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PREATMOSPHERIC SIZE OF THE BARWELL METEORITE: COSMIC-RAY TRACK, FUSION CRUST AND THERMOLUMINESCENCE STUDIES

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Abstract—Extensive measurements of cosmic-ray tracks have been made in three fragments of Barwell meteorite with a view to deduce the extent of atmospheric ablation of different crusted surfaces and in order to determine its approximate pre-atmospheric radius. Independent estimates of ablation made for several crusted surfaces from observations of fusion-crust mineralogy and thermoluminescence (TL) are in excellent accord. The observed agreement gives credence to the ablation theory and establishes usefulness of TL studies for determining atmospheric flight times. The preatmospheric 'radius' of Barwell is deduced to lie between 16 and 18 cm; the recovered mass amounts to 63 ± 11 % of the pre-atmospheric mass. The low ablation indicates that the atmospheric and geocentric velocities of the meteorite must be less than 15 and 10 km s^{-1}, respectively.

1. INTRODUCTION

DETAILED STUDIES of the fusion crust and thermoluminiscence properties of the Barwell meteorite carried out by Sears and Mills (1973) and by Sears (1975b) have provided estimates of the rate of ablation of the crust and the effective heating time of the meteorite during its atmospheric passage. These studies led to small values of ablation rates, of 0.2–0.4 cm s^{-1}. For a flight time of 10 s, this corresponds to the removal of perhaps only 2–4 cm of the original surface of the meteorite during atmospheric ablation. In the event of little or no fragmentation during ablation, this conclusion of small ablation could be easily tested from observations of tracks due to cosmic-ray iron-group nuclei in the meteoritic minerals. At shallow depths below the pre-atmospheric surface, one would expect to see large track densities as well as steep gradients in track densities (Fleischer *et al.*, 1967; Bhattacharya *et al.*, 1973). If, however, the meteorite fragmented soon after contact with the atmosphere, interior surfaces would get exposed and the fusion crusts formed would be 'secondary'; in this case the deduced depths of the fusion crusts from the exposed surface would have no relation whatsoever with the amount of total ablation encountered by the interior fusion-crusted surfaces. Thus, useful estimates of the rate of ablation based on measurement of cosmic-ray track densities could be obtained only if the Barwell meteorite did not fragment during traversal through the atmosphere when fusion crust formed. The likelihood of this was considered high because of the relatively small number of fragments produced in the Barwell meteorite shower, and the fact that seven of the fragments add up to more than 58 % of the total mass recovered, and further that less than 25 % of the surfaces are crusted.

The fall of Barwell has been discussed by Miles and Meadows (1966). They comment that the various fragments were recovered from a circular area, in contrast to the usually observed elongated area of fall, indicating a break-up late in flight. In support of this they remark on the lack of secondary burning on the surfaces of fragments and also the fact that several fragments found over the area of fall can be fitted

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together very accurately. In view of this we measured effective depths of fusion crusts studied by Sears and Mills (1973), with respect to the pre-atmospheric surface, using observations of cosmic-ray tracks. These studies also led to the conclusion that the Barwell fragment BM 1966, 57 has a post-atmospheric surface which has not undergone ablation by more than 2 cm. Detailed studies of cosmic-ray tracks and thermoluminescence were carried out in a narrow slice cut from this fragment to study TL characteristics and the pre-atmospheric radius of Barwell. The results of these studies are presented in this paper.

2. SAMPLE DESCRIPTION

The fusion-crust studies of Sears and Mills (1973) were made on samples from fragments BM 1966, 59; BM 1966, 65, and BM 1966, 57; the prefix BM referring to the British Museum, from which the samples were obtained. The initial track studies were therefore performed on spot samples taken from the same fragments from the crusted surfaces. A total of 7 samples were kindly provided by Dr. R. Hutchison. The total weights of the fragments BM 1966, 59; BM 1966, 65, and BM 1966, 57 are 4020 g, 2205 g and 2396 g, respectively. The first-mentioned sample is composed of several fragments. However, the latter two are single fragments and fit snugly on one of the fragmented faces.

