Rare Gases Implanted in Lunar Fines

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Rare gases implanted in lunar fines

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Rare gases implanted into lunar fines can be used to study processes in the lunar regolith as well as solar abundances. A short outline of some basic results about the distribution of solar rare gases in lunar soils is given and illustrated by two case studies: (1) Evidence for local endogenic activity near Shorty Crater is inferred from rare gas fractionations in soil 74241. (2) Rare gas concentration profiles measured with a new technique in single lunar soil particles underline the importance of radiation damage as governing factor of migration and promise future possibilities to determine ancient solar abundances free of secondary bias.

Introduction

The formation of the lunar regolith began right after crustal solidification. The continuous grinding process due to the influx of micro- and macrometeorites produced the lunar fines. Due to the general decrease of the density of interplanetary debris with time, soil production was most effective in the earliest times of the Moon's history. In addition to comminution, micro- and macrometeorite impacts caused turnover, mixing and lateral transport. It is during that process that the lunar soils became implanted with rare gases of various origin, i.e. solar wind, solar flares, and possibly photo-ionized atoms of the latent lunar atmosphere.

By quantity, the most important source of implanted rare gases is the solar wind. By and large this is a rather representative sample of solar matter continuously blown out from the corona. Its mean energy is quite low, in the order of 1 keV per nucleon. Correspondingly, the penetration power in solid material is only a few tens of nanometres, and only the very skin of the lunar surface will be implanted with solar wind. However, because of vertical turnover, nearly every soil particle will get its chance for top exposure. Even more so, the flux is so intense that almost each particle will become surface saturated with hydrogen and helium within less than 100 years of exposure.

The potential of the analysis of implanted gases is obviously twofold. One could either use the solar wind labelling in order to study transport processes within the regolith itself as the object of concern, or one may study solar abundances and use the lunar soil merely as catcher. The latter approach is particularly important since one could get access to very ancient solar wind which in turn can shed some light on the secular evolution of the Sun, at least as far as it is reflected in its corona. Besides, even in our time of intense space exploration outside of the Earth's magnetic field, data on the solar wind composition acquired by space probes are rather fragmentary and biased by short time fluctuations. Information available on solar isotopic abundances was altogether very sparse until lunar soils became accessible.

Outline of results

Soon after it was realized that most soils are saturated at least with the more abundant lighter rare gases it became apparent that distribution studies are absolutely necessary in order to distinguish the components and to extract useful information. This implies analysis of grain size fractions, mineral separates, etching experiments, single grain analysis, stepwise and linear heating experiments, and probe techniques with high local resolution employing electron beams, ion beams, or lasers as means of extraction.

The pattern which has emerged includes the expected surface concentration of the implanted gases, however not in an ideal sense, but with indications of some volume correlated component, caused by welding of preirradiated dust into agglutinates and by migration of the solar wind due to diffusion.

Furthermore, it was noticed that serious elemental fractionations occur during agglutination and migration as controlled by differences in the retention properties of the various minerals. The individuality of every single particle and basic differences between Ti-rich mare soils and Ti-poor highland soils were established, and core tube studies have clearly demonstrated preirradiation and multistage exposure. The isotopic composition of the solar wind has been found to resemble terrestrial rare gas patterns for Ar and Kr, but not for Ne and Xe, and the ^{4}He/^{3}He ratio seems to have decreased in time, which might indicate slow vertical element transport in the Sun. In addition it was noticed that ^{40}Ar from the lunar interior has found its way into the surfaces of lunar soil particles.

In the frame of this article I shall refrain from any elaborations of general findings (for recent references see Bogard, Hirsch & Nyquist (1974), Eberhardt (1974), Heymann *et al.* (1974), Hübner, Kirsten & Kiko (1975)) but instead present two case studies which might illustrate the type of problems involved. The lunar aspect is dominant in the first, the solar aspect in the second approach.

Implanted rare gases in soil 74241 (Hübner, Kirsten & Kiko 1975)

An unusual feature of the Apollo 17 regolith is the widespread occurrence of orange glass droplets. At the rim of Shorty Crater, orange glass occurs in almost undisturbed pockets overlaid by a seemingly ordinary grey soil (74241) and it has been proposed that local volcanic activity produced the orange soil (Heiken, McKay & Brown 1974). In this context it is interesting to note that the adjacent soil 74241 exhibits rather exceptional rare gas patterns like, for example, extreme *isotopic* fractionation of implanted rare gases. The ^{3}He/^{4}He and ^{20}Ne/^{22}Ne ratios observed in the various mineral fractions vary in a correlated manner by *ca.* 30 and *ca.* 10 % respectively (figure 1). The extent of isotopic fractionation is indicative of exceptional thermal stress. A similar conclusion can be drawn from correlated losses of tightly bound volume distributed spallogenic isotopes.

