Rocky samples from the Solar System – what do we learn from meteorites and lunar rocks?

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Extraterrestrial samples

- Small amount of extraterrestrial material
- Meteorites (~60,000)
- Composition of the Solar System objects
- Deep Earth objects
- Organic matter – signs of early life?
- Pre-solar grains, material older than the Solar System itself

**Stardust comet Wild 2 (2006) and Tempel 1 (2011)**

**Hayabusa Asteroid Itokawa 2010**

**Apollo & Luna (~380 kg)**

**Tenham L6**
**INTRO...**

**Meteoroid**
Small rocky object in outer space, significantly smaller than asteroid

**Meteor**
A meteor is a meteoroid that has entered the earth's atmosphere and becomes brightly visible due to the ionized molecules in the upper atmosphere

**Meteorite**
A meteoroid that reached surface of the Earth
**Introduction**

**Meteorite:** a meteoroid that survives that flight through the atmosphere (\(\sim\) minutes) and reaches the surface of the Earth

- Enters Earth’s atmosphere at speed 11-72 km/s
- Ionization begins at 100 km of height
- Fusion crust but **cold** surface
- Aerodinamical shape

- **Pad (Fall):** The flight was observed before collecting the meteorite (Chelyiabinsk)

- **Nalaz (Find):** all others
Josif Pančić, Soko-Banja prvi meteorit u Srbiji/ Glasnik Srpskog učenog društva, XLVIII (1880)
Meteorites

Undifferentiated

Differentiated

Stony meteorites

Achondrites

Irons

Stony-irons

Chondrites

Most studied meteorites fell to the Earth ≤0.1 Ma ago
Solar System formation was initiated 4.56 billion years ago by collapse of the interstellar matter.

Protoplanetary disc was formed and early planetesimals (> 1km) accreted.

Further accretion led to planet formation.

Closer to the Sun: terrestrial planets – snow line – gas planets.

The asteroid belt – source of the meteorites.
Early condensates: refractory droplets

- Refractory elements condensate first (> 1600 K)
- Local flash heating
- Metals: Re, Os, Hf, W, Zr, Ir, Ru
- Trace abundances – form small metal droplets (1mm)
Early condensates: refractory inclusions

- Furter on Ca, Al, Ti condensate – forming Ca-Al inclusions (CAI)
- High-T oxides (ceramics!): 1600 K
- The oldest dated material in the SS: 4567 (±2) million years-first solids in cooling protoplanetary disc
- Refractory droplets found within CAIs
Allende Ca, Al-rich inclusion (CAI)
Early condensates: chondrules

- Metals condensate: Fe, Mg and Si
- First silicate minerals
- **Olivine** \((\text{Fe,Mg})_2\text{SiO}_4\)
- **Piroxene** \((\text{Mg,Fe})_2\text{Si}_2\text{O}_6\)
- Chondrules: small (0.1-5 mm) silicate droplets that mostly contain olivine and pyroxene
- **First miny-rocks!**
- Formed 1 – 4 Myr after CAIs
- Other components: Ca-silicates, Fe-Ni metal...
Olivin

Olivin i piroksen
Chondrules: 1\textsuperscript{st} silicate rocks
Undifferenced meteorites: Chondrites

- **Asteroid type C**
- **Asteroid type M**
- **Asteroid type S**

- Carbonaceous: most primitive meteorites (water and organic m.)
- Ordinary: H (high iron), L (low iron), and LL (low total iron) (Sokobanjski, Jelički, Čeljabinsk)

The oldest meteorites in the SS
- Their bulk composition reflects the composition of the Sun
- Often used as reference material
Dhofar
(Ordinary Chondrite H)

(Petnička kolekcija)

North West Africa
(Ordinary L)

North West Africa
(CO)
Planetesimal accretion

- Planetesimal accretion due to chaotic impacts – mass and size growth (up to 500 km in diameter)
- That leads to internal temperature increase
- $^{26}\text{Al}$ and other short-lived radioactive isotopes produce heat (e.g. daughter-isotope $^{26}\text{Mg}$)
- Other sources of heat: impacts, collisions, gravitation & further accretion
- Melting of Fe-Ni ($\sim 1200\text{K}$) and silicates ($\sim 1300\text{K}$)
Formation of the protoplanets

- Silicate and metal liquids/melts are incompatible – causing separation and differentiation
- Metallic (Fe-Ni) melts are denser and sink to form a core
- Silicate melts (olivine, piroxene) melts migrate to the surface
Differentiated meteorites do not contain chondrules.

