*Meteoritics & Planetary Science* 33, 1311–1316 (1998)

# Cosmogenic effects in Mbale, L5/6 chondrite

S. V. S. MURTY[1], N. BHANDARI[1]*, K. M. SUTHAR[1], C. J. CLEMENT[1], G. BONINO[2,3]
AND G. CINI CASTAGNOLI[2,3]

[1]Physical Research Laboratory, Ahmedabad 380 009, India
[2]Dipartimento di Fisica Generale, Universita, Via P. Giurio 1, 10125 Torino, Italy
[3]Istituto di Cosmogeofisica, Corso Fiume 4, 10133 Torino, Italy
*Correspondence author's e-mail address: bhandari@prl.ernet.in

*(Received 1998 February 16; accepted in revised form 1998 August 18)*

**Abstract**–Measurements of particle tracks, cosmogenic radionuclides, and rare gas isotopes in Mbale indicate that the meteoroid had a simple, one-stage exposure for 30.2 Ma in interplanetary space. On the basis of the measured track production rates and $^{60}$Co and $^{26}$Al activities, the meteoroid is estimated to be a sphere with a radius of ~36 cm. The activities of several cosmogenic radionuclides (*i.e.*, $^{57}$Co, $^{54}$Mn, $^{22}$Na, $^{44}$Ti, and $^{26}$Al) in two fragments having different shielding, as estimated by their track density and $^{60}$Co activity, provide the depth variation in their production rates. Cobalt-57, $^{54}$Mn and $^{22}$Na activities agree with the production that is expected around the maximum of the solar cycle 22 as calculated from the Sunspot numbers. The U, Th-$^{4}$He and K-$^{40}$Ar ages are measured to be 0.54 Ga indicating a late thermal event which is in agreement with the thermal history of some other L group chondrites. The trapped N has $\delta^{15}$N of –57 ± 4‰, which is much lighter than the average L-group chondrite value; this indicates the presence of an isotopically anomalous light N component.

## INTRODUCTION

The Mbale meteorite shower fell on 1992 August 14 in Uganda at 12:40 UT. Over 863 fragments, weighing >150 kg, have been recovered out of the estimated 190 ± 40 kg fragments that fell to the Earth (Betlem, 1993; Jenniskens *et al.*, 1994). The fragments, ranging between 0.1 g to 27 kg, covered a strewn field of ~3 km × 7 km. The meteorite has been classified as an L5/6 chondrite (Jenniskens *et al.*, 1994). The fall, mineralogical and chemical characteristics, orbital parameters, and activities of some short-lived radionuclides measured immediately after the fall have been reported by Jenniskens *et al.* (1994). They also estimated the meteoroid mass to lie between 400 and 1000 kg. The cosmic-ray track density provides an independent method of determining the meteoroid mass. Therefore we have determined track densities in several fragments. Furthermore, as Mbale is a large shower, various fragments located at different depths within the meteoroid provide an opportunity to study cosmogenic effects as a function of depth. Such information is available only for a few other meteorites (*e.g.*, Udaipur, Bansur, Keyes, Madhipura , Knyahinya, St. Severin, Jilin, and Dhajala) and is necessary to understand the production profiles of different isotopes in meteoroids of different sizes (Bhandari *et al.*, 1993) and for testing the theoretical models developed to predict depth and size-dependent production of cosmic-ray effects in chondrites (Bhandari, 1981; Reedy, 1985; Graf *et al.*, 1990; Michel *et al.*, 1991).

Here we present the results on nuclear tracks, radionuclides, noble gases, and N in the Mbale meteorite. Preliminary results of this work were reported earlier (Suthar *et al.*, 1995). Some results on the activities of various radionuclides in a few other fragments of the Mbale meteorite have been reported also by Pistorius and Heusser (1994) and Merchel *et al.* (1997).

## SAMPLE DETAILS

Several fragments of the Mbale meteorite were kindly made available to us by Drs. Betlem and Heusser for track studies. To avoid samples that may have been heated during atmospheric entry, spot samples were taken from a depth of >0.5 cm from the fusion crust of each fragment; these were processed for tracks. On the basis of these measurements, two fragments (A and T)—weighing ~700 g and having the lowest and the highest shielding depths respectively—were selected for the present study. Radioisotopes $^{26}$Al, $^{60}$Co, $^{22}$Na, and $^{54}$Mn were measured in these fragments nondestructively using large Ge gamma ray spectrometers, one at the Physical Research Laboratory (PRL), Ahmedabad, India and the other at the Istituto di Cosmogeofisica, Torino, Italy. A chip weighing about a gram from fragment A was used for noble gas studies at PRL. The chip was split into two fractions (A1 and A2), weighing ~275 and 700 mg, respectively, for single fusion and stepwise temperature extraction of noble gases and N.

