DATING HEAVENLY BODIES AND MONTE CARLO MODELS. G. Turner, M. C. Enright and J. Hennessy, Physics Department, Sheffield University, Sheffield S3 7RH, U.K.

In principle the $^{40}Ar - ^{39}Ar$ method can be used as a geo-thermometer as well as its more common application in determining chronologies. The aim of the present work is to make use of both types of information to investigate the bombardment history of the inner solar system and in particular to see to what extent the history inferred from lunar observations can be extended or complemented by meteorite studies.

The lunar picture is well established with a strong clustering of ages around 3.9 Ga, a very sharp cut off at 3.8 Ga and a high age tail, possibly bimodal, extending up to 4.2 Ga. If it is assumed that the histogram is the result of a large number of impact events and can therefore be treated statistically, the form of the histogram, P(t), can be expressed as:

$$P(t) = \alpha(t) \exp\left[- \int_0^t \alpha(t')dt' \right]$$

where $\alpha(t)$ is the probability per unit time of a rock being reset by impact ($1/\alpha$ = lifetime against resetting) and is presumed to be proportional to the bombardment rate. Attempts to fit P(t) to the experimental histogram (fig. 1) using a monotonically decaying flux such as that calculated by Wetherill (1) are unsuccessful. The prediction of a sharp cut off at high age and long tail at low age, is the opposite of what is observed. A more successful fit is obtained (fig. 2) if a family of bodies in short lifetime orbits (~ 20 My) are introduced 4.0 Ga ago, for example by the perturbation of a single 200 km asteroid into an Apollo type orbit followed by disruption by tidal forces or other means, again as suggested by Wetherill (2).

Attempts to apply this sort of reasoning to meteorite outgassing ages face a number of additional difficulties. First of all the sampling situation is quite different. To a first order the surface of the moon can be regarded as a closed system which carries an integrated record of bombardment since the first crust formed. The meteorites are samples of metre sized fragments of interiors and surfaces of a range of different sized bodies. The interior samples may not carry any record of the early bombardment and the samples of ancient bombarded asteroidal surfaces may have been preferentially lost by comminution. Observationally the situation is also quite different in that meteorite ages frequently indicate relatively recent collisions i.e. with the last few 100 Ma. To gain a better insight into the significance of meteorite outgassing ages we are currently following two lines of attack, one experimental, the other theoretical.

To test ideas of interpreting low temperature $^{40}Ar - ^{39}Ar$ age plateau in terms of recent reheating events (3) we have carried out a heating experiment on the Barwell meteorite, prior to irradiation and stepped heating (fig. 3). Four fragments were heated for 30 minutes to temperatures of approximately 800°C, 1000°C, 1100°C and 1300°C. The expectation was that we would be able to reproduce the general form of the theoretical release patterns for meteorites showing partial argon loss and also be able to infer a zero age for the (artificial) outgassing event.

The 800°C, 1000°C and 1100°C samples behaved essentially as expected. The 1000°C and 1100°C samples gave well developed low temperature plateaux with zero initial ($^{40}Ar/^{39}Ar$) ratios (± 1% of ratio in the unheated sample). In contrast, the 1300°C gave a non zero plateau, (2.0 ± 0.4)% for the first 6 extractions, which would correspond to a meaningless outgassing age of 360 Ma.

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The reason for the breakdown of the outgassing model for the 1300°C sample is apparent from the thin section. The plagioclase is vitrified and, since it is generally enclosed by pyroxene, we infer that the non zero ratio has resulted from dissolution in the molten plagioclase of ^{40}Ar from the pyroxene phase. The experiment lends support to the interpretation of low temperature age plateaux as dating real events in samples where the temperatures experienced in the outgassing did not produce melting. Where melting has occurred, for example in shock produced glassy veins, caution should be exercized.

A second line of investigation we are following is to make use of ^{40}Ar - ^{39}Ar temperature release data to infer maximum outgassing temperatures and to see whether we can fit these into a model of asteroidal breakup thereby placing constraints on the temperature distribution and history of the fragments. The outgassing model assumes only that the fraction of argon lost, f, is a function of the product of a rate term (i.e. a diffusion coefficient), which depends exponentially on reciprocal temperature, and time.

i.e. $f = f(\exp(-E/RT).t)$

or $$(1/T - (R/E)\ln t) = C \qquad (1)$$

where C is constant for a given value of f. C can be determined in the laboratory by determining the temperature required to produce a fractional ^{39}Ar loss equal to the observed radiogenic ^{40}Ar loss.

