Interstellar radionuclides in lunar samples

Leticia Fimiani

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Outline

- Accelerator Mass Spectrometry at MLL
- $^{60}\text{Fe}$ and $^{53}\text{Mn}$
- Past work
- Results
- Summary
Accelerator Mass Spectrometry

- High-sensitive counting technique, primarily used for long-lived radioisotopes for determination of isotopic ratios (e.g. $^{60}\text{Fe}/\text{Fe} \sim 10^{-16}$).

- Tandem accelerator based systems: complete molecular background suppression.

- High energies ($\sim 150$ MeV): nuclear physics particle identification techniques.

- Only few milligrams of sample material needed.
Maier Leibnitz Laboratorium

Accelerator Mass Spectrometry at the 14 MV Munich MP Tandem
Ion source

• Exclusively for AMS
• Dedicated sources to different isotopes
• Spherical ionizer:
  - aimed sputtering
  - high mass resolution

Courtesy of P. Hartung
Gas-filled Analyzing Magnet System

\[ q \quad q+3 \quad q+2 \quad \text{Mn}^{q+} \quad \text{Cr}^{q+} \]

\[ q+1 \quad \text{Mn}^{q+} \quad \text{Cr}^{q+} \]

vacuum

foil

gas

foil

magnet chamber

slits

ionization chamber

53\text{Cr}^{q+}

53\text{Mn}^{q+}
Ionization chamber

9 „independent“ signals

Frisch grid: et
y-angle: dt
position: p
x-angle: dp
Standard sample: $^{60}\text{Fe}/\text{Fe} = 1.2 \times 10^{-12}$
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Sample 69921 (Apollo 16)

26.03.2013
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Sample 69921 (Apollo 16)
Sample 69921: $^{60}\text{Fe}/\text{Fe} = 1.2 \times 10^{-14}$
Production of $^{53}\text{Mn}$

Half life: 3.7 Myr

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In stars:
$^{53}\text{Fe}$: explosive silicon burning, rapidly decays to $^{53}\text{Mn}$

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**Via Cosmic Rays:**
Spallation processes in Fe targets
Production of $^{60}$Fe: via Cosmic Rays

Half life: 2.62 Myr

[Rugel et. al., PRL 103, 072502, (2009)]
Production of $^{60}$Fe: via Cosmic Rays

Spallation on nickel

Half life: 2.62 Myr

[Rugel et. al., PRL 103, 072502, (2009)]
• Shell He burning in massive stars \((M > 40 \, M_{\odot})\)
• Shell C burning in massive stars \((M < 40 \, M_{\odot})\)
• Explosive synthesis created by the blast wave as it passes through the mantle of the star.

Past work

Indication of a SN event near our Solar System (∼40 pc), 2-3 Myr ago.

Ferromanganese crust from equatorial pacific (9°18’ N, 146°03’ W), depth 4830 m

Fitoussi et al., PRL 101, 121101 (2008)

\[ ^{60} \text{Fe} : 10^{-5} - 10^{-4} M_\odot \]

\(~10^{50} \text{ atoms}\)

Growth rate: 2.37 mm/Myr

1.7 – 2.5 Myr
The Local Bubble

• Cavity of hot thin gas in the local ISM
• 13 Myr old
• Excavated by 10 – 20 SNe.

⇒ Maybe multiple SNe are responsible for the $^{60}$Fe peak

Feige; The connection between the Local Bubble and the $^{60}$Fe anomaly in the deep sea hydrogenetic ferromanganese crust, Magisterarbeit, Universität Wien, 2010

Breitschwerdt, Avillez; The history and future of the Local and Loop I bubbles. Astronomy and Astrophysics, 452:L1-L5, 2006
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Should be also seen on the Moon
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On the Earth…

- Samples easily obtainable
- Atmosphere
- Complex element cycles
- Sedimentation/growth rate
- Time resolved signal
- Uptake factor?
- Dilution of the signal?

On the Moon…

- Limited sample amount
- No atmosphere
- Direct surface exposure
- No sedimentation, but gardening
- No time resolution
- U = 100%
- Determination of fluence
The Apollo Program

- Six manned missions
- 12 men walked on the Moon
- 381.7 kg of material returned to Earth

We received samples from Apollo 12, Apollo 15 and Apollo 16:

~ 2 grams
First measurements: $^{60}\text{Fe}$

Cook et al, LPSC XXXIX (2009)
First measurements: $^{60}\text{Fe}$

Potential origins:

• Galactic Cosmic Rays
• Solar Cosmic Rays
• Deposition of SN debris.