## EXPERIMENTAL PROCEDURES AND RESULTS

### Particle Track Studies

Track densities were measured in mineral grains using standard procedures (Bhandari *et al.*, 1980). Briefly, olivines and pyroxenes (in polished grains/sections) were etched for six hours in boiling WN etchant (40% EDTA + 1% oxalic acid and orthophosphoric acid, made to pH 8 by adding NaOH; Krishnaswami *et al.*, 1971) and for one hour in boiling 1:1 NaOH, respectively. The results of track density measurements are given in Table 1. The error in the track density depends on the number of tracks counted; these are given in Table 1. The measured track densities in olivines varied between 2.14 to 3.7 × $10^5$ tracks/cm$^2$, and those in hypersthenes varied between 6.2 × $10^5$ and 1.8 × $10^6$ tracks/cm$^2$ at different spots of the fragment A; the track density gradient is small. Four samples from fragment T gave <2 × $10^4$ tracks/cm$^2$, which in terms of track density is more than a factor of ten smaller than A. Therefore we concentrated on one sample (I) and determined a track density of 1.6 × $10^4$ tracks/cm$^2$ in olivines and 3.35 × $10^4$ tracks/cm$^2$ in hypersthenes. These results indicate that this fragment was located much deeper within the meteoroid, where it was shielded, to a large extent, from cosmic-ray heavy nuclei. Because only a few tracks could be counted in this fragment, the errors in track density are large (~15%). However, because the track density decreases steeply with depth, the errors in determination of the shielding depth are comparatively small, as is discussed later.

TABLE 1. Measured track density in Mbale fragments.

| Fragment | Olivine (# of tracks) WN, six hours | Pyroxene (# of tracks) 1:1 NaOH, one hour |
|---|---|---|
| Fragment A | | |
| Spot 1 | $2.14 \times 10^5$ (27) | $6.2 \times 10^5$ (59) |
| Spot 2 | $2.9 \times 10^5$ (62) | $1.1 \times 10^6$ (143) |
| Spot 3 | $3.7 \times 10^5$ (48) | $1.8 \times 10^6$ (215) |
| Spot 4 | $2.2 \times 10^5$ (23) | $6.6 \times 10^5$ (41) |
| Spot 5 | $2.53 \times 10^5$ (39) | $9.8 \times 10^5$ (90) |
| Fragment T | | |
| I | $1.6 \times 10^4$ (35) | $3.35 \times 10^4$ (14) |
| Spot 1 | $<2 \times 10^4$ | – |
| Spot 2 | $<2 \times 10^4$ | – |
| Spot 3 | $<2 \times 10^4$ | – |

TABLE 3. Krypton in Mbale.

| Temp. (°C) | $^{84}$Kr $10^{-12}$ ccSTP/g | $^{80}$Kr | $^{82}$Kr | $^{83}$Kr | $^{86}$Kr |
|---|---|---|---|---|---|
| | | $^{84}$Kr = 100 | | | |
| Mbale A1 (274.76 mg) total fusion | | | | | |
| 1600 | 64.81 | 5.785 | 24.265 | 26.084 | 29.125 |
| | | ±0.325 | ±0.070 | ±0.047 | ±0.092 |
| Mbale A2 (708.26 mg) stepwise analysis | | | | | |
| 900 | 5.56 | 13.908 | 35.228 | 41.895 | 26.631 |
| | | ±2.830 | ±0.613 | ±1.040 | ±0.759 |
| 1200 | 15.65 | 8.636 | 30.220 | 29.784 | 29.210 |
| | | ±0.287 | ±0.147 | ±0.059 | ±0.125 |
| 1600 | 25.36 | 5.731 | 22.492 | 22.971 | 30.760 |
| | | ±0.093 | ±0.169 | ±0.149 | ±0.093 |
| Total | 46.57 | 7.684 | 26.609 | 27.520 | 29.746 |
| | | ±0.485 | ±0.214 | ±0.225 | ±0.183 |

Errors in isotopic composition represent 95% C.L.
Errors in concentrations are ±15%.

