Spectra of solar energetic particles and galactic cosmic rays over Myrs reconstructed using $^{26}$Al from lunar rocks

Stepan Poluianov$^1$
G. Kovaltsov$^2$ and I. Usoskin$^1$

$^1$- Space climate research unit and Sodankylä geophysical observatory, University of Oulu, Finland
$^2$- Ioffe physical-technical Institute, St. Petersburg, Russia
$^{26}\text{Al}$ produced in situ at the Moon

- Nuclides stay where they have been produced. No transport. No time resolution.
- Depth distribution of nuclides → information about the spectrum.
- Outside the magnetosphere → solar energetic particles significantly contribute to the total nuclide production.

- In this talk:
  only Al-26 (lifetime 1.03 Myr).

(NASA, AS15-87-11847,cropped)
Lunar samples

- **Deep drill core 1500x (Apollo-15)**
  
  [Rancitelli et al., 1975, Nishiizumi et al., 1984]

  Al-26 meas. down to \( \sim 400 \text{ g/cm}^2 \)

- **Lunar rock 64455 (Apollo-16)**
  
  [Nishiizumi et al., 2009]

  Al-26: 0.1-6 g/cm²

- **Lunar rock 74275 (Apollo-17)**
  
  [Fink et al., 1998]

  Al-26: 0.1-15.8 g/cm²

(Meyer, 2007; NASA S72-40132, S73-16018)
Measured depth profile

Al-26

Fink98 - rock 72425
Ni09 - rock 64455
Ni84, R75 - deep drill core Apollo-15

rock 64455
rock 72425
A-15 deep core
GCR and SEP contributions

[Graph showing the concentration of particles as a function of depth, with data points and error bars. The graph is divided into two sections: one for GCR and one for SEP, with references to Fink et al., 1998, Niishizumi et al., 1984, and Rancitelli et al., 1975.]


\[ Q(h) = \sum_i \int Y_i(E, h) \cdot J_i(E) \cdot dE \]

- Yield function approach - common model for GCR and SEP;
- Monte Carlo modelling of energetic particle transport in deep layers;
- Geant4.10 toolkit (QGSP + BIC + High-precision neutron model);
- Analytical at shallow depths.

- Appropriate chem. compositions, geometries, erosion rates for each of the samples;
- Individual yield func. for incident protons and \( \alpha \)-particles;
- Cross-sections: Nishiizumi et al., 2009; Reedy, 2007; Tatischeff et al., 2006; Reedy, 2013;
- The pion contribution is included (Li et al., 2017).
$^{26}$Al yield function

Sample 64455, depths in g/cm$^2$
Galactic cosmic ray fit

$X^2$-fit into Apollo-15 long core data

The result:

Mean modulation potential $\varphi = 496 \pm 40$ MV on the Myr time scale

For comparison:

Holocene (the last 11,000 years) $\varphi = 449 \pm 70$ MV

Modern Grand maximum $\varphi = 660 \pm 20$ MV

(all $\varphi$ for LIS Vos & Potgieter 2015)
Ideal integral spectrometer

The response is proportional to the integral flux:

\[ A(d) \rightarrow F(\geq E^*) \]

\[ d \rightarrow E^* \]
Effective energy and conversion coefficient

Int. particle flux:

\[ F(>E^*(d)) = K(d) \cdot A_{\text{meas}}(d) \]

Conversion coef. \( K = \frac{F_{\text{model}}(>E^*)}{A_{\text{model}}(d)} \),

Effective energy \( E^* \)

SEP int. spectra:

EXP: \( F_{\text{model}} = F_{0\ \text{EXP}} \cdot \exp(-R/R_0) \)

POW: \( F_{\text{model}} = F_{0\ \text{POW}} \cdot E^{-\gamma} \)
Effective energy and conversion coefficient

EXP: \( F = F_0 \cdot \exp(-R/R_0) \)

POW: \( F = F_0 \cdot E^{\gamma} \)
Effective energy and conversion coefficient

Al-26 measurements

$F(>E^*(d)) = K(d) \cdot A_{\text{meas}}(d)$

Al-26 as an integral spectrometer. Parameters.
Reconstructed SEP int. flux $F(\gtrsim E)$ at the Myr time scale
SEP occurrence probability distribution

$P(>F_{30})$ [yr$^{-1}$]

Annual fluence $F_{30}$ [$10^9$ cm$^{-2}$ yr$^{-1}$]

$F_{30}$ means $F(>30$ MeV)
Summary

Al-26 in Apollo-15 lunar deep-drill core:

- The average modulation potential is estimated as $\varphi = 496 \pm 40$ MV on the Myr time scale.
- It is close to the Holocene value $449 \pm 70$ MV and lower than one for the Modern Grand maximum ($660 \pm 20$ MV).

Al-26 in lunar samples 64455 and 74275:

- SEP integral spectrum $F(>E)$ reconstructed without any a-priori assumptions on its shape in the range 20-80 MeV.
- SEP flux on the Myr time scale is comparable with one over the last several decades.
- SEP occurrence probability: no expected events with annual fluence $>30$ MeV above $10^{11}$ part./($cm^2$ yr) on the Myr time scale.
Thank you!
Reconstructed SEP int. flux $F(>E)$ at the Myr time scale
Reconstruction of the Al-26 content