Determination of ~2 Ma Average Flux and Rigidity for Energetic Solar Protons from Lunar Rock 61016. D.H. Garrison\textsuperscript{1}, D. D. Bogard\textsuperscript{2}, M. N. Rao\textsuperscript{3}, and R. C. Reedy\textsuperscript{4}; \textsuperscript{1}Lockheed-Martin ES and \textsuperscript{2}code SN4, NASA Johnson Space Center, Houston TX 77058; \textsuperscript{3}Chemistry Dept., Texas A&M Univ., College Station, TX 77843; \textsuperscript{4}MS-D436, Los Alamos Natl. Lab., Los Alamos, NM 87545.

Introduction: Earlier NASA spacecraft measured real-time characteristics of energetic solar protons and found the flux and some other parameters to vary widely. The only way to determine some long-term, average characteristics of solar protons is by measuring their nuclear interaction products as a function of depth within the very few lunar rocks that have oriented geometries and simple exposure histories. Most previous studies utilized radionuclides such as \(^{26}\text{Al}\), \(^{38}\text{Mn}\), \(^{14}\text{C}\). We developed techniques to measure SCR (i.e., solar-proton-produced) \(^{21}\text{Ne}\), \(^{22}\text{Ne}\), and \(^{38}\text{Ar}\), and in lunar rocks 68815 and 61016 we reported average values for the flux and rigidity (i.e., particle energy distribution) for solar protons of >10 MeV over the past 2 Ma (1, 2). However, our initial work on rock 61016 included a limited number of samples and a less sophisticated method of deriving solar proton characteristics. Recently we measured SCR Ne and Ar in additional depth samples of 61016, using procedures previously reported (1, 2). Duplicate data sets between three measurement series were taken for four depths, and these values were averaged to normalize all of the data. Here we report more precise results for proton flux and rigidity determined from all our analyses of 61016.

61016 SCR Profiles: Figures 1 & 2 present concentrations of cosmogenic \(^{21}\text{Ne}\) and \(^{38}\text{Ar}\) as a function of sample depth within 61016. A very similar concentration-depth profile (not shown) was obtained for \(^{22}\text{Ne}\). The concentrations in the deepest (26 mm) sample are largely produced by galactic cosmic rays (GCR), and the increase in concentrations at shallower depths are due to production by energetic (>10 MeV) solar protons (SCR), which penetrate only a few cm into the rock. Because GCR and SCR \(^{21}\text{Ne}\) and \(^{22}\text{Ne}\) are produced in different proportions for samples with the composition of 61016, the \(^{21}\text{Ne}/^{22}\text{Ne}\) ratio differs substantially between the two components. We previously demonstrated that the precisely measured \(^{21}\text{Ne}/^{22}\text{Ne}\) ratio can also be used to derive the relative concentrations of SCR neon (1, 2). Fig. 3 shows the change in \(^{21}\text{Ne}/^{22}\text{Ne}\) versus depth for 61016 samples.

The curves in Figs. 1-3 give some examples of SCR concentrations and ratios calculated as a function of sample depth from the best available cross section data and the chemical composition of 61016 (3). In each case, calculations were made for four values of proton rigidity: \(R_0= 70, 85, 100, \) and 125 MV. The best fit between the concentration-depth profiles determined analytically and those theoretically calculated define the preferred values of energetic (>10 MeV) solar proton flux, \(J\), and the rigidity, \(R_0\). All calculations were made assuming a micrometeorite erosion rate of 1 mm/Ma and a rock density of 2.75 g/cm\(^2\) for 61016. We made a geometric correction for the fact that our 61016 depth samples were oriented ~30° away from vertical. This correction increased calculated \(J\) values by ~4%. To compare measured and theoretical data, we used methods developed by (2) and calculated the best value of \(J\) (4D, E>10 MeV; p/cm\(^2\)/s) that corresponds to each of the four values of \(R_0\) assumed. These model calculations allow the GCR component in the deepest sample to be a variable determined by the data. We then normalize the GCR concentration-depth profiles calculated from (4) to that calculated GCR value.