## Rare Gas Mass Spectrometry

Noble gases and N in a sample of fragment A were measured on a VG1200 mass spectrometer using standard procedures described earlier (Murty and Goswami, 1992). Briefly, the samples were heated in a pre-degassed Mo crucible by an RF generator to extract the gases. To remove surficial contaminants, the samples were subjected to combustion in 2 torr $O_2$ at 400 °C. In the smaller sample (A1), the combustion step did not release any significant amount of gas. Likewise in the larger sample (A2), the combustion step yielded Kr and Xe only at blank levels but gave small amounts of He, Ne, Ar, and N of sample origin (as deduced on the basis of the measured isotopic ratios). After this pretreatment, the sample A1 was degassed in a single step at 1600 °C, whereas sample A2 was sequentially degassed at 900, 1200, and 1600 °C. The evolved gases were cleaned, separated, and analyzed for their concentration and isotopic composition using standard procedures (Murty and Goswami, 1992). Blanks were run under identical conditions at each temperature step. The blank compositions are atmospheric within errors and are <5% for each gas for all temperature fractions. Air standard and an artificial He mixture were run to assess the sensitivities and instrumental mass discrimination for each gas. The data reported (Tables 2, 3, 4, and 5) have been corrected for blanks and mass discrimination. In addition, the data for Ne have been corrected for interference from $^{40}Ar^{++}$ (at $^{20}$Ne), $^{44}CO_2^{++}$ (at $^{22}$Ne), and from CO in $N_2$, as detailed in Murty and Goswami (1992). However, these corrections are negligible. Due to unresolvable benzene interference, data for $^{78}$Kr are not reported.

### Cosmogenic Radionuclides

The cosmogenic radioisotopes $^{22}$Na, $^{26}$Al, $^{44}$Ti, $^{54}$Mn, $^{57}$Co (produced in spallation reactions), and $^{60}$Co (produced by capture of thermal neutrons) were measured by gamma ray spectrometry, using low-background large hyper-pure Ge detectors at PRL and Torino. The PRL detector (148 cc) is located in a 12-cm-thick Pb shield (Bhandari *et al.*, 1998), whereas the Torino detector (370 cc) is located under Monte dei Cappuccini within a Pb shield of 20 cm thickness. Titanium-44 was determined by measuring its short-lived daughter $^{44}$Sc, using a coincidence system employing the hyper-pure Ge detector in coincidence with a well type NaI(Tl) scintillator (Bonino *et al.*, 1992, 1995). The effective efficiency of counting was determined using the inherent $^{40}$K as an internal standard, using the average K concentration of 909 ppm in Mbale determined by

TABLE 2. Light noble gases and nitrogen in Mbale.

| Temp. (°C) | $^{4}$He | $^{22}$Ne | $^{36}$Ar | $^{3}$He/$^{4}$He | $^{20}$Ne/$^{22}$Ne | $^{21}$Ne/$^{22}$Ne | $^{38}$Ar/$^{36}$Ar | $^{40}$Ar/$^{36}$Ar | N ppm | $\delta^{15}$N (‰) |
|---|---|---|---|---|---|---|---|---|---|---|
| | $10^{-8}$ccSTP/g | | | | | | | | | |
| Mbale A1 (274.76 mg) total fusion | | | | | | | | | | |
| 1600 | 402.6 | 9.65 | 1.94 | 0.1049 | 0.8573 | 0.8750 | 0.6963 | 125.5 | 0.724 | 27.33 |
| | | | | ±0.0067 | ±0.0083 | ±0.0056 | ±0.0003 | ±0.4 | | ±0.60 |
| Mbale A2 (708.26 mg) stepwise analysis | | | | | | | | | | |
| 400 | 0.80 | 0.004 | 0.047 | 0.1140 | 0.9114 | 0.8564 | 0.3424 | 122.0 | 0.130 | 8.31 |
| (Comb.) | | | | ±0.0100 | ±0.0317 | ±0.0084 | ±0.0045 | ±0.1 | | ±0.22 |
| 900 | 325.6 | 2.25 | 0.145 | 0.1173 | 0.8434 | 0.8667 | 1.052 | 739.3 | 0.532 | 13.29 |
| | | | | ±0.0076 | ±0.0078 | ±0.0044 | ±0.003 | 2.1 | | ±0.62 |
| 1200 | 41.2 | 4.71 | 0.636 | 0.1865 | 0.8709 | 0.8797 | 0.8639 | 107.3 | 0.040 | 31.99 |
| | | | | ±0.0120 | ±0.0082 | ±0.0044 | ±0.0005 | ±0.3 | | ±0.29 |
| 1600 | <1 | 2.14 | 0.582 | – | 0.9680 | 0.8763 | 0.7413 | 37.2 | 0.102 | 90.60 |
| | | | | | ±0.0093 | ±0.0081 | ±0.0002 | ±0.1 | | ±0.81 |
| Total | 367.6 | 9.11 | 1.411 | 0.1250 | 0.8869 | 0.8757 | 0.8152 | 144.1 | 0.803 | 23.22 |
| | | | | ±0.0081 | ±0.0084 | ±0.0053 | ±0.0005 | ±0.4 | | ±0.56 |

Errors in isotopic ratios and $\delta^{15}$N represent 95% C.L.
Errors in concentration are ±10%.