After track investigations, it was decided to cut a thin bar from the fragment BM 1966, 57 for detailed track and TL investigations. A bar of width 0.8 ± 0.1 cm, thickness 0.3 cm and length 12.7 cm resulted.

3. EXPERIMENTAL RESULTS

3.1 *Track studies*

Results of studies of tracks in seven spot samples from three fragments are summarized in Table 1,

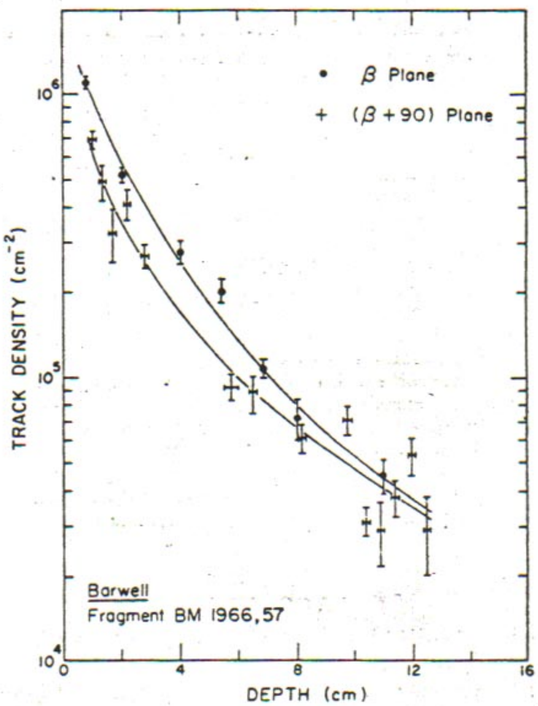

FIG. 1. Variation in the track densities in olivine grains along a 13 cm bar from the Barwell meteorite. Measurements were made along two orthogonal planes, marked β and $(\beta+90)$. The value of β is not known accurately but it is close to zero.

Table 1. Cosmic-ray track-density measurements in spot samples from three fragments of Barwell meteorite

Fragment number	Code number of sample	Track density in olivines (cm^{-2})	Track production rate* ($cm^{-2} \times 10^6$ y)	Estimated ablation (cm)
BM 1966, 59	1	3.6×10^5	3.8×10^5	3.5
	2	6.1×10^5	6.4×10^5	2.5
BM 1966, 57	3	1.0×10^6	1.1×10^6	1.5
	4	4.9×10^5	5.2×10^5	2.8
BM 1966, 56	5	3.8×10^5	4.0×10^5	3.5
	6	5.6×10^5	5.9×10^5	2.6
	7	2.1×10^6	2.2×10^6	0.6

*Based on cosmic-ray exposure age of 2.75×10^6 y (see text). The track production rate is normalized to the mean value that would be observed in the pyroxene and feldspar crystals, by multiplying the olivine track density values by a factor of 2.9 (see text).

