Solar Radiation Output: Reading the Record of Lunar Rocks

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The Moon has virtually no atmosphere and only a very weak magnetosphere. Thus, the radiation descending upon the lunar surface is essentially the unmodified radiation field at 1 AU, and radiation-induced signatures of the history of the inner solar system are uniquely preserved in lunar surface rocks and regolith in the form of long-lived or stable nuclides. Such nuclides have been evaluated in lunar surface samples brought back during the Apollo era. For example, of particular scientific interest is the historical trend of solar cosmic radiation (SCR) flux. It has been shown that the SCR flux is recorded in lunar surface rocks and regolith and can be reconstructed by measuring selected nuclide concentrations at various depths in the lunar surface (e.g., Reedy 1998). Most importantly, analysis of lunar samples provides a unique opportunity to obtain pristine and independent data on SCR flux during the past several million years. The SCR differential flux (J) per unit of rigidity (R) is expressed as

$$dJ/dR = k \bullet e^{-R/Ro}$$

where R is the momentum of a particle per unit charge (Reedy and Arnold 1972). The spectral parameter Ro for protons from solar flares typically ranges from ~20 to ~200 MV for event-integrated spectra observed over the last four decades (Reedy and Nishiizumi 1998, Nishiizumi et al. 2009).

A wealth of information on the interaction of galactic cosmic radiation (GCR) and SCR with the lunar surface has been obtained from Apollo samples. Soil, rock, and core samples were returned from each of the six landing sites on the near side of the Moon. Measurements have been made of nuclide reaction products to evaluate lunar surface chronology and surface remodeling, including ^{22}Na (half-life 2.6y), ^{14}C (5,730 y), ^{41}Ca (1.04×10^5 y), ^{36}Cl (3.01×10^5 y), ^{26}Al (7.05×10^5 y), ^{10}Be (1.36×10^6 y), and ^{53}Mn (3.7×10^6 y) (e.g., Nishiizumi et al. 1976, Fruchter et al. 1976, Fruchter et al. 1978, Reedy et al. 1983, Nishiizumi et al. 1984a, Nishiizumi et al. 1984b, Nishiizumi et al. 1989b, Reedy and Masarik 1994, Nishiizumi et al. 1997, Fink et al. 1998, Jull et al. 1998). However, few studies have provided the near-surface sampling precision required to accurately reconstruct SCR flux (Reedy 1998, Nishiizumi et al. 2009).

Lunar cores (some almost 3 m deep from Apollo--Lunar Source Book 1991) are ideal samples for investigation of cosmogenic nuclide production by GCR. Due to their high energies (Simpson 1983), GCR penetrate several meters into the lunar surface resulting in the production of characteristic nuclide depth profiles that can be readily measured. In contrast, SCR is of much lower energy (Wilson et al. 2006) and penetrate only a few cm in rock or soil. To measure an accurate SCR depth profile, each layer must be only about 1mm thick. This requires that the sample has experienced very little disturbance during the time relevant for the measurement (i.e., during the mean life of the radionuclide measured), and that very careful sample processing and analysis procedures are employed. For lunar soil, the top layers that contain SCR-produced nuclides have been mixed (gardened) by micrometeorite impact and core handling, in some cases to several cm (e.g., Nishiizumi et al., 1979; Langevin et al., 1982).

Hence, the soil cores are of limited accuracy for SCR depth profile measurement. Lunar surface rocks are the best archives for the past SCR record. Good documentation, orientation, and exposure histories of rocks are required to study SCR flux and energy and therefore only a handful of Apollo rocks have been used for detailed SCR studies to date. The profiles of nuclides made by solar protons have also been used to determine rates at which lunar rocks are eroding (mainly by micrometeorites) to be 0.25-3 mm/My (e.g., Kohl et al., 1978; Nishiizumi et al., 2009. The substantial range of erosion rates observed result from the varying hardness of different lunar rocks.