TABLE 4. Xenon in Mbale.

| Temp. (°C) | $^{132}Xe$ $10^{-12}$ ccSTP/g | $^{124}Xe$ | $^{126}Xe$ | $^{128}Xe$ | $^{129}Xe$ | $^{130}Xe$ | $^{131}Xe$ | $^{134}Xe$ | $^{136}Xe$ |
|---|---|---|---|---|---|---|---|---|---|
| | | $^{132}Xe$ ≡ 100 | | | | | | | |
| Mbale A1 (274.76 mg) total fusion | | | | | | | | | |
| 1600 | 110.8 | 0.6074 | 0.6491 | 8.473 | 130.07 | 16.147 | 81.915 | 38.753 | 33.206 |
| | | ±0.0161 | ±0.0109 | ±0.105 | ±1.06 | ±0.087 | ±0.249 | ±0.205 | ±0.348 |
| Mbale A2 (708.26 mg) stepwise analysis | | | | | | | | | |
| 900 | 5.66 | 0.6631 | 0.7306 | 9.085 | 123.65 | 16.555 | 83.440 | 37.811 | 32.578 |
| | | ±0.0404 | ±0.0144 | ±0.137 | ±1.05 | ±0.435 | ±0.676 | ±0.237 | ±0.546 |
| 1200 | 35.20 | 0.6852 | 0.6917 | 8.474 | 124.68 | 16.185 | 81.190 | 39.181 | 33.211 |
| | | ±0.0748 | ±0.0128 | ±0.094 | ±1.01 | ±0.157 | ±0.263 | ±0.214 | ±0.355 |
| 1600 | 62.83 | 0.5397 | 0.5661 | 8.496 | 136.78 | 16.290 | 82.167 | 39.023 | 32.825 |
| | | ±0.0162 | ±0.0103 | ±0.113 | ±1.12 | ±0.133 | ±0.363 | ±0.210 | ±0.371 |
| Total | 103.70 | 0.5958 | 0.6177 | 8.521 | 131.95 | 16.269 | 81.905 | 39.010 | 32.942 |
| | | ±0.0374 | ±0.0114 | ±0.108 | ±1.08 | ±0.158 | ±0.346 | ±0.213 | ±0.375 |

Errors in isotopic composition represent 95% C.L.
Errors in concentration are ±15%.

TABLE 5. Cosmogenic, radiogenic and trapped components in Mbale (ccSTP/g).

| | Cosmogenic | | | | | Radiogenic | | | Trapped | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $^{3}He$ | $^{21}Ne$ | $^{38}Ar$ | $^{83}Kr$ | $^{126}Xe$ | $^{4}He$ | $^{40}Ar$ | $^{129}Xe$ | $^{36}Ar$ | $^{84}Kr$ | $^{132}Xe$ |
| Sample | $10^{-8}$ | | | $10^{-12}$ | | $10^{-8}$ | | $10^{-12}$ | $10^{-8}$ | $10^{-12}$ | |
| Mbale A1 | 42.20 | 8.44 | 1.13 | 4.33 | 0.26 | 183.1 | 243.5 | 29.9 | 1.18 | 62.3 | 110.6 |
| Mbale A2 | 45.93 | 7.97 | 1.01 | 3.87 | 0.21 | 128.8 | 203.3 | 30.0 | 0.73 | 44.4 | 103.5 |

Jenniskens *et al.* (1994). The K estimates in two fragments of Mbale by Jenniskens *et al.* (1994) agree within statistical errors and also overlap with the mean K content of L chondrites, justifying the use of $^{40}K$ as an internal standard. The activity of radionuclides, calculated at the time of fall, is given in Table 6. The measurement of each fragment lasted ~9 × $10^6$ s in order to obtain the very low activity of $^{44}Ti$ with a reasonable precision.

## Data Analysis

The results of light noble gases (He, Ne, and Ar) and N measurements are summarized in Table 2, whereas the Kr and Xe data are listed in Tables 3 and 4, respectively. The cosmogenic, radiogenic, and trapped noble gas components are given in Table 5. The results reported in Table 5 indicate that $^{3}He$ and all Ne isotopes are purely of cosmogenic origin. Although Ar is a mixture of trapped, radiogenic and cosmogenic components, most of the Kr and Xe are of trapped origin. In decomposing the measured amounts into various components, we have used the trapped and cosmogenic end-member values suggested by Eugster (1988).

## Cosmogenic Noble Gases and Exposure Age

The shielding indicator $(^{22}Ne/^{21}Ne)_c = 1.13 \pm 0.01$ for both splits of fragment A (Table 2) suggests that it comes from a shallow depth. The production rates of $^{3}He$, $^{21}Ne$, $^{38}Ar$, $^{83}Kr$, and $^{126}Xe$ for this value of $(^{22}Ne/^{21}Ne)_c$ for L-chondrite chemistry have been calculated (Eugster, 1988), and the exposure ages so obtained are given in Table 7. The values lie in the range of 30.2 ± 4 Ma. The uncertainties on these exposure ages are ±10% for $T_3$, $T_{21}$, and $T_{38}$ and ±15% for $T_{83}$ and $T_{126}$. The exposure ages for both splits calculated using different isotopes agree within the errors of measurements. This exposure age coincides with the major cluster of exposure ages at ~28 Ma observed for L chondrites with low-gas retention ages (Marti and Graf, 1992). The cosmogenic ratio $(^{3}He/^{21}Ne)$ is 5.4 (Table 5), which is similar to the expected value (Eugster 1988); whereas the $^{3}He/^{38}Ar$ (41.4) and $^{21}Ne/^{38}Ar$ (7.7) ratios are higher than the expected values (36 and 6.7, respectively) by ~15%, which indicates that $^{38}Ar_c$ is underestimated by 15% or the $^{38}Ar$ production rate is overestimated by 15%. The latter possibility has been suggested

