^{40}AR/^{39}AR AGES *vs.* METEOROID DEPTH IN MURCHISON (CM2): A TEST OF THE SOLAR HEATING HYPOTHESIS.

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Introduction: Almost all K/Ar ages of CM chondrites are young, ~ 1 to ~ 3 Ga [1-4; *cf.* 5]. Very few of them approach the Mn/Cr or Pb/Pb ages of ~4.5 Ga that typify chondrites [6]. To explain the young K/Ar ages, [1] proposed that CM chondrites lost radiogenic argon recently, when the precursor meteoroids passed close to the Sun and temperatures rose. Consistent with this hypothesis, numerous modeling studies have shown that asteroids/meteoroids likely attain orbits with small perihelia (p<0.8 AU) [e.g., 7-9] late in their histories. If the Murchison meteoroid rotated slowly at distances between 0.5 and 1 AU, then diurnal variations in insolation could have caused thermal cycling by as much as 190 K [10]. The actual increases and the depth to which they extended are unknown. The presence of hydrated minerals or water ice may buffer temperature cycling in the near surface regions.

Evidence of a temperature gradient in the Murchison meteoroid and, more generally, the thermal history of Murchison is tested, by comparison of the ^{40}Ar/^{39}Ar systematics of several samples with the relative depths of the samples in the meteoroid. These are inferred from the activities of the cosmogenic radionuclides ^{36}Cl ($t_{1/2}$ = 0.3 Ma), ^{26}Al ($t_{1/2}$ = 0.7 Ma), and ^{10}Be ($t_{1/2}$ = 1.37 Ma). The dependences of these activities on meteoroid size and sample depth are known [11].

Experimental methods: By using accelerator mass spectrometry (AMS) [12], we measured the activities of ^{36}Cl or of ^{26}Al and ^{10}Be in bulk samples with masses of 50 to 100 mg. Carrier masses (mg) were ~8, 10, and ~5 for Cl, Al, and Be, respectively; AMS blanks [10-14] were: ^{36}Cl/Cl=5; ^{26}Al/^{27}Al=6., and ^{10}Be/^{9}Be=1.4.

Prior to argon isotope analysis, seven bulk samples of Murchison (230 to 750 μg) were irradiated for 78 hours at the USGS TRIGA nuclear reactor. The irradiated samples were heated stepwise with a CO_2 laser and the Ar isotopes released analyzed with a MAP215-50 mass spectrometer [13]. Typical blanks (10-18 mol) were: ^{40}Ar, <110; ^{39}Ar,3.8; ^{38}Ar,1.1; ^{37}Ar,23; ^{36}Ar,3.8.

Results: *Cosmogenic radionuclides (Table 1)* - ^{26}Al and ^{10}Be activities correlate as expected but are inconsistent in detail with model calculations [14]. These may be reconciled by raising the ^{10}Be activities by 0% to 10% and lowering the ^{26}Al activities by 10% to 0%. ^{36}Cl activities tend to rise with increasing ^{10}Be but scatter, possibly because of variable Cl concentration or of carrier loss before complete sample dissolution. To compare measured ^{36}Cl activities and modeled ^{36}Cl production rates, we combined the results of calculations of neutron capture rates [15] and of spallation production rates [11] assuming Cl = 470 ppm and a galactic cosmic ray flux of 4.8 p/cm^2/s. ^{36}Cl activities rise as observed to 90 dpm/kg, typically at depths of 15-20 cm in meteoroids at depths. Modeled ^{36}Cl production rates at first increase with depths of 50-60 cm, and then tend to plateau or decrease slightly (<5%) toward the center.

Ar isotopes – Concentrations (10^{-8} cm^3 STP/g) of ^{36,40}Ar are similar to published values: 32≤^{36}Ar ≤116; 200≤^{40}Ar≤2000. ^{36}Ar/^{38}Ar ratios (average, 4.0) are less

Figure 1. Integrated ^{40}Ar/^{39}Ar ages of 7 of 8 Murchison samples seem to decrease with increasing ^{10}Be activity and hence with increasing sample depth.

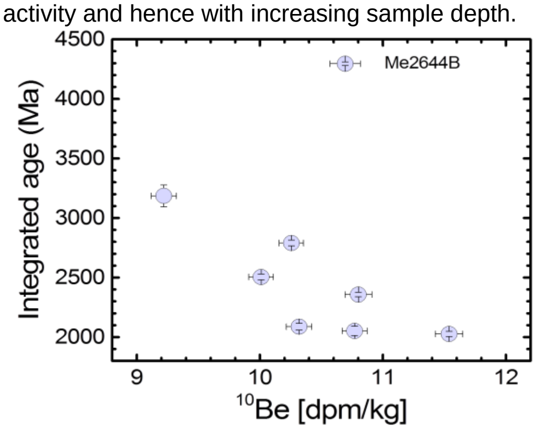
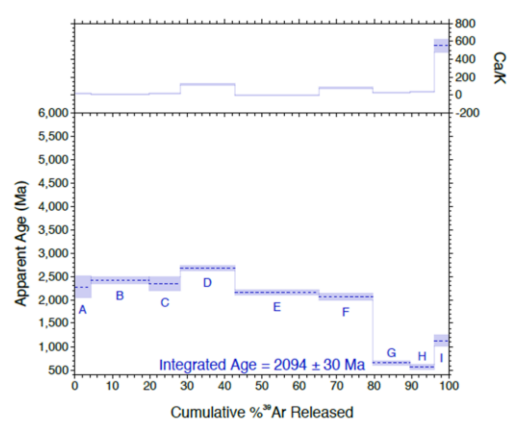


Figure 2. Most of the 'step' ages for sample Me2640 lie between 2.0 and 2.7 Ga, but do not define a plateau.



than the expected trapped ratio of 5.35, probably because of the presence of ^{38}Ar produced from chlorine in the TRIGA reactor.

