SOLAR FLARE NOBLE GASES PRESERVED IN LUNAR ROCK 61016

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By studying samples from known depths of a well-documented lunar rock with a simple exposure history it is possible to disentangle the nuclear interaction products of deeply penetrating, high-energy GCR (galactic cosmic ray) protons from the products of low-energy SCR (solar cosmic ray) protons. One such attempt was made earlier on the documented rock 68815 (1). We have made a study on samples from known depths of the well-documented anorthositic rock, 61016, which was ejected by South Ray Crater about 2 My ago and subsequently was exposed on the lunar surface under known geometry. Our preliminary results indicate that production rates of ^{21}Ne and ^{38}Ar increase with decreasing sample depth due to SCR proton interactions. Consequently, near-surface samples show different ^{21}Ne/^{22}Ne cosmogenic ratios than the deep samples, where SCR effects become negligible.

A sample of rock 61016,381 was carefully cut into ~1-2mm thick sections parallel to the exposed (pitted) surface to yield samples of known depth. Sample numbers and their depths are; 393a, 1.25mm; 393b, 2.7mm; 398a, 4.1mm; 398b, 5.7mm and 401, 8.2mm. Additionally, loose sample ~26mm from the surface was taken from the rock. An aliquant of the top sample, 393a, was lightly etched (LE) to remove solar wind (SW) gases present only in this sample. Samples were analyzed for chemical composition [V.Yang;NASA-JSC] using a Cameca electron microprobe and are composed of >98% plagioclase (Mg=0.04%) containing some ~100μ pyroxene inclusions.

Neon: Ne isotopic ratios determined in samples from different depths of the anorthositic rock 61016 are plotted in Fig. 1. The pure GCR composition is represented by the deepest sample, 383, and by the theoretical GCR value (triangle) calculated from the production rates of Hohenberg et al. (2) at ~6g/cm^2 shielding using the 61016 chemical composition. The SCR Ne composition as a function of shielding shown in Fig. 1 was also calculated from (2). The unetched surface sample, 393a UE, shows the presence of SW in the 600^{o}C and 1200^{o}C fractions, whereas the 1600^{o}C fraction plots on the SF-GCR tie line. For the lightly etched surface sample, 393a LE, the 600^{o}C point plots close to the SF end-point while the 1600^{o}C point plots near the GCR end-point but to the left of the SF-GCR line. The intermediate, 1200^{o}C, release falls slightly above the SF-GCR line, possibly due to residual trapped Ne from the pyroxene inclusions. The 1600^{o}C extractions for the five other 61016 samples plot near the GCR component in a depth dependent sequence that suggests increasing domination of the GCR component with increasing depth (insert Fig 1.). These data, however, suggest a slope different from the two component SF-GCR mixing line, indicating that the cosmogenic Ne in the near surface samples is likely to be a mixture of GCR- and SCR-produced Ne in varying proportions according to depth.

Cosmogenic ^{21}Ne concentrations obtained for these samples are plotted vs. depth in Fig. 2, and suggest a decrease from the top-most sample, 393 (1.25mm), to the bottom-most sample, 383 (26mm). Because ^{21}Ne in 383 is solely due to GCR production (Fig. 1), the increase in cosmogenic ^{21}Ne concentrations with decreasing depth is due to the contribution from SCR protons. This depth profile for SCR ^{21}Ne production is similar to the trend observed in the near surface samples of rock 68815 (1). Similar concentrations of GCR-produced ^{21}Ne were measured in 61016 (0.271x10^{-8} ccSTP/g at 26mm) and in 68815 (0.233x10^{-8} ccSTP/g at 17mm).

The cosmogenic ^{21}Ne in 393a LE is 0.27x10^{-8} ccSTP/g after correcting for the trapped (SF) Ne contribution, and represents the combined GCR and SCR production. Assuming that the depth dependant production profile for the combined GCR and SCR ^{21}Ne extrapolates smoothly to 0 g/cm^2 (not considering erosion), the expected concentration for 393a LE is 0.31x10^{-8} ccSTP/g. There seems to be a loss of ~0.04x10^{-8}ccSTP/g of ^{21}Ne from the top-most etched sample; a similar loss was observed in 68815 (1). This loss may be due to the increased diffusion at the surface of these rocks because of the temperature gradient within each rock during exposure to solar radiation on the lunar surface.

Argon: With the exception of the top-most sample 393a, all samples released ~99% of their Ar in the 1600^{o}C extractions with ^{36}Ar/^{38}Ar ratios of <0.94, permitting accurate evaluation of cosmogenic ^{38}Ar abundances by the lever rule. Solar wind dominated the unetched 393a sample; >90% of the total ^{38}Ar with an ^{36}Ar/^{38}Ar ratio of 5.35 was released in the 1200^{o}C fraction. From the lightly etched 393a sample, the 600^{o}C fraction released ~20% of the gas and gave a ratio of 5.3, which may have been due to residual SW retained in the pyroxene inclusions. The 1200^{o}C extraction released ~75% of the total with an ^{36}Ar/^{38}Ar value of 4.91, which is the same as earlier SF values (3). We consider the 1600^{o}C fraction, with a measured ^{36}Ar/^{38}Ar ratio of 1.19, to contain the GCR+SCR produced Ar in this sample. Plotting the comogenic ^{38}Ar concentrations from all but the UE sample (Fig. 2.), there is an observed decrease in concentration with depth, which is similar to that observed in ^{21}Ne. By analogy to ^{21}Ne, we infer that cosmogenic ^{38}Ar in the deepest sample, 383, is solely due to GCR production and that in the near surface samples there is a significant production of ^{38}Ar due to SCR proton spallation.