TABLE 6. Calculated activity* of some cosmogenic radioisotopes at the time of fall.

| | | | Fragment A (Shielding depth = 10 ± 1.5 cm) | | Fragment T (Shielding depth = 24 ± 1cm) | | |
|---|---|---|---|---|---|---|---|
| Radio-isotopes | Half-life | Gamma Energy (keV) | count rate (cpm) | activity (dpm/kg) | count rate (cpm) | activity (dpm/kg) | Activity Ratio (T/A) |
| $^{57}Co$ | 270.02 day | 122.06 | 0.022 ± 0.0023 | 9.7 ± 1 | 0.043 ± 0.0025 | 13.1 ± 0.7 | 1.35 |
| $^{54}Mn$ | 312.5 day | 834.83 | 0.134 ± 0.0014 | 65.4 ± 0.6 | 0.274 ± 0.0016 | 97.2 ± 0.6 | 1.48 |
| $^{22}Na$ | 2.602 year | 1274.51 | 0.325 ± 0.0020 | 71.7 ± 0.4 | 0.480 ± 0.0022 | 92.6 ± 0.4 | 1.3 |
| $^{60}Co$ | 5.27 year | 1173.24 | 0.011 ± 0.0011 | 1.41 ± 0.14 | 0.199 ± 0.0022 | 23.5 ± 0.3 | 16.7 |
| | | 1332.5 | 0.013 ± 0.0011 | 1.67 ± 0.14 | 0.186 ± 0.0020 | 23.1 ± 0.3 | 13.8 |
| $^{44}Ti$ ($^{44}Sc$) | 59.2 year | 1157 | 0.0024 ± 0.00024 | 1.0 ± 0.1 | 0.0020 ± 0.00027 | 0.8 ± 0.1 | 0.8 |
| $^{26}Al$ | 7.16 × $10^5$ year | 1808.65 | 0.437 ± 0.002 | 60.4 ± 0.26 | 0.536 ± 0.0020 | 72 ± 0.3 | 1.19 |

*The reported standard deviations concern only the counting statistics.

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TABLE 7. Cosmic ray exposure and gas retention ages.*

| Sample | Cosmic ray exposure age (Ma) | | | | | | Gas retention age (Ga) | |
|---|---|---|---|---|---|---|---|---|
| | $T_3$ | $T_{21}$ | $T_{38}$ | $T_{83}$ | $T_{126}$ | Average | U-Th-$^4$He | K-$^{40}$Ar |
| Mbale A1 | 26.3 | 28.5 | 25.5 | 38.6 | 39.0 | 31.6 | 0.62 | 0.58 |
| Mbale A2 | 28.7 | 26.9 | 22.8 | 34.5 | 31.7 | 28.9 | 0.45 | 0.50 |

*The production rates are taken from Eugster (1988).

by many groups (see Alexeev, 1998). However, we can also expect underestimation of $^{38}Ar_c$. This is possible if part of the $^{36}$Ar in the sample is produced in the neutron-capture reaction $^{35}$Cl (n,γ)$^{36}$Cl → $^{36}$Ar resulting in an underestimation of cosmogenic $^{38}$Ar. Although low concentrations of $^{60}$Co (1.5 dpm/kg) in fragment A (Table 6) indicate low-thermal neutron fluence, integrated over its long exposure time, adequate amounts of $^{36}$Ar can accumulate from $^{36}$Cl decay to account for this observation. A widespread occurrence of $^{35}$Cl (n,γ)-produced $^{36}$Cl → $^{36}$Ar in large chondrites has been suggested earlier by Smith *et al.* (1977) and more recently by Bogard *et al.* (1995). Expected associated effects from (n,γ) reactions on Br and I at Kr and Xe, respectively, are not clearly visible in Mbale, most likely due to the dominant spallation Kr and Xe components.