Cook et al, LPSC XXXIX (2009)
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$P_{60^{\text{Fe}}-\text{GCR}} = (0.88 \pm 0.44)$ dpm/kg Ni

$P_{60^{\text{Fe}}-\text{SCR}} = 0.07$– 0.45 dpm/kg Ni on the surface


Cook et al, LPSC XXXIX (2009)
Potential origins:

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$^{60}$Fe depth profile

Potential origins:
- Galactic Cosmic Rays
- Solar Cosmic Rays
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Quantification of the local interstellar fluence:

$$\Phi^{60\text{Fe, LIF}} \approx 1 \times 10^7 \text{ at} \frac{\text{at}}{\text{cm}^2}$$

$^{53}$Mn depth profiles: 12025/8

![Graph showing $^{53}$Mn depth profiles with data points from This work and Nishiizumi (1990).]
$^{53}\text{Mn}$ depth profiles: 15008
$^{53}$Mn depth profiles: 60007/6

![Graph showing depth profiles of $^{53}$Mn](image)

- **This work**
- **Imamura (1974)**
- **Nishizumi (1976)**

Depth [g/cm²]

$[^{53}$Mn [dpm/kg Fe]]
Comparison

Nishiizumi et al, EPSL 44 (1979)

Nishiizumi et al, EPSL 44 (1979)
Excess of $^{53}\text{Mn}$?

? Mixing of the regolith

? Addition of irradiated material

? SN debris

? ...

GAMS (2012)  
Nishiizumi et al. (1979)
$^{60}\text{Fe}$ vs $^{53}\text{Mn}$

1-2: Apollo 12 samples
3-4: Apollo 16 shaded samples
5-7: Apollo 15 samples
8-11: Apollo 16 samples
12-18: Meteorites
$^{60}\text{Fe}$ vs $^{53}\text{Mn}$

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$^{53}\text{Mn}$ [dpm/kg Fe]

$^{60}\text{Fe}$ [dpm/kg Ni]

cosmogenic
$^{60}\text{Fe}$ vs $^{53}\text{Mn}$

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$^{53}\text{Mn}$ [dpm/kg Fe]

$^{60}\text{Fe}$ [dpm/kg Ni]
Summary and future work

♦ Indication of SN debris deposition on the lunar surface.
♦ Local interstellar fluence of $^{60}\text{Fe} \approx 1 \times 10^7 \text{ at/cm}^2$.
♦ The surplus of $^{53}\text{Mn}$ is conceivable to be of SN origin.
Summary and future work

- Indication of SN debris deposition on the lunar surface.
- Local interstellar fluence of $^{60}$Fe $\approx 1 \times 10^7$ at/cm$^2$.
- The surplus of $^{53}$Mn is conceivable to be of SN origin.

Thank you for your attention!
Past work

\[ ^{60}\text{Fe}: 10^{-5} - 10^{-4} \, \text{M}_{\odot} \]

\(~10^{50} \text{ atoms}\)

\[ \Phi^{^{60}\text{Fe,crust}} = (2.9 \pm 1.0) \times 10^6 \frac{\text{at}}{\text{cm}^2} \]

Model with many assumptions and uncertainties:

- Accretion rate of extraterrestrial material on Earth
- Local flux of \(^{53}\text{Mn}\)
- ...

\[ U_{\text{Fe}} = \frac{\Phi^{^{60}\text{Fe,crust}}}{\Phi^{^{60}\text{Fe,TOT}}} = \left( \frac{C_{\text{Mn,water}}}{C_{\text{Fe,water}}} \right) \times \left( \frac{C_{\text{Fe,crust}}}{C_{\text{Mn,crust}}} \right) \times U_{\text{Mn}} = 0.6\% \]

Local interstellar fluence:

\[ \Phi^{^{60}\text{Fe,LIS}} = \frac{4}{U_{\text{Fe}}} \times \Phi^{^{60}\text{Fe,crust}} = 2 \times 10^9 \frac{\text{at}}{\text{cm}^2} \]

Revised value: \(~100\) times smaller than the one above.
Apollo 12: Drive Tube 12025/8

Alan Bean placing and hammering the core tube into the Lunar surface

AS12-49-7285

AS12-49-7286

Nishiizumi et al, EPSL 44 (1979)
Apollo 15: Drive Tube 15008

David Scott
Alfred Worden
Jim Irwin

Nishiizumi et al, LPSC XXI (1990)

This work
Fruchter et al. LPSC 12, 567 (1981)

\[ 23 \text{Al} \text{[dpm/kg]} \]

\[ \text{Mn-53} \text{[dpm/kg Fe]} \]

Nishiizumi et al, LPSC XXI (1990)

AS15-87-11847

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Nishiizumi et al, LPSC XX1 (1990)

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Apollo 16: Deep Drill Core 60007

John Young  Ken Mattingly  Charles Duke

Apollo 16: 69921/41/61

John Young  Ken Mattingly  Charles Duke

69921 & 69941 collected from the shade cast by this boulder

69961 was collected from the soil underneath the boulder, after being rolled over
On the Moon…

- Net sedimentation rates are small: $U_{60Fe} \sim 100\%$
- Ni concentrations are in general low: low in-situ production of $^{60}Fe$

- Gardening of the lunar surface: $\sim 2-3$ cm reworking depth in 10Myr

- Hard to reach