Focusing on the SCR contribution near the surface, Nishiizumi et al (2009) measured ^{10}Be, ^{26}Al, and ^{36}Cl in Apollo 16 rock 64455. Their results are plotted in Figure 2 and clearly show the contribution from SCR in the case of ^{26}Al and ^{36}Cl, but not for ^{10}Be. Also shown are the relevant production cross sections for these nuclides. It is observed that the measured depth profiles reflect the corresponding cross sections. The profile for ^{10}Be is nearly flat at these depths showing essentially no detectable contribution from SCR, which is consistent with the rapidly diminishing cross sections for the production of ^{10}Be at energies below a GeV. In contrast, ^{26}Al and ^{36}Cl exhibit clear depth profiles resulting from SCR consistent with their relatively large production cross-sections below 100 MeV where SCR protons dominate.

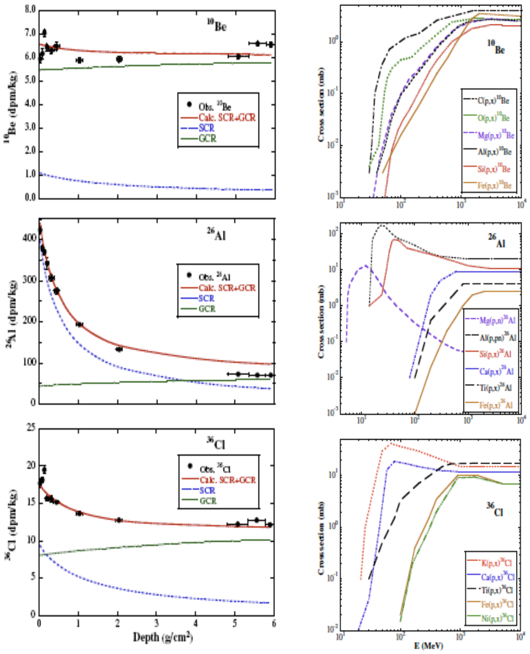

Figure 2. Left panel: Depth profile measurements and calculations in a lunar rock from Apollo 16 (rock number 64455) for ^{10}Be, ^{26}Al, and ^{36}Cl. The contributions from SCR and GCR were calculated. Measurements were made using AMS. Right panel: Production cross-sections corresponding to the measured depth profiles. From Nishiizumi et al. 2009 (the reader is referred to Nishiizumi et al. 2009, Reedy 2007, and Reedy 1998 for in-depth discussion of these and similar data).

The results in Fig. 2 illustrate that it is indeed possible to make the very precise near-surface depth profile measurements required to determine SCR flux from lunar surface rocks. It's noted that the limited number of samples available from Apollo suitable for precise SCR analysis make it critical that those rocks that are suitable be evaluated to the maximum extent possible, and enhances the importance of new samples from future missions to the Moon.

Estimates of Trends in SEP Flux

Reedy (1998) reviewed the data available from Apollo samples to estimate the SCR flux during the past 5 million years. This was accomplished using solar proton-induced products in lunar regolith having half-lives ranging from 2.6 y to 3.7 My. The results are plotted in Figure 3 and show a consistent trend with lower average flux 5 million years ago than today. Proton flux data were presented for several proton energy intervals and all exhibit the same overall trend. These are important observations and provide clear evidence that the solar proton flux can be obtained from the concentration profiles of specific nuclides measured in lunar samples. The results show that the SCR flux has increased substantially during the past 2 million years and appears to be continuing to increase. There appears to be fine structure in the data. Additional measurements should be made to better define these curves and fill-in the gaps, e.g., there is only one nuclide measured between 5y and 100,000y (^{14}C).