## Radiogenic/Fission Components and Gas Retention Age

From the measured $^4$He, we subtract the cosmogenic contribution, using $(^4He/^3He)_c = 5$ and attribute the remaining $^4$He to *in situ* production from U, Th decay. All of $^{40}$Ar is attributed to the radiogenic component. Using Th = 36 ppb, U = 9 ppb, and K = 909 ppm (Jenniskens *et al.*, 1994), we derive a U, Th-$^4$He age of 0.54 Ga. The K-Ar age of 0.54 Ga (Table 7) is also the same, agreeing with the U, Th-$^4$He age. Wasson and Wang (1991) found a peak U, Th-$^4$He age at 0.4–0.5 Ga for L chondrites, signifying a major thermal event on the L chondrite parent body around that time.

The elevated values of $^{136}$Xe/$^{132}$Xe as compared to AVCC-Xe clearly indicate the presence of a fission Xe component. We calculate a total $^{136}Xe_f$ component of (in $10^{-12}$ ccSTP/g units) 2.04 ± 0.37 and 1.33 ± 0.38 for Mbale A1 and Mbale A2, respectively. For a U content of 9 ppb (Jenniskens *et al.*, 1994) and accumulation over 4.5 Ga, the spontaneous fission of $^{238}$U will only contribute $0.03 \times 10^{-12}$ ccSTP $^{136}$Xe /g. Hence, it appears that almost all $^{136}Xe_f$ has originated from the decay of extinct $^{244}$Pu. This amount of $^{244}$Pu fission $^{136}$Xe for Mbale is within the range of values reported for L5/6 chondrites (Eugster *et al.* 1993) that have Pu-Xe ages similar to Angra dos Reis (ADOR). This suggests that the late thermal event, wherein the radiogenic $^4$He and $^{40}$Ar have been lost, did not affect the Xe content to any appreciable extent. About $3 \times 10^{-11}$ ccSTP/g of $^{129}$Xe from *in situ* decay of the extinct $^{129}$I is found to be present in Mbale.

## Trapped Noble Gas Components

Trapped $^{36}$Ar amounting to $\sim 1 \times 10^{-8}$ ccSTP/g and trapped $^{132}$Xe of $\sim 1 \times 10^{-10}$ ccSTP/g are present in Mbale (Table 5). These values lie within the range observed in L chondrites of petrologic grade 6 (Marti, 1967). This agreement indicates that the late thermal event that led to the loss of the radiogenic $^4$He and $^{40}$Ar had also not resulted in any appreciable loss of trapped noble gases.

## Nitrogen

The N content of Mbale is ~0.8 ppm with $\delta^{15}$N of +23‰ (Table 2). In Fig. 1, the release pattern of N isotopes in Mbale A2 is shown. The major release of N occurs at 900 °C (Table 2); whereas for Ar, Kr, and Xe, the principal release is at >1200 °C (Tables 2, 3, and 4), which indicates that the major carrier phase of N and those of noble gases are different. The $\delta^{15}$N value is observed to be 8‰ in the 400 °C combustion step that progressively increases to 90‰ at 1600 °C (Table 2). Due to the long cosmic-ray exposure age combined with the low N content, the positive $\delta^{15}$N is mostly due to the presence of cosmogenic N. This is because of the very high value (>1) for the $^{15}$N/$^{14}$N ratio for the cosmogenic component, as against a very low value (~0.0035) for the trapped component. From the amount of $^{21}Ne_c$, and the relation $^{15}N_c = (4.5 \pm 0.5)^{21}Ne_c$ (Mathew and Murty, 1993), we can estimate the $^{15}N_c$ and correct the $\delta^{15}$N of the total sample. The cosmogenic corrected $\delta^{15}$N (‰) for Mbale A1 and Mbale A2 are –52.6 ± 3.3 and –61.9 ± 3.9, respectively. These values of $\delta^{15}$N refer to the average trapped N in Mbale, although in principle there can be multiple trapped N components with different isotopic ratios present in it. For ordinary chondrites, the trapped $\delta^{15}$N is usually in the range of +10 to –20‰ (Kung and Clayton, 1978; Hashizume and Sugiura, 1995). The trapped $\delta^{15}$N of –57.2‰ in Mbale is therefore much lighter, implying the presence of an additional anomalously light N component. A light N component has been observed in the L3 chondrite Allan Hills 77214 (Sugiura and Hashizume, 1992). A light N component of about –100‰ has also been found in Acapulco (Sturgeon and Marti, 1991), ureilitic diamonds (Murty, 1994), and some iron meteorites (Franchi *et al.*, 1993; Prombo and Clayton, 1993; Murty and Marti, 1994).