Ages – Integrated ages, that are equivalent to K/Ar ages, range from 1.9 Ga to 3.2 Ga for 7 of the 8 samples (Figure 1; see also [17]). One sample, Me2644B, has a much older integrated age of 4.3 Ga, because of apparent ages >4.5 Ga at three intermediate temperatures (55% of the ^{39}Ar released). The Ar concentrations reported by [16] give K/Ar ages from 0.7 Ga to 4.7 Ga for an assumed K concentration of 400 ppm. Only one of 'our' samples, Me5443, satisfied the formal criteria for a plateau (~3.2 Ga; [3]), but individual step ages for most samples tend to fluctuate within a limited range of ~±300 Ma (e.g., Figure 2).

Generally lower ages (0.5-2.0 Ga) predominate for the last 5-20% of the gas released. Among three possible explanations – recoil, atmospheric ^{40}Ar contamination at lower temperatures, and argon redistribution [4], we prefer the last. Isochron ages are poorly defined (MSWD > 1), but correlate well with the integrated ages and intercept the *y*-axis at values indistinguishable from zero, minimizing the likelihood of atmospheric argon contamination.

Discussion: External heating would have led to larger fractional losses of radiogenic ^{40}Ar and lowest apparent ages close to the meteoroid surface. Figure 1 shows a contradictory trend, i.e., one toward lower integrated ages at larger pre-atmospheric depths (higher ^{10}Be). The behavior of water near the surface of an ice-cemented meteoroid may provide an explanation. Ar solubility in water is maximized near 0^oC [18]. At the surface of a meteoroid any H_2O will sublime immediately with no effect on the Ar inventory. With increasing pressure at depths of perhaps 1-2m in the cometary precursor, however, a narrow zone of liquid water may stabilize, (perhaps near the triple point: ~273.1K; 612Pa) and clay-water interaction could then lead to Ar dissolution. Orbital variation of heating from the surface to the interior would result in the migration and rapid loss of this transient, Ar-bearing fluid [19] at temperatures significantly below normal Ar closure temperatures. Direct petrographic observations would help test our proposed linking of the extent of aqueous alteration with fractional loss of radiogenic ^{40}Ar.

Table 1. Activities (dpm/kg) of Murchison.

	^{36}Cl	^{26}Al	^{10}Be
U5443	20.9±0.5	30.4±0.7	9.2±0.1
Me2682A	37.8±0.8	32.0±0.8	11.5±0.1
U5452	24.8±0.7	32.5±0.8	10.0±0.1
U5450	45.0±1.1	32.6±1.0	10.3±0.1
Me2752	72.9±1.6	34.2±0.9	10.3±0.1
U5469	54.8±1.2	34.2±0.9	10.0±0.1
U5481	31.5±0.7	35.2±0.8	11.0±0.1
Me2644B	89.9±2.7	36.0±1.0	10.7±0.1
Me2644A		36.2±0.8	10.7±0.1
Me2640	69.1±1.7	36.7±1.1	10.8±0.1
U5387	49.1±1.4	37.2±0.9	10.7±0.1
Me2684	55.9±1.1	38.1±1.0	11.3±0.1
Me2682B	84.6±2.4	39.6±0.9	11.5±0.1
U5461	89.3±1.9	39.7±1.0	10.8±0.1

U=US National Museum; Me=Field Museum of Natural History.

We obtained apparent ages of less than 2.0 Ga (83% loss of ^{40}Ar) for several temperature steps of most samples. These results imply that the 3.08-Ga plateau age that we reported for Murchison [3] has no chronological significance. They may instead reflect the number of orbits during which Ar dissolution in water occurred. The ^{40}Ar losses could have occurred recently as proposed by [1], or earlier [3].

Conclusions: The $^{40}Ar/^{39}Ar$ release patterns for 8 sub-milligram samples of Murchison give no chronometrically significant plateaus. Seven of eight integrated ages fall in a limited range between 2.0 and 3.2 Ga and may decrease with depth within the top ~50 cm of the meteoroid. This trend is more consistent with dissolution in liquid water that is more stable at depth, than with a simple thermal gradient imposed by external solar induced maximum. Any depth dependence aside, a pre-atmospheric depth of 30 cm in the Murchison meteoroid may have reduced, but clearly did not prevent ^{40}Ar loss. A search for retentive mineral phases in CMs is needed to establish the reliability of $^{40}Ar/^{39}Ar$ dating of CM meteorites and CM-like asteroids.

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