IMPLANTED AND COSMOGENIC ^{38}Ar AND ^{36}Ar IN LUNAR IMPACT SPHERULES. J. Levine[1,2], R. A. Muller[1,3], and P. R. Renne[4,5], [1]Department of Physics, University of California, Berkeley, California 94720, USA, [2]Presently at Chicago Center for Cosmochemistry and Department of Geophysical Sciences, University of Chicago, Chicago, Illinois 60637, USA (jlevine@geosci.uchicago.edu), [3]Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA, [4]Berkeley Geochronology Center, 2755 Ridge Road, Berkeley, California 94709, USA, [5]Department of Earth and Planetary Science, University of California, Berkeley, California 94720, USA.

Introduction: We recently published formation ages of 81 lunar impact spherules, determined by the ^{40}Ar/^{39}Ar isochron technique [1]. These spherules from Apollo 12 soil sample 12023 may be compared with those of Culler et al. [2], which were from Apollo 14 sample 14163. On the basis of an overabundance of impact spherules younger than 400 Ma, [2] argued for an increase of the meteoroid bombardment flux in the inner solar system since that time. The distribution of spherule ages we observed in [1] is consistent with this explanation, but alternatives cannot be ruled out. In particular, we suggested that the abundance of <300 Ma spherules in trench sample 12023 is the result of impact ejecta in the lunar soil being stratified and overturned relative to pre-impact stratigraphy. This is consistent with the models and laboratory experiments of Melosh [3, p. 79].

In addition to their geochronological implications, argon isotopes measured on lunar samples also contain information about the abundance and distribution of calcium and potassium (which we report in a companion abstract [4]), exposure to cosmic rays, and implantation of solar wind and solar energetic particles. Here we report ^{38}Ar/^{36}Ar ratios of the implanted component in lunar spherules, as well as cosmic ray exposure ages calculated from the ratios of cosmogenic ^{38}Ar to ^{37}Ar$_{Ca}$. Though we present only Apollo 12 spherule data here, we have also examined the Apollo 14 spherule data of [2], and results are quite similar.

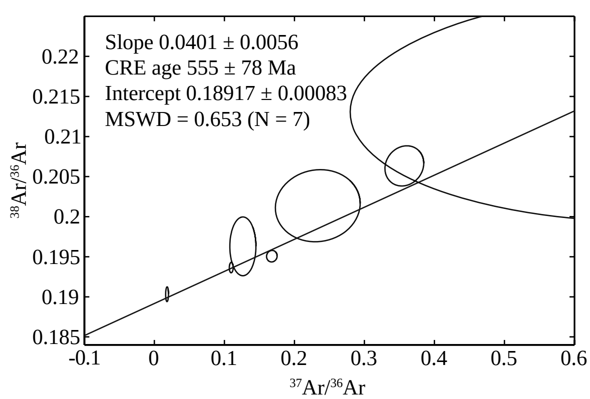

Fig. 1. Cosmochron diagram for Apollo 12 spherule H06. Ellipses contour 1σ.

Identification of Implanted and Cosmogenic Components: We measured abundances of $^{36\text{-}40}$Ar by laser stepwise heating on individual spherules, degassing each spherule in 7-20 heating steps. All ^{37}Ar is created by neutron irradiation, chiefly by ^{40}Ca(n,α)^{37}Ar. After correction for reactor interferences, ^{38}Ar and ^{36}Ar measurements represent binary mixtures of implanted and cosmogenic contributions. If we follow [5] and assume that cosmogenic argon is created by spallation of calcium (or other spallation targets co-distributed in the sample with Ca), then we may use a "cosmochron" diagram of ^{38}Ar/^{36}Ar vs. ^{37}Ar/^{36}Ar (so-called by analogy with a ^{40}Ar/^{36}Ar vs. ^{39}Ar/^{36}Ar isochron) to unravel the mixing of the two components (Fig. 1). The intercept of the trend line gives the ^{38}Ar/^{36}Ar ratio of the implanted component, and the slope S is related to the cosmic ray exposure age by

$$S = \left(1 - \frac{\left({}^{38}\text{Ar}/{}^{36}\text{Ar}\right)_{\text{implanted}}}{\left({}^{38}\text{Ar}/{}^{36}\text{Ar}\right)_{\text{cosmo}}}\right)\frac{P\tau_{CRE}}{40F\sigma_{40}},$$

where P is the production rate of cosmogenic ^{38}Ar (we adopt 1.4×10^{-8} cm^3 ^{38}Ar per gram of ^{40}Ca per Myr from [4]), τ_{CRE} is the effective duration of cosmic ray exposure, F is the neutron fluence experienced by the samples, and σ_{40} is the fission-spectrum averaged cross section for ^{40}Ca(n,α)^{37}Ca. The factor of 40 appearing in the denominator is the atomic mass of ^{40}Ca. While the ^{38}Ar/^{36}Ar ratio of the implanted component can be determined from the cosmochron line, the isotopic composition of the cosmogenic component must be assumed. We use $({}^{38}\text{Ar}/{}^{36}\text{Ar})_{\text{cosmo}} = 1.6\pm0.1$ to encompass the value of [6], but with a large uncertainty because of the dependence of this ratio on specimen composition.