Helium: After applying a cosmogenic correction to the He data in the top-most samples, 393a UE and 393a LE, we obtain ^{4}He/^{3}He ratios of 2660±200 and 3190±300, respectively. The ^{4}He/^{3}He ratio in the unetched sample seems to be similar to SW. The ^{4}He/^{3}He ratio from the etched sample is closer to the SF value of 3800±200 obtained recently (3,4) than to the long-term average solar flare ^{4}He/^{3}He ratio of 12 deduced from the study of the near surface layers of rock 68815 (1). The measured ^{4}He/^{20}Ne ratio in sample 393a LE is 28.1, which is similar to the values found in some IDPs measured by (4).

The three deepest samples, 383 (26mm), 401 (8.2mm) and 398b (5.7mm), have an essentially constant ^{3}He content of 0.34x10^{-9} ccSTP/g, which is considered to be only a GCR component. The two near surface 61016 samples, 393b and 398a, have cosmogenic ^{3}He concentrations of 0.63 x10^{-9} ccSTP/g and 0.61 x10^{-9} ccSTP/g, respectively. The apparent cosmogenic ^{3}He excess observed in the near surface samples may be due to SCR spallation, as observed in ^{21}Ne and ^{38}Ar. Considerably higher ^{3}He concentrations of 0.24-0.33x10^{-8} ccSTP/g were found in the deep (~17mm) samples from 68815 (1). Using reasonable 3He GCR production rates for the moon (5) would imply a ^{3}He exposure age for 61016 of only ~0.03 My. In addition, the measured cosmogenic ^{3}He/^{21}Ne ratio in 61016 of ~0.15 is considerably smaller than the anticipated ratio of ~6 (2). These three observations indicate that 61016 has lost substantial amounts of GCR ^{3}He, and probably SCR ^{3}He as well.

Xenon: The isotopic composition of Xe has been measured in 61016, and results will be reported.

GCR and SCR Ages: Using a cosmogenic ^{21}Ne concentration of 0.237 x10^{-8} ccSTP/g (from the deepest sample 383) and a GCR production rate of 0.175 x10^{-8} cc/g-My for feldspar (2), gives a GCR exposure age of 1.35 My for rock 61016. We infer that the difference in ^{21}Ne concentrations between the 393aLE sample (~0.32 x10^{-8} ccSTP/g) and the 383 sample (0.271 x10^{-8} ccSTP/g) is due to production by SCR protons in the top-most few millimeters of 61016. Taking this SCR component and the SCR production rate of 0.07 x10^{-8} cc/g-My (2) gives a SCR exposure age of 1.2 My, in good agreement with the GCR age. Using a cosmogenic ^{38}Ar concentration of 0.241 x10^{-8} ccSTP/g (from the deepest sample 383) and a GCR production rate of 0.13 x10^{-8} cc/g-My for feldspar (2) and corrected to 61016 composition, gives a GCR exposure age of 1.7 My for rock 61016. Again we infer that the difference in ^{38}Ar concentrations between the 393aLE sample (~0.425 x10^{-8} ccSTP/g) and the 383 sample (0.241 x10^{-8} ccSTP/g) is due to production by SCR protons in the top-most few millimeters of 61016. Taking this SCR component and the ^{38}Ar SCR production rate of 0.3 x10^{-8} cc/g-My at a depth of 0.3 g/cm^{2} (2) gives an SCR exposure age of 0.6 My. The SCR Ar ^{38}age seems low by a factor of 2-3 which may indicate that the predicted SCR ^{38}Ar production rates are too high (2).

References: (1) Yaniv and Marti, AP.J. *247*, L143-146 (1981); (2) Hohenberg et al., Proc. LPSC XIX, 2311-2344 (1978); (3) Rao et al., LPSC XXI (abs), 995-996; (4) Nier and Schulter, Meteoritics *25* (1990); (5) Kaiser, Proc. Second LSC, 1627-1641, (1971).

Fig. 1. Three-isotope correlation plot for Ne. Errors for all data are smaller than the symbols. 600°C, 1200°C and 1600°C data (left to right) are plotted for both surface samples. Other samples had only two extratctions; only the 1600°C data are plotted. The 600°C data account for 3-22% of the total release and fall within errors of 1600°C points. Depth is given in mm from existing surface, uncertainty in depth is ±0.5mm.

Fig. 2. Cosmogenic ^{21}Ne and ^{38}Ar concentrations vs. depth. For all samples except 393a (1.3mm), ~99% of the cosmogenic ^{38}Ar was released in the 1600°C extraction.