Figs. 1-3 list, for each of four assumed values of \(R_0\), the best calculated value of \(J_{E>10}\) and the percent SCR contribution in the deepest (26 mm) sample. These \(J_{E>10}\) values range over 24-81 for \(^{21}\text{Ne}\); 30-84 for \(^{22}\text{Ne}\); 27-62 for \(^{38}\text{Ar}\); and 44-86 for the \(^{21}\text{Ne}/^{22}\text{Ne}\) ratio. The fraction of each cosmogenic component in the 26 mm sample that is SCR ranges over 3-11%, 4-15%, and 6-21% for \(^{21}\text{Ne}\), \(^{22}\text{Ne}\), and \(^{38}\text{Ar}\), respectively. An SCR component of ~10% for \(R_0\) of ~70-85 MV at a depth of 26 mm is consistent with our findings in rock 68815 (2). Allowing ~10% SCR contribution to the 26 mm data, we calculate (3, 4) that GCR and SCR exposure ages are each ~2 Ma, in agreement with previously reported GCR ages for 61016. We also made model calculations by fixing the GCR component in the 26 mm sample (2) to that calculated from the theoretical model of (4). For this case, unrealistically high values of \(R_0\) are required, >125 Mv in the case of \(^{21}\text{Ne}\) and \(^{22}\text{Ne}\). This suggests that the theoretical GCR model of (4), does not accurately calculate cosmogenic Ne concentrations for samples having very low Mg and high Al, such as 61016.
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Comparison with Other Data: Because \( J_{E>10} \) and \( R \) vary inversely, it is difficult to assign preferred values for \( J_{E>10} \) and \( R \) to 61106. Figure 4 shows the relationship between the best calculated value of \( J_{E>10} \) for each of four \( R \) values, as determined from \( ^{21}\text{Ne} \), \( ^{22}\text{Ne} \), \( ^{38}\text{Ar} \), and the \( ^{21}\text{Ne}/^{22}\text{Ne} \) ratio in rock 61106. We also show equivalent values determined from \( ^{22}\text{Ne} \), \( ^{26}\text{Al} \), and \( ^{53}\text{Mn} \) for lunar rock 68815 (2). \( ^{21}\text{Ne} \) and \( ^{38}\text{Ar} \) data for 68815 give similar curves to that shown for \( ^{22}\text{Ne} \), whereas \( ^{53}\text{Mn} \), \( ^{26}\text{Al} \), and \( ^{14}C \) data suggested higher \( J_{E>10} \) values, particularly at high \( R \) values.) The \( J_{E>10} \) vs. \( R \) profiles determined from \( \text{Ne} \) for 61106 are similar to the \( \text{Ne} \) and \( \text{Ar} \) profiles determined for 68815, but indicate \( J_{E>10} \) values \(-10\%\) lower. The \( J_{E>10} \) value determined from \( ^{38}\text{Ar} \), however, is \(-35\%\) lower for 61106 compared to 68815. For 68815, (2) concluded that \( R \) values of 70-85 MV were preferable. For \( R = 70 \) MV and 1mm/Ma erosion, \( ^{21}\text{Ne} \), \( ^{22}\text{Ne} \), \( ^{38}\text{Ar} \), \( ^{26}\text{Al} \), and \( ^{53}\text{Mn} \) gave similar calculated fluxes for 68815 from \( J_{E>10} \sim 80-100 \) p/cm\(^2\)/s. The flux for 61106 deduced from SCR Ne is \( J_{E>10} \sim 85 \) p/cm\(^2\)/s for \( R = 70 \) MV and falls within this range. A recently reported SCR depth profile for \( ^{26}\text{Al} \) in oriented lunar rock 64455 suggests \( R = 75 \) MV and \( J_{E>10} \sim 100 \) p/cm\(^2\)/s (5). Use of a lower density for 61106 would decrease our calculated flux. If the erosion rate for 61106 were higher, say 2mm/Ma, then the derived proton flux would be increased by \(-10\%\).

Because all SCR nuclides were produced by the same solar proton flux, only one set of \( J_{E>10}/R \) values is correct. Three different lunar rocks suggest that over the past \(-2\) Ma solar protons had a rigidity of \(-70-85 \) MV and a flux of \(-80-100 \) p/cm\(^2\)/s. We are still examining possible explanations for the low flux indicated by SCR \( ^{38}\text{Ar} \) in 61106.