AN IN-DEPTH STUDY OF NEON AND ARGON IN LUNAR SOIL PLAGIOCLASES, REVISITED: IMPLANTED SOLAR FLARE NOBLE GASES
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In this paper, we return to the discussion of our investigations of He, Ne, and Ar in plagioclase separates from the highland soil 61501 (1, 2). For these studies we prepared, besides a grain size suite, aliquots of four grain-size fractions from which we removed surface layers of different thickness (~1 to ~30 μm) by acid etching. Since then we duplicated the noble gas determination on the etched 25-42 μm fraction. The new results do not agree with the previous ones. Because of a very small sample amount in the first experiment we reject its results. The corresponding data point is given in Fig. 2 in the paper by Etique et al. (2). Fig. 1 shows the Ne data in a 3-isotope correlation plot. All data points of the etched plagioclase separates plot on a straight line. This line is distinctly different from the straight line through the data points of the unetched grain size suite. The position of the data points from the etched plagioclases reveals the presence of solar-type Ne down to a depth of at least 30 μm. The concentrations of this Ne decrease with increasing depth as seen from the correlation with etching depth. The extrapolated 20-Ne/22-Ne ratio of the solar component is distinctly lower than the value deduced for retained solar wind Ne in the unetched plagioclases of the grain size suite. Inward migration of implanted solar wind would increase the 20-Ne/22-Ne ratio, and therefore cannot be the sole reason for the difference between the two lines. Evidently, the plagioclases contain at least one more component in addition to the retained solar wind Ne and the spallogenic Ne produced by galactic cosmic ray particles (GCR). The following two possibilities or combinations thereof will be discussed:
1) gases produced by solar cosmic ray particles (SCR)
2) implantation of solar flare noble gases.
Assuming the spallogenic gases to be a superposition of SCR and GCR gases requires a mixing ratio which is independent of grain-size and depth within the grain. Only under this condition, the superposition cannot be detected by our

Figure 1: 20-Ne/22-Ne versus 21-Ne/22-Ne three-isotope correlation plot for etched plagioclase separates of soil 61501. Different grain sizes are indicated by different symbols. Symbols encompassed with ○ represent samples obtained by magnetic separation (plagioclase concentrate), the other samples have been prepared by handpicking. Samples contaminated with adhering material are indicated with □. This material was removed by the etching procedure. Numbers beside the data points indicate the approximate thickness (in μm) of the surface layer etched off. The different points given by ♦ represent: SWC = solar wind Ne (3); A, B, C = Neon-A, Neon-B and Neon-C, respectively (4); L = GCR-produced Ne in plagioclases (5). Data for the unetched plagioclase grain-size suite of the same soil (2) are also indicated.

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etching experiments. Equally, a mixture of trapped solar flare and solar wind have to fulfill the same condition with respect to their distribution.

Spallogenic Neon. According to Hohenberg et al. (6) the production rates of Ne by solar flare protons show the steepest decrease with depth right at the surface and decrease only by a factor of about 2 between a shielding depth of 0 and 1 g/cm². This shows that the diameters of the plagioclase grains investigated here are very much smaller than the mean interaction length of solar cosmic ray protons. Spallogenic neon produced either by solar or galactic cosmic rays does therefore neither depend on size of the grains nor on depth within the grains and both components are mixed in equal proportions everywhere in the samples studied. Consequently, the existence of a mixture cannot be resolved by etching or by stepwise heating experiments. Also diffusive loss of spallogenic Ne is not expected to lead to detectable alterations of the mixing proportion.

The 21-Ne/22-Ne ratio of the spallogenic Ne obtained from the solid line in Fig. 1 is within the error limits the same as the ratio given by Lugmair et al. (5) for a plagioclase separate from rock 76535. This rock has acquired most of its spallogenic gases at a depth of about 30 cm and the 21-Ne/22-Ne ratio in its plagioclase is likely to be very close to that of pure GCR-Ne. Therefore, at best a minor fraction of the spallogenic Ne in our plagioclases originates from solar flare produced spallation. This is in accord with models simulating regolith dynamics, indicating that the residence time of regolithic matter in the uppermost few cm is small compared to the residence time at larger depths (e.g. 7). Furthermore, the comparison between times of exposure to the solar wind and to the galactic cosmic rays (about 10'000 y and about 300 Myr, respectively (8)) also supports the conclusion of a negligible contribution of SCR produced Ne and Ar.

