IN SITU NOBLE-GAS BASED CHRONOLOGY ON MARS.

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Determining radiometric ages *in situ* on another planet's surface has never been done, and there are good reasons to think that it will be extremely difficult [1]. It is certainly hard to imagine that such ages could be measured as precisely as they could be measured on returned samples in state-of-the-art terrestrial laboratories. However, it may be possible, by using simple noble-gas-based chronology techniques, to determine ages on Mars to a precision that is scientifically useful.

This abstract will 1) describe the techniques we envision; 2) give some examples of how such information might be scientifically useful; and 3) describe the system we are developing (under a PIDDP grant), including the requirements in terms of mass, power, volume, and sample selection and preparation.

Techniques: By determining the abundances of major and minor elements in a sample, heating that sample to release noble gases trapped within it, and then analyzing the abundances of the isotopes of the three lightest noble gases (He, Ne, and Ar), two different types of ages can be determined.

Since one of the naturally occurring isotopes of potassium (K) decays to ^{40}Ar, the abundances of potassium and ^{40}Ar can be used to determine a K-Ar age. This gives the time since the sample was last heated enough to release Ar (several hundred degrees C). For terrestrial samples, metamorphism often resets some, but not all, of the minerals within a rock, so the ^{40}Ar-^{39}Ar technique has largely superseded the K-Ar echnique. On Mars, K-Ar ages are likely to date the crystallization of the rock, unless it has experienced a long or unusual impact history. K-Ar ages are likely to be measurable for martian samples ranging in age from a few million years old to the age of the planet.

The other type of age that can be determined is a cosmic-ray-exposure (CRE) age. Bombardment of any rock by cosmic rays will produce a wide variety of nuclei, including those of the noble gases, by "spallation" nuclear reactions. Since the surface of Mars is only partially shielded from cosmic rays, these cosmogenic nuclides will build up in any rock that is within about 1 meter of the surface. If the abundances of the target elements (basically, the major and some minor elements in the rock) and the cosmic-ray-produced noble gases are measured, and the production rate can be calculated, this gives the length of time the sample has been at the surface. If many samples on a surface have the same exposure age, that age probably represents the age of the surface itself. CRE ages are likely to be measurable from about 100,000 years to a few tens of millions of years. These measurements also give the radiation dose that a sample has experienced, which could be valuable information for quarantine considerations.

Examples: We believe the system described below can measure K-Ar and CRE ages with a precision of about 10%. This leads to two questions. First, are there places on Mars where an age with that precision would be scientifically useful? Second, would the ages determined by those techniques be interpretable in terms of martian chronology?

There are at least two types of terrain on Mars where 10% precision ages would be valuable. 1) Although the relative ages of various surfaces have been determined by crater counts, the absolute ages are very poorly known. Various estimates of the ages of some surfaces encompass virtual the entire history of the planet (e.g., the Late Hesperian-Early Amazonian boundary is anywhere from 0.6 to 3.5 Ga [2]). A single set of K-Ar ages from a suitable surface could pin down the entire cratering curve. 2) Determining the ages of the youngest volcanic or fluvial events would be of immense interest, and could be done by determining CRE ages (and, in the case of volcanics, K-Ar ages) from the surface.

A major concern with the K-Ar system is whether trapped martian ^{40}Ar, from either the mantle or the atmosphere, could lead to erroneous ages. As a first test of how meaningful K-Ar ages might be, Table 1 compares K-Ar of martian meteorites with the crystallization ages of those meteorites [3], using data from

Table 1: K-Ar ages of martian meteorites

Meteorite	Crystallization Age (Ga)	K-Ar Age (Ga)	Ref.
ALH84001	4.51(11)	4.1	3
Chassigny	1.34(5)	1.32(7) 1.46(17)	3 6
Nakhla	1.27(1)	1.30(3) 1.1(3) 1.4(3)	7 8 8
Lafayette	1.32(3)	1.36(3)	7
G. Valadares	1.33(1)	1.34	9
Shergotty	0.165(4)	.14-0.40	3
ALH77005	0.178(6)	0-3.6	3
EET79001B	0.173(3)	0-1.9	3
QUE94201*	0.327(10)	0-0.66	3
Y790327	0.212(62)	0-1.9	3
Zagami*	0.177(3)	0.15-0.24	3