## Particle Tracks and Radionuclides

Tracks provide a reliable method of estimating shielding depths, ablation, and the meteoroid size. The shielding depths of fragments A and T can be calculated from the observed track densities following the procedure of Bhandari *et al.* (1980). Assuming the meteoroid to be spherical, a minimum radius—corresponding to the total material fallen on the Earth (190 ± 40 kg), as estimated by Jenniskens *et*

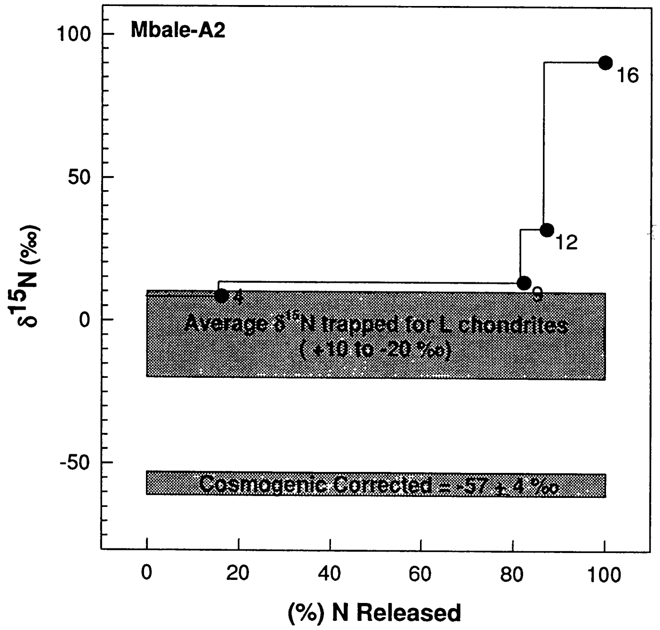

FIG. 1. Nitrogen release pattern for Mbale A2. Temperature in 100 °C units is indicated against each point. The average trapped $\delta^{15}$N for L chondrites as well as that for Mbale (corrected for the cosmogenic component) are indicated by the shaded boxes.

*al.* (1994)—can be taken as ~25 cm. Their estimated meteoroid mass (400 to 1000 kg) corresponds to a radius of 30 to 40 cm. In such a body, the shielding depth of fragment A is determined to be 10 ± 1.5 cm from the track density given in Table 1, using the exposure age of 30.2 Ma. The fragment T gives a shielding depth of 24 ± 1 cm. A better constraint on the size of the meteoroid is obtained from the $^{60}$Co and $^{26}$Al data (Table 6). The $^{60}$Co value in fragment T is 23.3 dpm/kg (Table 6), and its shielding depth can be estimated by comparing it with the production rates given by Spergel *et al.* (1986) and Eberhardt *et al.* (1963). The highest activity of $^{60}$Co measured so far is 37.5 dpm/kg in the fragment Mbale-33 (Pistorius, Laubenstein and Heusser, pers. comm., 1995), which did not show any measurable track density. Therefore, this sample must have been located nearest to the center of the meteoroid. The track density and $^{60}$Co in fragment T are both consistent with the inferred shielding depth of ~25 cm, if the meteoroid size is taken to be 33 cm. On comparison with the production profiles for chondrites (corrected for L group chemistry) given by Bhandari *et al.* (1993), we find that the observed $^{26}$Al activity in both fragments is consistent with a preatmospheric body of 35 to 40 cm in radius. Thus, we infer that the track density, $^{60}$Co, and $^{26}$Al are consistent with a meteoroid radius of 36 ± 4 cm. This estimate of meteoroid size and computed mass ablation (~80%) are consistent with the low geocentric velocity (11.2–13.8 km/s) given by Jenniskens *et al.* (1994).

The two shielding depth indices, that is, track production rate (TPM) and the cosmogenic $^{22}$Ne/$^{21}$Ne (NeR) ratio can be used to ascertain if the meteorite had a simple or complex exposure history. The data for Mbale fall in the region within a one-stage, simple exposure history on the TPM *vs.* NeR diagram (Bhandari, 1986).