In consequence, three points are to be noted: ●The SCR produced spallation Ne admixture is too small to explain the data in Fig. 1. ●The line through the data points of the grain size suite is not a two-component mixing line. ●Indications of a Ne component of spallogenic nature with a 21-Ne/22-Ne ratio around 0.76 in plagioclase is no indication for the presence of a significant fraction of SCR-Ne as we and others have concluded previously (2, 9, 10).

Trapped solar flare gases. Plagioclase separates have undoubtedly lost a substantial part of their solar wind implanted Ne and especially He. In contrast, Ar of any origin is much more tightly held in plagioclases under lunar conditions. Even solar wind Ar is well retained (11) and inward migration of trapped solar wind Ar can probably be neglected. We therefore first examine the Ar data obtained from the plagioclases and compute the solar portion (SW and/or SF) of the 36-Ar detected after etching. We thereby assume the solar and spallogenic 36-Ar/38-Ar ratios to have values of 5.35 and 0.658 (5), respectively. Because the solar portion in the etched samples is small, the result does not critically depend on the isotopic ratio used for solar Ar. An approximated depth profile of solar 36-Ar to a depth of 30 µm is thus obtained (similar to Fig. 2 in Ref. (1)). The comparison of this profile with the profile of the track densities obtained by Blanford et al. (12) on a lunar rock shows a good agreement of the shapes of the profiles down to 30 µm. We therefore interpret the solar 36-Ar detected at a depth between 1 and 30 µm as having been implanted by solar flares during the grains' exposure at or very close to the real surface of the regolith. If this hypothesis is correct, the ratio of 36-Ar in the solar wind and in the solar flares averaged over 50 Myr (11) is 1.4. This value is at least 10 times higher than estimates of this ratio by Price et al. (13). Unfortunately no detailed discussion of solar 36-Ar and solar flare tracks can be...
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carried out on the basis of the available data. Ar determinations to depths > 30 μm were not possible and no measurements of track density distributions within the grains have been made.

We now turn to the discussion of solar Ne as pointed out above. From Fig. 1 it is evident that even the strongly etched samples contain an appreciable fraction of solar-type Ne. After the indication that the grains contain solar flare implanted 36-Ar obtained above, we examine whether this Ne has the same origin. Because of the mobility of Ne in plagioclase, two cases have to be considered: Either the solar Ne is predominantly of solar flare origin, or it is a superposition of solar flare Ne and a substantial fraction of migrated solar wind Ne.

In the first case, the solar flare Ne would have, as read from Fig. 1, a 20-Ne/22-Ne ratio around 11.3. This is above the values measured by satellite borne instruments (14, 15), marked m in Fig. 1. A possible explanation for this disparity could be the different energy ranges sampled: In the plagioclases, the solar flare neon now found in the 30 μm thick skin of the grains is integrated over energies up to about 5 MeV/nucleon, because the implantation took place mostly at or near the regolith surface. In the space experiments, ions with energies between 11 and 43 MeV/nucleon were counted. Conversely, fluctuations of the 20-Ne/22-Ne ratios with time and/or the vastly different integration times may contribute to the disparity.

In the second case, the superposition of solar flare and migrated solar wind Ne requires a process leading to a grain-size and depth independent mixing ratio of the two components. Such a mixing could result if migrating Ne is preferentially retained in highly retentive sites produced by heavy particles from solar flares. The solar flare Ne has, in this case, a 20-Ne/22-Ne ratio < 11.3. Because diffusive losses have affected solar wind and spallogenic Ne quite differently, no value for the ratio of Ne in the solar wind and solar flares can be given.

Summary. Ne and Ar with isotopic compositions close to those of solar gases are detected in plagioclase separates from soil 61501 even after etching the grains down to a depth of 30 μm. Evidence is presented that these gases are at least partly trapped from solar flares, essentially during direct exposure of the grains to the sun. The integration time is of the order of 10^5 y spread over some 50 My. Our interpretations lead to the following values:

\[ \frac{36\text{Ar}_{\text{SW}}}{36\text{Ar}_{\text{SF}}} \approx 140 \quad \text{and} \quad \frac{20\text{Ne}}{22\text{Ne}_{\text{SW}}} \approx 11.3 \]

(SW and SF stand for solar wind and solar flare, respectively.)

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References