Only a minor (8%) group of total number of meteorites.

Mostly younger than chondrites.
Differentiated meteorites: core and mantle

- Core and mantle of once existing protoplanets
- Core samples of destroyed protoplanets = **Iron meteorites**
- Mantle: contact of core and deep mantle
- Incompatible melts of metal and silicate:
  - **Pallasite** (metal and olivine)
  - **Mesosiderite** (rich in silicates)

Gibeon, oktaedrit, 1836
**Widmanstätten-Pattern**

Palasit Fukang, China, 2000
1003 kg
Differentiated meteorites: crust

- **Achondrites**: Meteorites sampling asteroids’ surfaces
  
  HED (4 Vesta) Hovardite; Eucrite; Diogenite

- Originate from the surface of differentiated bodies – rich in silicates, depleted in metals

- Very similar to terrestrial basalts: volcanic textures

- Asteroid 4 Vesta (asteroid belt, 530 km diameter)

Textural similarity of the basaltic eucrite Stannern (left; pyroxenes white to gray; pyroxene, brown to buff) compared with a terrestrial basalt (right; same with highly colored olivine grains).
Differentiated meteorites: crust

- **Lunar & Martian meteorites**
  - **Lunar (138 meteorites, 222 kg):** blasted of $<20$ Ma ago, but mostly few hundred thousand, small craters
  - Many originate far from PKT (low Th)
  - **Martian (124):** wide range of crystallization ages, launched in last 20 Ma
  - Noble gases composition (Ar) confirmation of Mars atmosphere
  - *Shergottite, Naklithe i Chassignite different groups*
  - *ExoMars possible sample return 2030*

![stishovite](image1)
![Shocked quartz](image2)
SUMMARY

Asteroid type C
Asteroid type M
Asteroid type S
Collecting meteorites systematically

- Until 1978 only about 3000 meteorites around the world
- Antarctic, Sahara, Botswana missions
- Micrometeorites collected in snow ice and deep sea sediments
It was the year 1969...

- Fireball Feb 8th 1969, Pueblito de Allende
- 2 tonnes of meteorite (largest piece 110kg), covering 50km area
- Served as laboratory preparation for Apollo missions (Apollo 11 July 1969)
- Best studied meteorite CAIs & organic matter
Lunar samples

- Core tubes
- Tongs
- Scoops
- Rakes
- Hammers
- Drills
Sample return

- **Luna sample return:** Luna 16, 20 and 24 collected 0.3 kg of lunar soil

- **Apollo sample return:** Six Apollo missions ~382 kg of **rocks** and soil
  - Apollo 11: 22kg (basalts and breccias)
  - Apollo 12: 34 kg (almost all basalts)
  - Apollo 14: 42 kg (mostly breccias)
  - Apollo 15: 76 kg (basalts and breccias)
  - Apollo 16: 96 kg (mostly breccias)
  - Apollo 17: 111 kg (highland samples and breccia)

Apollo 17 – a geologist on board; focused selection of the acquired samples
Geology of the Moon

**Highlands (crust)**
- Light in colour
- Represent lunar crust
- Several different types of rocks
- Ancient

**Maria:**
- Dark in colour
- Basalts (cooled lava)
- Younger

To understand where the difference comes from, we have to consult mineralogy.
Intro to mineralogy

- These are the most abundant elements on Moon & Earth
- Elements are combined into inorganic (crystalline) compounds **i.e. minerals**
- Minerals join together to form a rock

