**COULD IN SITU DATING WORK ON MARS?** T. D. Swindle, Lunar and Planetary Laboratory and Department of Geosciences, University of Arizona, Tucson AZ 85721-0092. tswindle@u.arizona.edu

Could noble gas-based chronology, in particular K-Ar dating, be performed in situ on Mars? Analyses of martian meteorites suggest a single K-Ar age of a single martian sample might not give a useful result. However, it would be unlikely to give a result that is patently wrong, and if K-Ar ages were determined for multiple samples, and cosmic ray exposure ages were determined simultaneously, the result should be a vast improvement in martian chronology. This analysis is consistent with recent arguments both for [1,2] and against [3] the idea of in situ dating on Mars.

**Potential and potential complications:** K-Ar ages are based on the decay of radioactive $^{40}K$ to $^{40}Ar$, and are determined by measuring the abundances of $^{40}Ar$ and K in the sample. There are two critical assumptions, a) that all of the $^{40}Ar$ produced within the sample is still in the sample, and b) that all of the $^{40}Ar$ within the sample comes from K decay.

a) Argon loss can result from heating, a fact that is exploited in the $^{40}Ar$-$^{39}Ar$ technique that has largely replaced K-Ar dating in terrestrial applications. However, martian rocks are unlikely to have experienced metamorphism (the most common natural cause for loss on Earth). Impact heating could also cause $^{40}Ar$ loss, but in any given impact, only a small fraction of the material affected by the impact is heated significantly. Most of the ejecta, for example, is physically displaced without being degassed, a fact which makes it notoriously difficult to date impact craters. The heavily cratered southern highlands of Mars, however, may have suffered an impact history long and complex enough for many samples to suffer Ar loss.

b) There are several ways to inherit $^{40}Ar$ that does not come from K decay. The most common way to acquire non-radiogenic $^{40}Ar$ is from an atmosphere. Most samples analyzed in terrestrial laboratories contain some contamination from the terrestrial atmosphere, while several of the martian meteorites, in particular the shergottites, contain martian atmospheric contamination. Another way is for the rock to have formed from a magma which had enough gas that not all of it could escape. This may have been the case for some martian meteorites, particularly Chassigny.

In performing $^{40}Ar$-$^{39}Ar$ dating on terrestrial samples, it is commonly assumed that any $^{36}Ar$ encountered results from atmospheric contamination, and that it will be accompanied by $^{40}Ar$, with the terrestrial $^{40}Ar/^{36}Ar$ ratio of 296. For martian samples, the situation is more complex. First, the $^{40}Ar/^{36}Ar$ ratio of the martian atmosphere is probably about 1700-1900 [4], so $^{36}Ar$ has to be measured more accurately to make the correction as precise. Second, there is a suggestion of another indigenous martian component, perhaps magmatic, with $^{40}Ar/^{36}Ar$ of 200 to 400 [4]. Martian meteorites may have terrestrial contamination, although this will not affect in situ analyses. Finally, while virtually all $^{36}Ar$ in a terrestrial sample must come from atmospheric contamination, martian rocks also contain $^{36}Ar$ produced by high-energy cosmic rays. Cosmic rays also produce the third stable argon isotope, $^{38}Ar$, so in principle it is possible to separate out the cosmic-ray contributions to $^{36}Ar$ by using $^{38}Ar/^{36}Ar$. In practice, cosmic rays add another source of uncertainty to the amount of atmospheric $^{36}Ar$, and hence the atmospheric $^{40}Ar$.

**Martian meteorite database:** To see how this might work, I have taken data from various analyses of Ar in martian meteorites. I have made assumptions about the kinds of analyses that will be possible on the martian surface. While these appear to be feasible on the martian surface [1,2], they might also be viewed as measurement requirements. These assumptions are that: a) K abundance can be determined to 10% precision on a homogenized sample (i.e., powder) on which Ar abundance can also be determined to that precision; b) Ar isotopic ratios can be determined to an uncertainty of 1-2%; and c) it will be possible to obtain an interior sample, free from the ubiquitous dust.

Various calculations are given in Table 1. For comparison, the first column gives the "accepted" age [5]. The next column gives bulk K-Ar ages (uncorrected for any atmospheric or mantle argon) determined by $^{40}Ar$-$^{39}Ar$ experiments [4,6,7]. The next column lists the percentage of $^{36}Ar$ that is "trapped" (not cosmic-ray-produced). For shergottites, this number comes directly from the original study [4]. For other meteorites, it comes from taking the range of $^{38}Ar/^{36}Ar$ ratios in the literature [8], and doing an isotopic decomposition between ratios of 0.25 (martian atmosphere) and 1.50 (cosmogenic). The next column gives the range in maximum amount of $^{40}Ar$ that could be "trapped," using data from the literature [8] and assuming trapped $^{40}Ar/^{36}Ar \leq 1900$. The next column gives a corrected age for each meteorite, assuming $200 \leq {}^{40}Ar/^{36}Ar \leq 1900$ for "trapped" gas and using the $^{38}Ar/^{36}Ar$ decomposition of the authors [4] for the shergottites or the sample with the least trapped $^{40}Ar$ (from [8]) for the others. The latter would correspond to the most precise expected analysis, although in many cases there are several comparable samples.