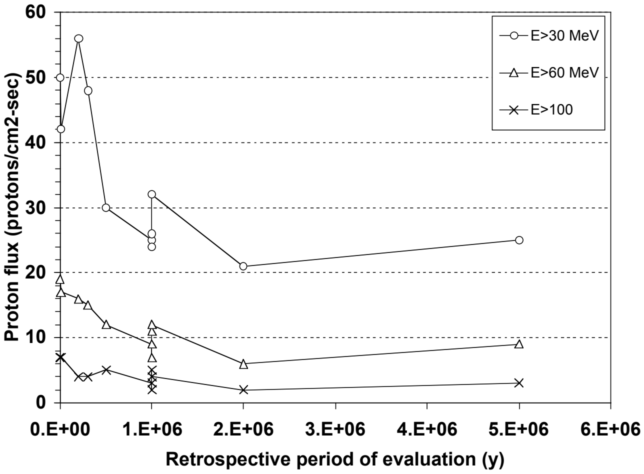

Figure 3. Long-term trend in SCR flux measured in samples from the lunar surface. Plotted from data in Reedy (1998). Nishiizumi et al. (2009) have recently added to these data based on their new depth profile measurements of ^{26}Al and ^{36}Cl illustrated in Fig. 2.

The principal source of information on the historical trends of SCR flux has been the polar ice core data. McCracken et al (2001a, 2001b) evaluated nitrate deposition in ice cores from Greenland and Antarctica to detect solar flare events that have occurred during the past several hundred years (from 1561 to 1994). They concluded that impulsive nitrate measured in ice cores is a reliable indicator of the occurrence of large events and that they provide a quantitative measure of such events. They have further proposed a hypothesis in which variations in coronal densities modulate the efficiency of SCR production throughout the Gleissberg cycle, which suggest that the past ~50 years may have been a period of comparatively benign space radiation climate and that the frequency of large SCR may increase from its present level by a factor of 6 to 8 commencing perhaps in the next Schwabe cycle. An independent source of SCR estimates, i.e., from lunar samples, would provide a critically important comparison to the ice core data.

The evaluation of SCR flux from ice cores and lunar samples involves very different approaches, i.e., ice cores record the deposit of annual layers over time and therefore can be dated similarly to tree rings, while lunar cores contain a SCR flux record that is integrated over a duration that depends on the half-life of the cosmogenic nuclide measured. Unlike cosmogenic nuclides in lunar samples, the variation of nitrate in ice cores was influenced by several factors including atmospheric circulation, climate, and snow accumulation rate, which are not directly correlated with SCR events. Hence, the ice cores have potential problems with knowing the source of the nitrate while the lunar samples are of limited availability and require sophisticated analytical methods to measure near surface depth profiles of cosmogenic nuclides. Most importantly, however, lunar cores can provide independent measurement of time-dependent variations in the SCR flux and spectrum. The ice cores may show the trends in integral flux but not information on the spectrum. By measuring cosmogenic nuclide concentrations at different depths in the lunar samples, spectral information can be extracted because of the different excitation functions for each cosmogenic nuclide produced.

Recommendations for Future Work

1. Take advantage of important analytical advances since Apollo. In particular, accelerator mass spectrometry (AMS) has emerged since the Apollo era with an extensive repertoire of nuclides that can be quantitatively detected at ultra-trace levels (10^4-10^5 atoms). This permits measurement of very small samples, which is required to obtain accurate SCR depth profiles in lunar samples.

2. Sampling strategies for future lunar missions should consider needs for SCR analysis. Samples currently available from the Moon suitable for SCR analysis are very limited. Also, because they were not collected for the purpose of SCR analysis, orientation and other relevant properties (e.g., rock hardness) may not have been considered to the extent required.

3. Continue to strengthen available data of retrospective SCR flux estimates based on available Apollo samples, and search for additional cosmogenic reactions in lunar samples exposed to SCR, particularly those with half lives less than 100,000 y. This should take into account advances in sample chemistry and AMS measurement capabilities.

4. Enhance existing computational models to accurately relate the incident radiation field, lunar soil composition, and isotopic abundance as a function of depth.

5. Finally, ensure the continuation and advancement of this very specialized field of study. The Apollo-era scientists who pioneered this field are approaching retirement and it is critical that their expertise is transferred to the next generation of scientists during the coming years. This requires long-term training of young scientists in this kind of sample chemistry and processing, AMS analysis, and computational modeling that are so critical to the success of this work.

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