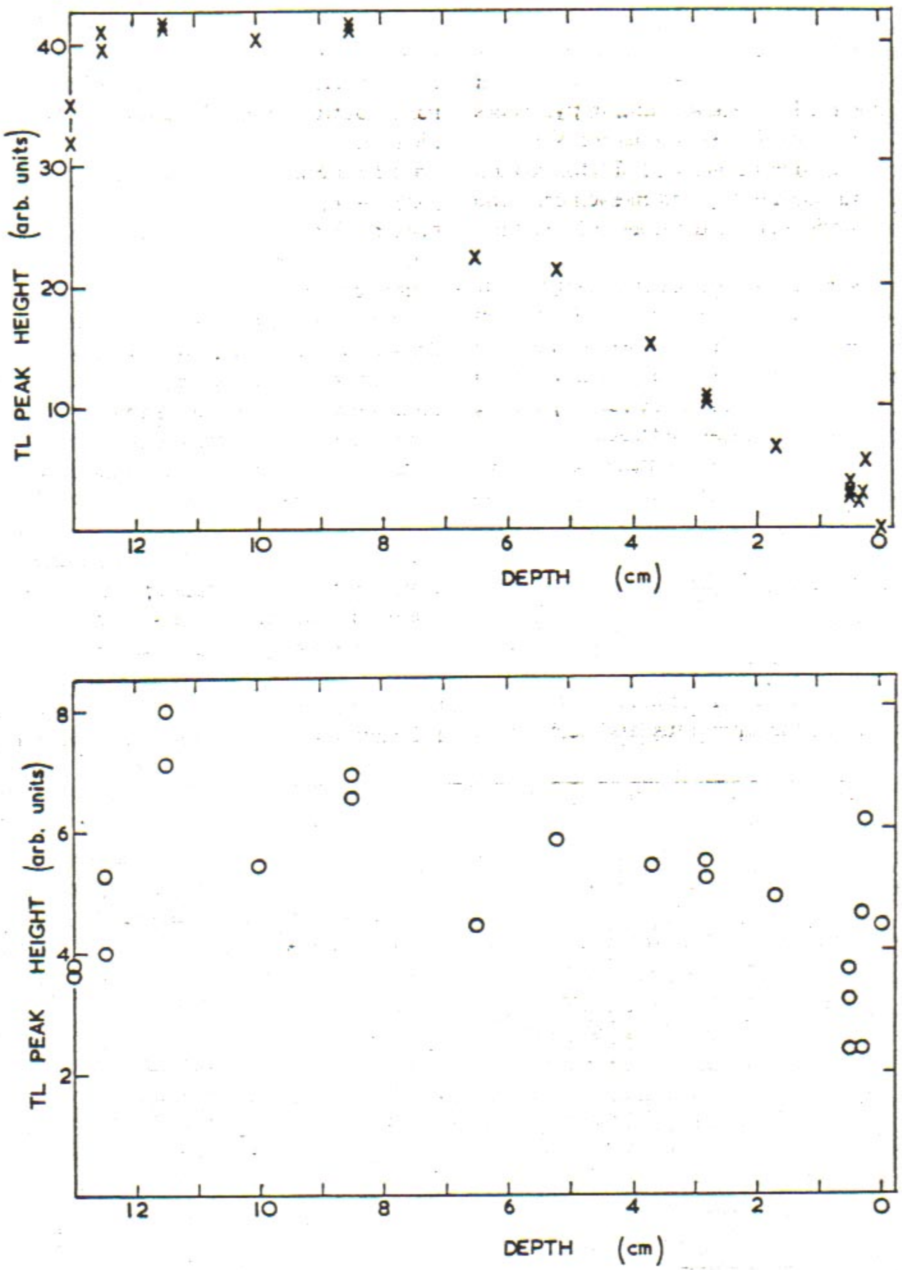

FIG. 2. Variation in the thermoluminescence intensity along a 13 cm bar from the Barwell meteorite. The crosses (Fig. 2a) represent the low temperature (about 200°C) thermoluminescence, and the circles (Fig. 2b) represent the high temperature (about 350°C) thermoluminescence.

where data are given only for tracks observed in olivine grains. Grain mounts were prepared from the spot samples using the methods described by Lal *et al.* (1968). Tracks were revealed in olivine grains by etching in WN solution at boiling point (Krishnaswami *et al.*, 1971) for 4 h, and in pyroxenes by etching in aqueous NaOH solutions (6 g NaOH : 5 ml water) at boiling point (Lal *et al.*, 1968) for 90 min. More than 200 tracks were counted in each case; the statistical uncertainties in track densities in Table 1 are less than 7%.

Results of measurements of track densities in the bar cut from BM 1966, 57 are shown in Fig. 1. Thin slices (0.5–1.0 mm) were cut from the bar along two orthogonal planes, using 10 mil diamond wafering blades, after firming the portions to be cut by painting them with epoxy resin. The measured track densities in thin sections are given in Fig. 1 separately for the two orthogonal planes, as a function of distance from the nearest crusted surface. The procedures for cutting, mounting and grinding/polishing are the same as those described by Bhandari *et al.* (1972).