**Important for general mineral & rock composition of the planets:**
- Si, Al, Fe, Ca and Mg are the most common elements on Earth and Moon
- Note the high amount of Ti on Moon
- Note the low amount of Na and K on Moon (easily evaporated elements i.e. volatile)

**Useful analogy:** letters form words, words form sentences
- Rocks are like sentences – we read geologic history by understanding the meaning of each word and their context
Intro to mineralogy

- These are the most abundant elements on Moon & Earth
- Elements are combined into inorganic (crystalline) compounds i.e. minerals
- Minerals join together to form a rock

**Moon crust:**

**Common minerals:**
- Plagioclase (Ca$_2$Al$_2$Si$_2$O$_8$)
- Pyroxene (Ca,Mg,Fe)$_2$Si$_2$O$_6$
- Olivine (Mg,Fe)$_2$SiO$_4$
- Ilmenite FeTiO$_3$
- And few dozen accessory minerals

**Useful analogy:** letters form words, words form sentences
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**Earth crust:**

**Common minerals:**
- Plagioclase (Ca$_2$Na$_2$Al$_2$Si$_2$O$_8$)
- Feldspar (K, Na)$_2$Si$_2$O$_6$
- Quartz (SiO$_2$)
- Pyroxene (Ca,Mg,Fe)$_2$Si$_2$O$_6$
- Mica, Amphibole (contain water)
- And few thousand accessory minerals

**Elements are combined into inorganic (crystalline) compounds i.e. minerals**
- The fact that the Moon has only a handful of different minerals
- Moon’s history is frozen in time – processes in early Solar System
Surface rocks

Maria (ca. ~3.9-3.2 Ga, and younger)
Minerals:
• Pyroxene (black or green)
• Ilmenite (black)
• Olivine (green)
• Some plagioclase (white)
• A LOT of accessory minerals
Rocks:
• Mare basalts, KREEP basalts, and volcanic glasses

Crust (ca. 4.5 – 3.9 Ga)
Minerals:
• Dominantly plagioclase (white)
• Some pyroxene (black or green)
• Some olivine (green)
• Some accessory minerals
Rocks:
• Primary crust – anorthosite (plagioclase)
• Secondary crust – Mg suite, alkali suite

(after Gilin 2010)
Surface rocks

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**Surface rocks**

**Crust (ca. 4.5 – 3.9 Ga, & younger)**
- Minerals:
  - Dominantly plagioclase (white)
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  - Some olivine (green)
  - Some accessory minerals
- Rocks:
  - Primary crust – ferroan anorthosite
  - Secondary crust – Mg suite, alkali suite

**Maria (ca. 4.35, ~4 – 1 Ga, 100 Myr?)**
- Minerals:
  - Pyroxene (black or green)
  - Ilmenite (black)
  - Olivine (green)
  - Some plagioclase (white)
  - A LOT of accessory minerals
- Rocks:
  - Mare basalts, KREEP basalts, and volcanic glasses
  - Variable content of Ti and KREEP (lead to the overturn)

**Two other important types of rocks**

- Orange volcanic glass
- Breccia
- Troctolite 76535
- Basalt 15058
- Crust
  - Basalt
Analysing rocks

- Rocks are like sentences – we read geologic history by understanding the meaning of each word and its context.
- Thin-sections of rocks to read the story.
- Texture, composition and reactions (solid-state transformations).

https://www.virtualmicroscope.org/content/12039-45-pigeonite-basalt
Analysing rocks

- Thin sections, *in situ* mineral analyses
- Secondary Electron Microscopy (SEM); Electron Microprobe Analyser (EPMA) – elemental abundance
- Electron Backscatter Diffraction (EBSD), Transmission Electron Microscopy (TEM) to understand (IR, Raman) crystal structure
- Secondary Ion Mass Spectrometry (SIMS) for isotopic species (e.g. H and D; oxygen isotopes, U-Pb age)
- Atom Probe Tomography (nm-scale elemental & isotopic composition)
What do surface rocks tell us?