Another line of argument arises from the exceptionally high concentration of surface correlated ^{40}Ar in soil 74241. The latter isotope is not contained in the solar wind (like, for example, ^{36}Ar), but it is generally accepted that one is dealing with radiogenic ^{40}Ar outgassed from the lunar interior. Three modes of emplacement into the soil particle surfaces have been proposed: reimplantation by the incoming solar wind (Heymann & Yaniv 1970), surface deposition of K-vapour with subsequent radioactive decay (Baur *et al.* 1972), and direct adsorption of ascendent ^{40}Ar (Kirsten *et al.* 1972). We prefer the latter interpretation since the finest particles (< 2.5 μm) have the highest ^{40}Ar/^{36}Ar ratios in spite of the fact that for micrometre sized particles it is less likely to become exposed at the lunar skin than for larger particles (Dran *et al.* 1975*a*). As a result, top exposure seems not required for ^{40}Ar emplacement.

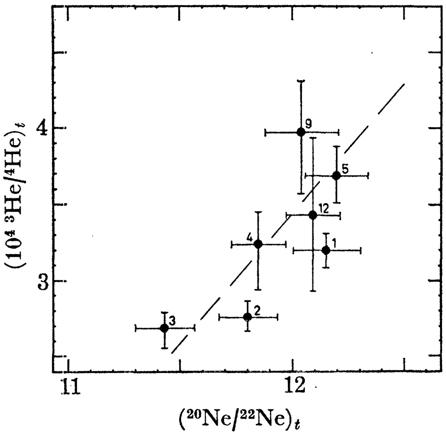

FIGURE 1. Isotopic fractionation of trapped gases in mineral separates of soil 74241. Correlation of He- and Ne-isotopic ratios suggests diffusion as responsible mechanism. Large error bars are caused by corrections for spallogenic isotopes. 1, agglutinates; 2, scoriaceous glass; 3, scoriaceous glass, etched; 4, devitrified glass; 5, ilmenite; 9, orange glass ; 12, bulk (109–272 μm). (Hübner *et al.* 1975)

The observed variation of the ^{40}Ar/^{36}Ar ratio in grain size separates indicates different retention of implanted ^{40}Ar and ^{36}Ar. The particularly low ^{40}Ar/^{36}Ar ratio in agglutinates (6.1 as opposed by 9.5 in bulk < 2.5 μm) suggests that ^{40}Ar is lost preferentially to solar ^{36}Ar during particle growth by welding and agglutination. The extent of this effect and the exceptional absolute amounts of surface correlated ^{40}Ar in soil 74241 are again indicative of unusual thermal stress. We have thus proposed that it reflects the effects of local endogenic activity, causing the formation of the orange soil and intense exhalation of volatiles. An extreme local heat burst or volcanic vent may have produced the orange soil and at the same time left its record in the overlaying regolith in form of strong diffusive fractionation and ample supply of volatile exhalations (^{40}Ar, also mercury and halogens (Jovanovic & Reed 1974)). The 'hot spot' had to be locally confined (like the orange soil pocket) since soil 74121, collected 0.7 km away from 74241 yields a rather regular ^{40}Ar/^{36}Ar ratio of 0.85. In addition, one may argue that the strongly fractionated solar gases in soil 74241 must be very ancient since orange soil was formed 3.7 Ga ago (Husain & Schaeffer 1973).

RETENTION AND RADIATION DAMAGE (H. W. Müller, Kiko & Kirsten 1975)

As evident from the above discussion, the solar wind is subject to solid state diffusion after its implantation into the lunar soil. This implies elemental and isotopic fractionation and prevents a straightforward interpretation of the measured rare gases in terms of solar abundances. There are two potential keys to solve this problem: either to study the diffusion properties by linear heating techniques with the aim of quantitative corrections and/or to search for particles which experienced only a minimum of diffusion by direct measurement of rare gas concentration profiles with high local resolution.

Diffusion is controlled by material parameters and temperature. In both respects, a given lunar soil particle is distinct from any other because of its uniqueness with regard to chemical composition, natural imperfections, shock- and radiation damage, sputtering, and to residence times within various layers of the regolith, which corresponds to different effective temperatures. Therefore, it is necessary to investigate individual soil particles rather than multiparticle assemblages (Kirsten, Steinbrunn & Zähringer 1971; Kirsten *et al.* 1972; Ducati *et al.* 1973).