The activity of radionuclides $^{57}$Co, $^{54}$Mn, $^{22}$Na, $^{60}$Co, $^{44}$Ti, and $^{26}$Al in the two fragments, corrected to the time of fall measured by the gamma ray spectrometer at Torino, are given in Table 6. The measurements of fragment A were also made at PRL, and the values obtained (in dpm/kg) are $^{54}$Mn (63 ± 5), $^{22}$Na (77 ± 3), $^{60}$Co (1.8 ± 1), and $^{26}$Al (62.2 ± 3). These are slightly different from the preliminary values reported earlier (Suthar *et al.*, 1995) because of longer counting data available now. The measurements at Torino and at PRL agree with each other. Several radionuclides, including many short-lived radionuclides ($^{52}$Mn, $^{48}$V, $^{51}$Cr, $^{7}$Be, $^{58}$Co, $^{56}$Co, and $^{46}$Sc) were measured by Jenniskens *et al.* (1994) and Pistorius and Heusser (1994) in some fragments soon after the fall of the meteorite shower. Recently, Merchel *et al.* (1997) have reported the measurements of $^{53}$Mn, $^{10}$Be, and $^{26}$Al in several fragments. The measured activities of various radionuclides (Table 6) fall within the ranges reported by Pistorius, Laubenstein and Heusser (pers. comm., 1995), Jenniskens *et al.* (1994), and Merchel *et al.* (1997) of $^{57}$Co (6.4 to 15.4 dpm/kg), $^{54}$Mn (53.9 to 105.3 dpm/kg), $^{22}$Na (49.0 to 100.1 dpm/kg), $^{60}$Co (<1.5 to 37.5 dpm/kg), and $^{26}$Al (45.6 to 76.4 dpm/kg). The activities of all the radionuclides, except $^{44}$Ti, in fragment T are larger than those measured in fragment A by factors ranging between 1.2 and 1.5 for the low-energy spallation products and by about a factor of 15 for the neutron-capture isotope $^{60}$Co (Table 6). The variation in activities of various radionuclides in the two fragments is shown in Fig. 2. Although the depth dependence of production rates of various radionuclides can only be described when a large number of samples having different shielding depths are analyzed, it is clear from Fig. 2 that the slope decreases with the energy of the spallation reaction responsible for their production. The slope is minimum for the high-energy product $^{44}$Ti and maximum for $^{54}$Mn. The small change in $^{44}$Ti activity by ≤20% (Bonino *et al.*, 1995) is consistent with the recent production profiles given by Neumann *et al.* (1997). The results (Table 6 and Fig. 2) indicate that fragment A was located at a place within the meteoroid where the nuclear cascade is not fully developed, which is consistent with the track data. Cobalt-60, produced by capture of thermal neutrons, in fragment A is measured to be ~1.5 ± 0.14 dpm/kg.

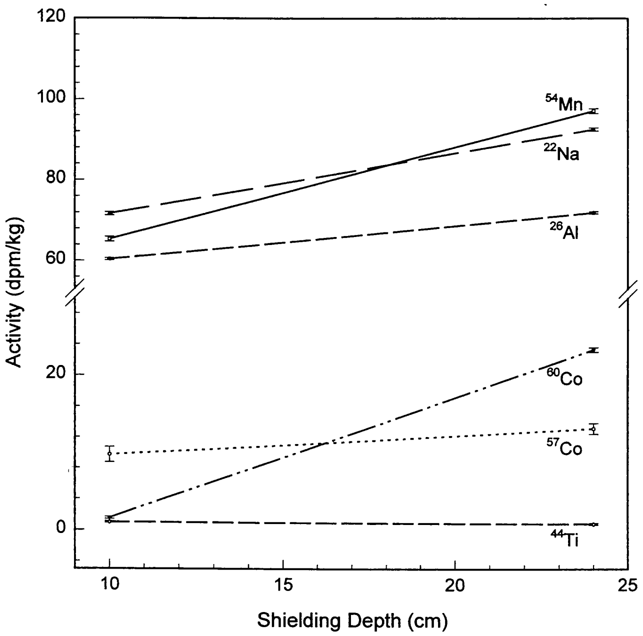

FIG. 2. Activity of various radionuclides in the two fragments of Mbale having shielding depths of 10 and 24 cm, respectively. The data points have been joined to illustrate the change in activities with depth.

The meteorite fell shortly after the maximum of solar cycle 22. Production of $^{22}$Na and $^{54}$Mn as well as the other short-lived nuclides depends upon the modulation of galactic cosmic-ray flux by the heliospheric magnetic field. The activity ratio $^{22}$Na/$^{26}$Al is, however, nearly unaffected by shielding; and the observed value of ~1.23 is close to the expected value (within ±10%), which is calculated from the climax neutron monitor data following the procedure of Bhandari *et al.* (1993). Bhandari and Ballabh (1995) have computed the orbit of Mbale based on the parameters given by Jenniskens *et al.* (1994) that shows that the meteoroid approached the Earth from the northerly heliographic latitude. The results reported here are consistent with small heliolatitudinal and radial gradients as observed by *Ulysses* (McDonald *et al.*, 1997).

## SUMMARY

The results on cosmogenic radionuclides, tracks, and noble gases show that Mbale had a simple, one-stage exposure history. Its exposure age is calculated to be 30.2 Ma. The data also confirm a small (36 ± 4 cm) size for the meteoroid. The activity levels of the short-lived radioisotopes are consistent with the values expected shortly after the maximum of the solar cycle 22 as calculated from the Sunspot numbers. There is evidence of a major thermal event in the history of this meteorite at 0.54 Ga ago, when most of the $^{4}$He and $^{40}$Ar were degassed as has been reported in some other L group chondrites. This event probably occurred on the parent body of the L group meteorites.

*Acknowledgements*–We are grateful to Dr. H. Betlem for kindly loaning us the meteorite fragments for this work. We have benefited by discussions with Dr. G. Heusser, with whom we have carried out similar work on other fragments of Mbale.

*Editorial handling*: L. Schultz

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