- Constraints on the Moon-forming impact (e.g. oxygen isotopes)
  - **Pre-Apollo:** Co-accretion; Fission; Capture
  - **Post-Apollo:** Giant-impact (with variations of impact-origin)

- Apollo samples have virtually identical isotopic signatures compared to Earth rocks for isotopes of O, Cr, Ti, K, Si and H (water), in contrast to all meteorites
- Lunar rocks and terrestrial basalts show a 3 to 4 ppm (parts per million), statistically resolvable, difference in oxygen isotopes (Greenwood et al. 2018) – highest achievable precision up to date!
What do surface rocks tell us?

- Derive the age of the crater forming and crater filling events
- Absolute ages on Apollo samples tied to specific lunar craters
- Concept of Late Heavy Bombardment (LHB)
- Application to age dating of surfaces of other bodies in the inner Solar System

Credit: K. Joy adapted from the Stoffler et al. (2006)
What do surface rocks tell us?

- New clues about water & volatile content of the lunar interior
  - **Early-Apollo:** 'bone-dry' Moon (<1 ppb H$_2$O)
- Lack of hydrous minerals in Apollo and Luna samples (Papike et al. 1998)
- Any water detected considered terrestrial contamination (e.g., Epstein and Taylor, 1970)
- Lack of global remote sensing data & high-resolution mass spectrometry until recently

**Water from the interior**

**Water formed on the surface**
What do surface rocks tell us?

- New clues about water & volatile content of lunar interior
  
  **Early-Apollo:** ‘bone-dry’ Moon’s interior (<1 ppb H$_2$O)

  **Current estimates:** > 10 – 300 ppm (Earth’s mantle-like)

Mineral apatite (Ca$_5$(PO$_4$)$_3$(OH,Cl,F) contains H$_2$O)

H$_2$O abundance was measured from this small 10x10 µm pit using very high-resolution mass-spectrometry (instrument named Nano-SIMS)

(e.g. Saal et al., 2008 Nature; Hauri et al. 2011 Science; Barnes et al. 2014; 2016; etc.)
What do surface rocks tell us?

- New clues about water & volatile content of lunar interior

**Pre-Apollo:** ‘bone-dry’ Moon’s interior (<1 ppb H$_2$O)

**Current estimates:** > 10 – 300 ppm (Earth’s mantle-like)

- Current data and models agree with the delivery of volatiles to the Moon mainly by C chondrite-type asteroids (=very primitive material) with minor input from comets

(e.g. Saal et al., 2008 Nature; Hauri et al. 2011 Science; Barnes et al. 2014; 2016; etc.)

Barnes et al. 2016
Summary and Future Directions

• Almost 50 years on, Apollo lunar samples continue to yield valuable data about the origin and evolution of the Moon and the inner Solar System.

• Major concepts (e.g., magma ocean; giant-impact; LHB) in Planetary Sciences have been developed through research on Apollo samples.

• Uniformity of $\delta D$ between mantles of Earth, Moon, and HED (Vesta) parent body argues for a common origin for water in the inner Solar System.

• Returned samples allowed remotely sensed data to be properly calibrated, interpreted and expanded to areas from which no samples have been yet returned.

• Information from these studies would provide key input to future sample return missions from different target bodies (e.g, Phobos, Moon, Mars, Benu).

• Careful curation and distribution of Apollo sample by NASA CAPTEM has played a key role in maximising science outputs from analytical advances.

• A large proportion of Apollo samples remain sealed (e.g., drive tubes). Time to open some of these in light of recent research? **One core just got open!**
Reklame!

Školica u ISP

(planirano 2020)

Meteoriti na PMFu i izložba meteorita: Alena & Nataša

Europlanet u Srbiji
Unique characteristics of lunar rocks:

• No unique chemical elements on Moon, but unique ratio and hence mineral composition

• Moon has a handful of major minerals; no major minerals that contain water (lice micas on Earth)

• Earth has more than 1000 minerals, and about 150 major minerals

• Moon has very low Na and K

• Moon has Fe$^{2+}$ iron (Earth has mostly Fe$^{3+}$)

• Abundant Ti

• Cosmogenic nuclides (CRE)
Thank you!

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