3.2 *Thermoluminescence studies*

The thermoluminescence of 21 samples from the bar was measured using the apparatus and techniques described by Mills *et al.* (1977). In ordinary chondrites the TL is emitted predominantly at two temperatures, 200°C (which we will here refer to as LT) and 350°C (HT). The TL intensity of the natural powder at these two temperatures as a function of distance along the bar is shown in Fig. 2. The two points to note are the high intensity of the TL in the bar, and, especially with LT, the steep increase in intensity with increasing distance into the bar. The TL intensity of the 200°C peak at 10 cm is a factor of 5 greater than at 2 cm (see Fig. 2a), and, at this depth, is a factor of about 6 greater than in most ordinary chondrites which belong to the high retentivity group. This group was defined by Sears and Mills (1974) who found that ordinary chondrites tend to belong to one of two groups which have differing abilities to retain thermoluminescence. The intensity of the 350°C peak in the natural powder also shows a steady build up with depth, but this is not so great as with LT, and the scatter is greater. HT is less sensitive to the radiation and thermal history of the specimen but equally sensitive to sample inhomogeneity. The effect of sample inhomogeneity can therefore frequently be removed by considering the peak height ratio, i.e. LT/HT (Fig. 3). The quality of the line which results from this exercise shows that most of the scatter in the HT values in Fig. 2 is due to sample inhomogeneity,

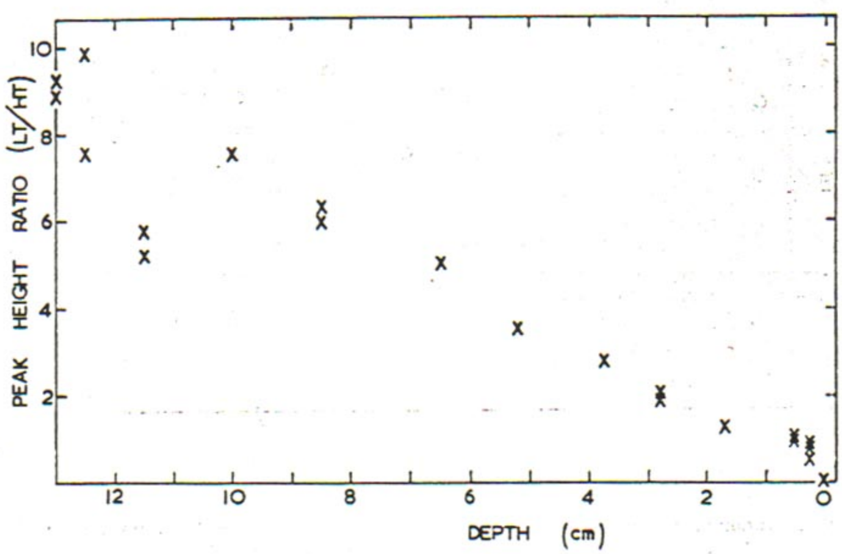

FIG. 3. Ratio of the thermoluminescence at high temperatures over that at low temperatures as a function of depth in the meteorite. This ratio removes the effect of sample inhomogeneity.

except perhaps for the points at 11.5 cm and within 0.5 cm of the crust where heating during atmospheric passage has drained the TL.

There appears to be a drop in LT at 13 and HT at 12.5 and 13 cm in the natural TL. However it is unlikely that this is significant because when expressed as the LT/HT ratio these points conform to the overall trend and were presumably displaced by sample inhomogeneity.

4. DISCUSSION OF RESULTS

4.1 *Track data*

Track densities were studied in olivine grains in each sample and in pyroxene grains only for samples 1 through 4. Our observations of track densities in pyroxene grains are consistent with the results for olivine grains; individual values in pyroxenes were higher by a factor of (2 ± 0.5) compared to the values observed in olivine grains, in good agreement with the earlier results of Bhandari *et al.* (1972).

We will now calculate the shielding depths of the various spot samples studied, on the basis of cosmic-ray track data, as has been done earlier for several meteorites (Fleischer *et al.*, 1969; Finkel *et al.*, 1975; Bull and Durrani, 1976). These estimates of shielding depths would correspond to atmospheric ablation unless the Barwell stone underwent a fragmentation in space during its cosmic-ray exposure history; in such an event, one would of course, overestimate ablation values since the tracks accumulated in the Barwell spot samples would then correspond to a period of time shorter than its total cosmic-ray exposure age.