On the basis of isotopic abundances, <10% of the ^{38}Ar and ^{36}Ar in the spherules is typically cosmogenic; the rest is from the implanted component. However, attempts to quantitatively constrain the initial depth of the implanted argon in the spherules have thus far been unsuccessful. Over the limited range of spherule sizes in this study (~200-500 μm), there is a weak tendency for larger spherules to have contained more implanted argon than smaller ones.

Results: *Implanted $^{38}Ar/^{36}Ar$.* Fig. 2 shows the $^{38}Ar/^{36}Ar$ ratio of the implanted endmember for each of the 81 Apollo 12 spherules dated by [1]. Nearly all values are isotopically heavier than terrestrial atmospheric air [7]. Though early estimates of the solar-wind $^{38}Ar/^{36}Ar$ ratio were indistinguishable from air [e.g. 8], more recent measurements suggest that the solar wind is offset toward lower $^{38}Ar/^{36}Ar$ ratios [9,10]. The offset toward higher $^{38}Ar/^{36}Ar$ ratios which we observe is much too large to be explained by production of ^{38}Cl (which quickly decays to ^{38}Ar) during neutron irradiation. Either the solar wind $^{38}Ar/^{36}Ar$ ratio is greater than inferred by [10] or the implanted ^{38}Ar and ^{36}Ar in our spherules is dominated by so-called solar energetic particle (SEP) implantation rather than the lower-energy solar wind. Our measurements agree with the SEP isotopic compositions of [6,9,10], both in the absolute values and the spread in $^{38}Ar/^{36}Ar$.

The relative abundance of SEP argon compared with "normal" solar-wind argon in lunar samples is orders of magnitude larger than the ratio of their fluxes [9]. Wieler et al. [9] argue for very poor retention of the weakly implanted solar wind in lunar plagioclase and ilmenite grains. The present observations suggest that glass too routinely loses most implanted argon from the low-energy solar-wind.

We hope that samples from the Genesis spacecraft will convincingly identify the argon isotopic composition of the solar wind and its relation to both the terrestrial atmosphere and the trapped component in lunar grains.

Cosmic ray exposure ages. Cosmic ray exposure ages for the spherules dated in [1] are shown in Fig. 3. The most striking observation is that individual spherules from the same scoop of soil (ours is from ~20 cm depth in ejecta of Sharp Crater, the diameter of which is 14 m) have experienced vastly different exposure and transport histories in the lunar regolith. By contrast with the results of [5], we see no particular clumping of exposure ages that might reflect the Sharp impact event. Sharp Crater is much smaller than that studied by [5], and may have excavated little fresh material from below the cosmic ray penetration depth. Moreover, unlike some mineral grains, our impact spherules were necessarily created near the surface, meaning that each specimen must have experienced cosmic ray irradiation prior to the Sharp event.

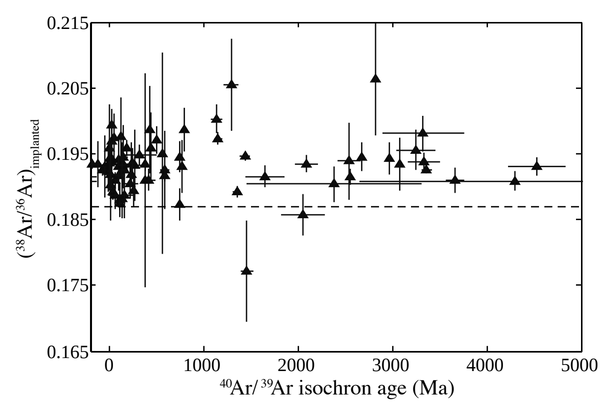

Fig. 2. $^{38}Ar/^{36}Ar$ ratio of the implanted endmember in Apollo 12 spherules, as a function of formation age from [1]. Dashed line is atmospheric value from [7].

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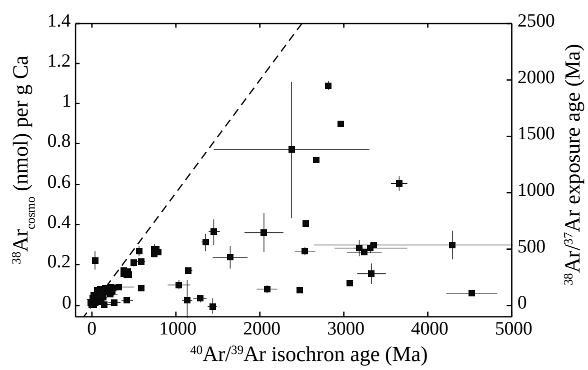

Fig. 3. $^{38}Ar/^{37}Ar$ cosmic ray exposure age as a function of $^{40}Ar/^{39}Ar$ formation age for Apollo 12 spherules from [1]. Dashed line represents the physical limit $\tau_{CRE} = \tau_{formation}$. The outlying datum comes from a spherule that suffered considerable post-formation loss of Ar on the Moon; we suspect that we underestimated its isochron age in [1].