The temperature, T, of a fragment of radius, a, following a single impact heating event, can then be determined. The major outgassing of a cooling fragment will occur during the time when the diffusion rate is close to the maximum value (let us say, for ease of calculation, within a factor e). Setting $\ln(D_1/D_2) = (E/R)(1/T_2 - 1/T_1) \approx 1$, we obtain for the temperature interval, ΔT, where significant loss occurs

$$(\Delta T/T) \simeq RT/E \qquad (2)$$

The centre of a fragment of radius, a, will cool through the temperature interval, ΔT, in a time, t, given by

$$\frac{T}{(T - T_o)} = \frac{6}{\sqrt{\pi}} \left(\frac{\kappa t}{a^2}\right)^{\frac{1}{2}} \qquad (3)$$

where T_o is the surface temperature of the fragment (~ 170 K). Combining (1), (2) and (3) we obtain for the outgassing temperature, T:

$$T \simeq \left[C + \frac{R}{E} \ln \frac{\pi a^2 R T^2}{36 \kappa E (T - T_o)} \right]^{-1} \qquad (4)$$

This can be solved for T by iteration. Detailed results of applying this formula to published and unpublished ^{40}Ar - ^{39}Ar data will be presented elsewhere due to limitations of space. Required values of T range from $\leqslant 450$°C to 1300°C with a = 1 metre (and E = 45 K cal/mole) and from $\leqslant 230$°C to 520°C with a = 1 km.

In order to evaluate the significance of these outgassing temperatures a Monte Carlo fragmentation model has been generated in which a single 10 km parent asteroid is fragmented to produce a population of fragments with a size distribution, $g(m)dm = A\, m^{-\alpha}\, dm$. Fragments are selected for further breakup on the basis of $g(m)$. The fragmentation probability is assumed to be proportional to $m^{(5/3-\alpha)}$ and is used to determine the time of breakup. The sequence is followed down in mass until an object of 10 - 10^{-3} kg (a potential meteorite) is formed and its history recorded. The fragmentation probability of this size range is normalized to the cosmic ray exposure age distribution. A typical 'meteorite' is the result of between 2 and 4 fragmentation events and may therefore have been sequentially in heated bodies of radii decreasing

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by roughly an order of magnitude per event. The meteorite temperature histogram is thus a product of several precursor histograms but can in principle be used to infer the temperature distribution of impact ejecta.

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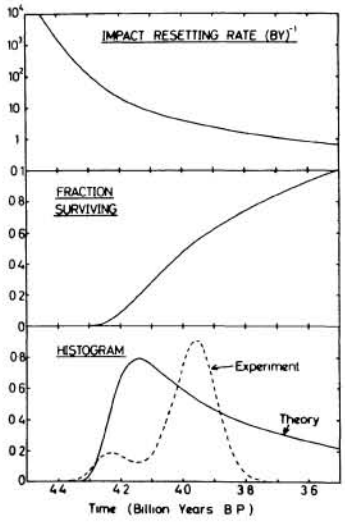

Fig. 1

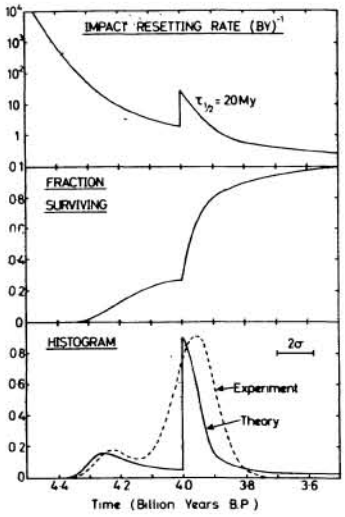

Fig. 2

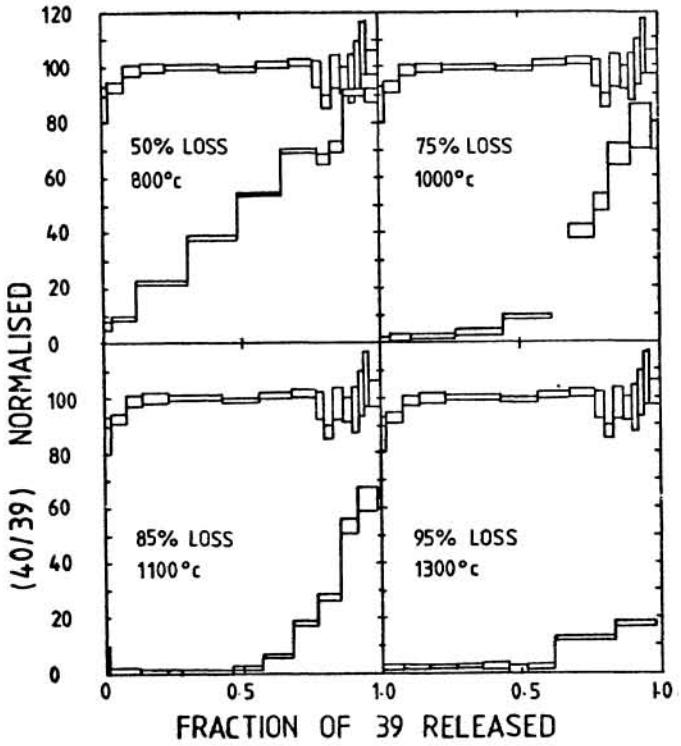

Fig. 3

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