For estimating shielding depths we need to estimate the track-production rates at different positions and compare them with the expected values. We adopt the semi-empirical calculations of Bhattacharya *et al.* (1973) which give the average track-production rates in feldspar and pyroxene grains in chondrites of specific gravity 3.58. The results in Table 1, however, are for olivine grains. The track-recording characteristics are different for these minerals which results in appreciably different track densities in the three minerals (Bhandari *et al.*, 1972) for an identical exposure condition:

$$\rho_0 : \rho_P : \rho_F :: 1 : 2 : 3.75$$

where ρ is the track density and the subscripts 0, P, and F refer to olivine, pyroxene, and feldspar, respectively.

For obtaining track-production rates, (tracks/cm^2 $\times 10^6$ y) normalized for feldspar-pyroxene grains, we have multiplied the olivine track density values in Table 1 by $(3.75+2.0)/2=2.9$, and divided the result by 2.75, the latter being the exposure age of Barwell ($\times 10^6$y), based on spallogenic ^{3}He and ^{21}Ne.

The concentrations of cosmic-ray spallation-produced ^{3}He and ^{21}Ne isotopes have been measured in stone meteorites by Cressy and Bogard (1976). They obtained values of 5.9×10^{-8} cc STP g^{-1} and 0.89×10^{-8} cc STP g^{-1} for ^{3}He and ^{21}Ne, respectively. The ratio of ^{3}He to ^{21}Ne exceeds 4.5, indicating no or little He diffusion loss (Eberhardt *et al.*, 1966). The ^{3}He age is therefore expected to be quite reliable. Using for the production rate of ^{3}He, P_3, a value of 2×10^{-14} cc STP g^{-1} y^{-1} (Kirsten *et al.*, 1963), we obtain for the ^{3}He cosmic-ray exposure age a value of 2.95×10^6 y. The Ne age is calculated to be 2.55×10^6 y using the production rate P_{21}, incorporating shielding effects as given by Eberhardt *et al.* (1966) and based on the formula:

$$P_{21} = P_3 \left[23.4 \left[\left(\frac{^{22}\mathrm{Ne}}{^{21}\mathrm{Ne}} \right)_{sp} - 1 \right] + 2.40 \right]^{-1}$$

The calculated track-production rates and the estimated ablation values for the 7 spot samples are given in Table 1.

The track data observed for the bar in BM 1966, 57 (Fig. 1) show a monotonic decrease with depth along the slice, the decrease being by a factor of more than 20. The track-density values for the plane labelled β ($\simeq 0°$) are systematically higher than those for the orthogonal plane, $(\beta+90)$. Within the scatter, the track-density ratios for the two planes are quite consistent with the expected behaviour (Maurette *et al.*, 1969) for a meteorite of ~ 20 cm radius.

The fact that track densities do not show any tendency to level off suggests that the pre-atmospheric radius of the Barwell meteorite exceeds 15 cm, which is the sum of the length of the bar and the estimated shielding depth of the crusted surface of the bar. The preatmospheric diameter of Barwell can be deduced from the measurements in Fig. 1, using the geometrical method proposed by Gupta and Lal (1977). If track measurements are made on three points A, B and C along a straight line within a sphere of radius R, then:

$$R = \frac{a(ab + \Delta X_2^2 - \Delta X_3^2) + b(ab + \Delta X_2^2 - \Delta X_1^2)}{2a(\Delta X_2 - \Delta X_3) + 2b(\Delta X_2 - \Delta X_1)} \quad (1)$$

where ΔX_1, ΔX_2 and ΔX_3 are the shielding depths for the three points A, B and C, respectively; and a and b are the linear distances AB and BC respectively. This method is applicable only for a nonradial slice; the denominator becomes zero for a radial slice and the errors in the estimation of the denominator become large for a nearradial slice.

Using Relation (1) and the estimated shielding depths for the two end-points and for the mid-point of the bar (Fig. 1), the preatmospheric radius of Barwell is found to be ~16 cm. These calculations yield a value of 17.5 cm as the upper limit for the preatmospheric radius of the meteorite.