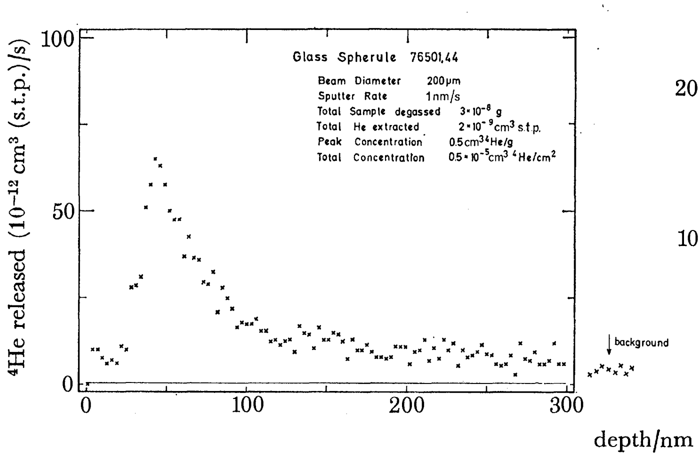

FIGURE 2

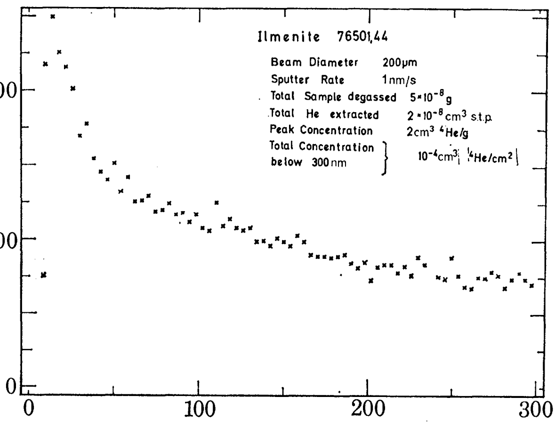

FIGURE 3

FIGURE 2. ^{4}He concentration profile in an Apollo 17 glass spherule. The outer 30 nm are free of solar He, migration is confined to ~ 300 nm. Rare gas ion probe analysis. (H. W. Müller *et al.* 1975.)

FIGURE 3. ^{4}He concentration profile in an Apollo 17 ilmenite crystal. The outer 30 nm contain unmigrated solar He. Penetration extents up to 2 μm depth (not shown). Rare gas ion probe analysis. (H. W. Müller *et al.* 1975.)

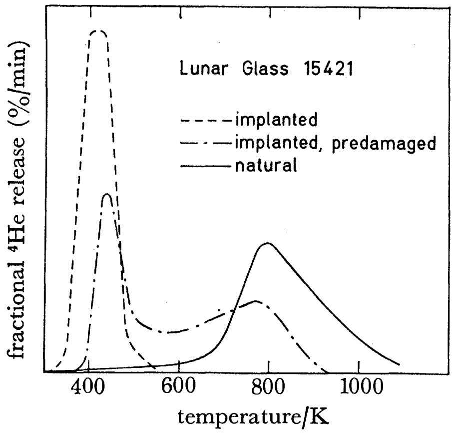

FIGURE 4. Gas release patterns from linear heating experiments of lunar glass spherules. Solar ^{4}He collected at the lunar surface, is degassed at release temperatures much above those for glass spherules artificially bombarded with 4 keV ^{4}He-ions. Proton damage before irradiation increases retentivity (see text). (Ducati *et al.* 1973.)

We have developed a new technique in which the gases are extracted by ion sputtering, ionized by electron impact, and detected by fast scanning high sensitivity quadrupole mass spectrometry (H. W. Müller *et al.* 1975). Surfaces of singly mounted crystals are sputtered on a circular area of 200 μm diameter at rates adjustable between 0.1 and 5 nm s^{-1}. 10^{-12} cm^3 ^{4}He/s are easily detected. Six Apollo 17 lunar glasses contain no ^{4}He in the outer 30 nm, peak between 50 and 200 nm and fall off with maximum ranges between 200 and 500 nm (example in figure 2). Apollo 17 ilmenite (figure 3) contains ^{4}He even in the outer 1 nm, peaks at 20 nm and falls off more like erfc $(1-\int e^{-x^2})$, as would be expected for constant source diffusion. Why then are these profiles so different? To answer this question let us first discuss some results of linear heating experiments with individual glass spherules (figure 4). The release temperature for a spherule implanted on the Moon is much higher than for an artificially implanted glass spherule. However, if one simulates not only the solar wind implantation, but also the radiation damage to which lunar particles are subjected, then the release temperatures will rise dramatically and resemble those obtained for natural samples (figure 4). From this we have concluded that rare gas migration on the Moon is largely affected by radiation damage. Solar flare ions produce radiation damage traps (latent tracks) of large annealing energies. The diffusing solar wind atoms become captured in the traps and the energy required for a jump out of a trap into the undisturbed lattice is larger than that required for a jump from one to another interstitial in the crystal. For this reason, the rare gas concentration profile of glass reflects the population of flare produced damage traps with migrating solar wind, and deeper penetration by regular volume diffusion is prevented (Ducati *et al.* 1973) (figure 2). On the other hand, the ilmenite lattice is trap hostile. The absence of resistent damage traps results in a regular volume diffusion profile (figure 3). The different behaviour within the outermost 30 nm is caused by a completely amorphous layer in the case of glass and its absence in ilmenite, in accordance with high-voltage electron microscopic observations (Dran *et al.* 1975*b*). The further development of this technique is very promising. As soon as it becomes possible to measure the exact composition of the implanted gases in the outer 30 nm of e.g. ilmenites, true solar abundances should result. In addition, range studies should yield solar wind energy spectra.

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