Uncertainty in last digit(s) given in parentheses
* Feldspar separate

the literature for the K-Ar ages. In the shergottites, which contain measurable trapped Ar for other isotopes, trapped ^{40}Ar has been corrected for by assuming a trapped ^{40}Ar/^{36}Ar ratio of 200-1900, which encompasses likely values for the mantle and atmosphere [4]. For the other meteorites, the listed K-Ar ages are values reported in the literature. The only old sample (ALH84001) gives a K-Ar age slightly (roughly 10%) younger than its crystallization age, presumably reflecting later impacts. Four intermediate-aged samples give K-Ar ages indistinguishable from their crystallization ages. The six youngest samples all have a significant amount of trapped ^{40}Ar. Only two of them give demonstrably non-zero ages. However, these ages, while uncertain to much more than 10% because of the corrections that have to be applied, do agree with the crystallization ages. Hence the meteorites all give ages that either agree with the crystallization ages (to 10% or the uncertainty, whichever is larger), if they give ages at all. Furthermore, it is possible that a large fraction of the trapped argon in the shergottites was implanted by the impact that ejected the meteorites from Mars, so *in situ* measurements might be less affected by trapped Ar.

There should be little doubt that CRE ages could determine the age of a surface. The technique has already been used to determine the ages of young lunar craters in the vicinity of the Apollo landing sites (e.g., Cone, North and South Ray Craters) [5]. CRE ages have also been used for terrestrial surfaces, but in terrestrial applications, larger samples and higher precision measurements are required than will be necessary for Mars, where the cosmic-ray flux is roughly 1000 times higher.

Proposed system: Under a PIDDP grant for which funding has just started, we are developing a system that can determine noble-gas-based ages *in situ* at 10% precision, using components developed through other programs by three different laboratories. The system is summarized in Table 2. Basically, we used Laser-Induced Breakdown Spectroscopy (LIBS) to measure elemental abundances, an oven modified from MPL TEGA to heat the samples, and a miniature quadrupole mass spectrometer array to measure the noble gases. All of the component parts have been developed with spacecraft applications in mind, so all are miniaturized. The ovens will be significantly redesigned from TEGA. Since we do not need to perform calorimetry, but do need higher maximum temperatures, the requirements for that part of the system will change (mass and volume will certainly become smaller, we expect power consumption to remain the same or decrease). Note that the subsystems operate sequentially, so the total power required is the maximum power for any individual subsystem.

The system would determine K-Ar and CRE ages (both could be determined on each sample) on 12 samples of a few milligrams each. It assumes that material will be provided in the form of powder (e.g., from a drill), from within rocks at a site than has been characterized well enough to know where in martian stratigraphy it falls, and whether there are nearby large impact craters that could be affecting ages. Note that the LIBS analysis guarantees a chemical analysis of the sampled rock. Since the ages determined will be much less accurate than what could be done with a returned sample, we suspect that our system will be more valuable on an *in situ* mission than a sample return mission. However, it could provide help in sample selection or radiation verification for a sample return.

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References: [1] Swindle T.D. et al. (1996) *Planetary Surfaces Instruments Workshop* (LPI/TR 95-05), 21-40; [2] Tanaka K.L. (1986) *Proc. LPSC 17th*, in *JGR* 91, E139-E158; [3] Nyquist L. E. et al. (2000) *Evolution of Mars* (ISSI), submitted; [4] Bogard D.D. and Garrison D.H. (1999) *Meteoritics & Planet. Sci.* 34, 451-473; [5] Arvidson R. et al. (1975) *Moon* 13, 259-276; [6] Lancet M.S. and Lancet K. (1971) *Meteoritics* 6, 81-84; [7] Podosek F.A. (1973) *EPSL* 19, 135-144; [8] Ganapathy R. and Anders E. (1969) *GCA* 33, 775-787; [9] Bogard D.D. and Husain L. (1977) *GRL* 4, 69-71.

Table 2: *In situ* geochronology system

Subsystem	**Developer(s)**	**Mass (kg)**	**Power (W)**	**Volume (cm^3)**
Elemental analyzer (LIBS)	D. Cremers, LANL	1.4	2.3	1400
Oven (TEGA)	W. Boynton, LPL	5.7	60	4000
Mass spectrometer (QMSA)	A. Chutjian and M. Darrach, JPL	1.8	12	2150
Total		8.9	60	7150

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