4.2 *Thermoluminescence data*

Thermoluminescence and charged-particle tracks represent the two extreme ways in which cosmic radiation may interact with a meteorite in space. The tracks studied here are the result of damage by a very restricted range of radiation, namely the heavy (iron group) nuclei. As a consequence they are produced by the primary radiation which is rapidly attenuated with depth. On the other hand TL seems to be produced by any form of ionizing radiation, and secondary radiation dominates in its production. TL intensity therefore increases with depth as the build up of secondaries takes place ('nuclear cascade'). The only laboratory measurements with which one can compare these results appear to be those of Lalou *et al.* (1970) who bombarded a meteorite simulation with 3 GeV protons. Durrani *et al.* (1973; and S. A. Durrani, personal communication) bombarded stacks of concrete slabs measuring up to a total of $127 \times 76 \times 66$ cm^3 with 7 GeV protons, in which different TL phosphors (LiF, quartz and meteoritic powder) had been placed at varying depths. The efficiency of TL production compared to 1 MeV β's and γ's was found to range from 0.5 ± 0.2 to 0.9 ± 0.2; but their complete results have not yet been published. Lalou *et al.* (1970) observed an increase in intensity with depth, similar to that in the Barwell bar, to a depth of 10 cm where the intensity was a factor of 1.6 greater than at the surface. Although these experiments were performed using a unidirectional beam, while in space the radiation was omnidirectional, the increase in TL intensity in the bar is so much greater than 1.6 that other factors may be contributing to the gradient.

An important additional contribution to the thermoluminescence comes from the radioactive decay products of the long half-life isotopes in the meteorite. One would predict that the radiogenic TL throughout most of the meteorite is uniform, being affected only by sample inhomogeneity. However γ-rays may travel up to 10 cm through the meteorite. On the preatmospheric surface, therefore, the dose from this source would be only half that of the interior and within 10 cm of the surface would drop towards the edge. This effect would therefore add to the cosmogenic gradient and exaggerate it; but again this requires that the bar sampled was well within 10 cm of the preatmospheric surface. The intensity of the TL and the steepness of the gradient are consistent with the track evidence that only a few centimeters of material have been ablated.

As with the other specimens of the Barwell meteorite, and specimens of other meteorites, the heat generated during atmospheric passage has penetrated about 0.5 cm into the meteorite (Sears, 1975b; Prachyabrued *et al.*, 1971; Houtermans and Leiner, 1966). Calculations based on this measurement indicate that the duration of heating was in the order of 10 s (Sears, 1975b). One of the specimens used in the ablation-rate studies of Sears and Mills (1973) was taken a few millimeters from the fusion-crust end of the bar and an ablation rate found was 0.18 s^{-1}. Assuming constant ablation, about 2 cm of material would have been removed during atmospheric passage.

4.3 *Preatmospheric mass and the meteorite's velocity*

The total recovered weight of Barwell is 47 kg, corresponding to a mean recovered radius of 14.6 cm (assumed density = 3.6 g cm^{-3}). The mean ablation value for the seven samples is 2.43 ± 1.1 cm (Table 1). If this value is assumed to be representative, the preatmospheric radius becomes 17.0 ± 1.1 cm. The agreement between this estimate and the one made earlier is fairly good but too close; it does not allow for much ablation in the remaining fragments not sampled. It may be noted here that the total weight of the three fragments sampled is 8.62 kg, i.e. only ~18% of the total recovered weight.

The ablation estimates discussed above imply that if the preatmospheric shape of Barwell was spherical, the magnitude of ablation is indeed small for the entire body of Barwell: the depth of ablation of most of the surfaces must be $\lesssim 4$ cm. The preatmospheric shape of the Barwell stone may however not be a sphere as may be natural to expect and has also been observed in some cases (Cantelaube *et al.*, 1969; Sears, 1975a).

Even invoking moderate ellipticity would allow for larger ablation in the case of some of the fragments.

The preatmospheric mass of Barwell, assuming it to be a sphere of radius 17 ± 1 cm, is estimated to be 75 ± 14 kg. The corresponding value of mass ablation is 28 ± 14 kg; the recovered mass amounts to $63 \pm 11\%$ of the preatmospheric mass.

For such a small ablation, the atmospheric entry velocity of Barwell, based on calculations presented by Baldwin and Schaeffer (1971) and Opik (1958), must be below 15 km s^{-1} which corresponds to geocentric velocities of < 10 km s^{-1}.

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