Difficult to explain the large angular momentum
How do we infer the water content in a planet?

**Geological (geochemical) obs.**
(direct, limited regions and depth)

**Geophysical obs.**
(global, indirect)

Need a microscopic model (theory) based on **mineral physics**
Probability of ejected materials to go to the proto-Earth surrounding orbit (case B)

Gaseous phase expands (large $\chi = \frac{h}{R_\oplus}$) → more chance to get into the proto-Earth surrounding orbit (in previous studies, materials going to the orbit were mostly from the impactor)

Stevenson (1987)
Is the Moon formed mostly from the impactor or from the proto-Earth?

Collision ejects materials → materials that are ejected to a certain height and velocity could become the Moon.