Table 1

| | "True" Age | Unc. Age | $^{36}$Ar %tr | $^{40}$Ar $\%tr_{max}$ | Corrected Age |
|---|---|---|---|---|---|
| **Shergottites** | | | | | |
| A77 | 178 | 3940 | 90 | 100 | 0-2230 |
| E79 | 173 | 2100 | 86 | 95-100 | 0-1920 |
| Y79 | 212 | 2080 | 50 | 100 | 0-1890 |
| Sh. | 165 | 405 | 16 | 11-100 | 204-384 |
| Zag. | 177 | 243(fs) | 30 | 100 | 170-235 |
| Q94 | 327 | 719(fs) | 41 | 100 | 0-652 |
| **Nakhlites** | | | | | |
| Nak. | 1270 | 1300 | 5-36 | 18-100 | 1120-1280 |
| Laf. | 1320 | 1360 | 2-23 | 7-100 | 1290-1350 |
| GV | 1330 | 1340 | 2 | 6 | 1280-1330 |
| **Unique meteorites** | | | | | |
| Ch. | 1340 | 1320 | 32-66 | 25-100 | 1070-1290 |
| A84 | 4510 | 4100 | 26-58 | 28-100 | 3580-4050 |

**Martian meteorite interpretation:** Let us then consider what kind of interpretations we might have, if we analyzed these rocks on Mars.

For a site where every rock was like ALH84001, we would get some rocks with apparent ages of 3600-4100 Ma, others with less certain ages that would be consistent with this range. We would conclude that this site was >3600 Ma old. While correct, this is not particularly useful chronological information, since crater chronologies do not differ by that much for sites that old. But this would probably be a geologically complicated site, the type for which any type of radiometric chronometry is most difficult.

For a nakhlite site, we would find some rocks about 1300 Ma old, and others which would be consistent with that age or younger. The limiting factor on the determination of the age would be instrumental uncertainties (roughly 10%), so we could average the best determinations to reduce the uncertainty.

If Chassigny is from the nakhlite site, it would be a rock that would give a less certain age. If from a separate site, we might have a 20% uncertainty in age (1070 to 1300 Ma). Current uncertainties for Amazonian sites are typically factors of two to four [9].

At the shergottite site, most rocks would have so much atmospheric contamination that we would obtain nothing more than an upper limit. Shergotty, however, has far less. This analysis gives an age that is outside the accepted range for the crystallization age by about 20% (slightly larger than the total uncertainty would be expected to be). Crater-based chronologies might be uncertain by a factor of several [9]. The Zagami feldspar sample analyzed by [4] is the most precise, because it has by far the least atmospheric contamination (the "maximum % trapped" for $^{40}$Ar is based on literature whole-rock measurements). However, a mineral separate may not be pertinent. Hence we might expect that less than half our samples at the shergottite site, but at least one or two out of 10, might give useful ages. The rest would simply give upper limits consistent with those more precise ages. The situation, however, could be much better for samples measured in situ than for the martian meteorites. The uncertainty in the shergottite ages is driven largely by the atmospheric contamination, which was added to the rock by the impact events that launched them from Mars. Consequently, pristine igneous samples on the surface of Mars should not be similarly contaminated.

If a surface rock has a longer cosmic-ray exposure history than those of the meteorites (1-15 Ma), the isotopic decompositions would be less certain. This, in turn, would make the correction for atmospheric or mantle effects less certain, and increase the uncertainty on the K-Ar age. Thus, the best samples to analyze would generally be those recently ejected by a crater on a surface thick enough that the crater did not penetrate through it. However, the exposure age also provides a lower limit on the age of a rock, so for very young surfaces (shergottite age or younger), the exposure age is also chronologically significant.

To summarize, there are many individual rocks for which it is not possible to put any meaningful constraint on the age [3]. On the other hand, each set of rocks has at least some (typically ≥50%) that give ages far more precise that the current absolute ages based on interpretation of crater counts. In only two cases is an age range calculated that does not include the accepted value of the crystallization age, and in neither case is it ridiculous. In one case, ALH84001, what is usually considered the correct impact age is obtained in a situation (complicated old terrain) where in situ chronology would not be expected to be fruitful. In the other, shergottites, the age differs by slightly more than the anticipated uncertainty. By analyzing multiple samples, and making use of exposure ages, in situ chronology should result in significant improvements in the calibration of martian history.

**References:** [1] Swindle T. D. [2000] *Concepts and Approaches for Mars Exploration* (LPI), 294. [2] Swindle T. D. [2000] *Assessing Chronometric Techniques for Quantifying Surficial Processes on Mars* (U. Illinois-Chicago), 34-35. [3] Nyquist L. E. and Bogard D. D. [1999] *Mars Exploration Program and Sample Return Missions* (CNES, Paris). [4] Bogard D. D. and Garrison D. H. (1999) *Meteoritics & Planet. Sci., 35,* 451-473; [5] Nyquist L. E., et al. (2001) in *Evolution of Mars* (ISSI). [6] Bogard D. D. and Husain L. (1977) *GRL, 4,* 69-71. [7] Podosek F. A. (1973) *Earth Planet. Sci. Lett., 19,* 135-144. [8] Schultz L. and Kruse H. (1989) *Meteoritics, 24,* 155-172. [9] Tanaka K. L. et al. (1992) in *Mars* (UA Press), 345-382.