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# Nuclear tracks and light noble gases in Allan Hills 84001: Preatmospheric size, fall characteristics, cosmic-ray exposure duration and formation age

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**Abstract**–Cosmic-ray produced nuclear tracks and noble gases have been studied in the martian orthopyroxenite Allan Hills 84001 to delineate its cosmic-ray exposure history, preatmospheric size, and fall characteristics. A K-Ar age of 3.9 Ga, cosmic-ray exposure duration of 16.7 Ma, and a preatmospheric radius of 10 cm have been deduced from the noble gas and track data. The track data suggest ALH 84001 to be a single fall that has suffered atmospheric mass ablation in excess of 85%, higher than the value deduced for the shergottites, ALHA 77005, EETA 79001, and Shergotty. The formation age, as well as the cosmic-ray exposure duration, determined in this work are in good agreement with values reported earlier and are distinctly different from other shergottite, nakhlite, and chassignite (SNC) meteorites analysed so far. The high cosmogenic $^{22}$Ne/$^{21}$Ne ratio of 1.22 most probably reflects an effect due to non-chondritic composition of ALH 84001 as the track data suggest high shielding (≥5cm) for the analysed samples. There are signatures in the noble gas data that indicate the possible presence of trapped Ar and Ne of martian atmospheric origin in ALH 84001.

## INTRODUCTION

The shergottite, nakhlite, and chassignite (SNC) meteorites have overwhelming evidence for a martian origin (McSween, 1994), and their study should provide important insights into the evolution of the planet Mars and its atmosphere. Studies of cosmogenic effects (*e.g.*, nuclear tracks, noble gases) in these meteorites allow us to deduce their preatmospheric size, atmospheric mass ablation, and Mars-Earth transit time, parameters that are important in understanding the delivery mechanism of the martian meteorites. Several martian meteorites have been identified in the Antarctic collection. The recently discovered martian meteorite ALH 84001 from this collection (Mittlefehldt, 1994a) appears to be unique because of its older age (Ash *et al.*, 1996) and distinct records of aqueous alteration effects (Romanek *et al.*, 1994). Also, it has the highest cosmic-ray exposure age among the SNC meteorites, and the Xe and N isotopic records in this meteorite suggest the presence of a martian atmospheric component (Miura *et al.*, 1995; Swindle *et al.*, 1995; Murty *et al.*, 1995). In this paper, we present results obtained from our combined study of nuclear track and noble gas records in ALH 84001 and discuss their implications in terms of its formation and cosmic-ray exposure ages, its preatmospheric size, extent of atmospheric ablation, and fall characteristics. Initial results from this study have been reported in Sinha and Goswami (1994) and Murty *et al.* (1995).

## SAMPLE DETAILS AND EXPERIMENTAL PROCEDURE

We have analysed a total of nine samples from different locations of ALH 84001 for nuclear track records (see Fig.1). Most of the samples were in the form of small chips taken from locations very close to the recovered surface, mostly within <0.5 cm from the fusion crust. The noble gas studies were carried out in a bulk sample and in three density separates. Since the minerals of interest happen to be maskelynite (<3g/cm$^3$), orthopyroxene (>3g/cm$^3$) and carbonates of intermediate density, the sample was first crushed to ~100 $\mu$m size in a clean bench and then suspended in a solution of sodium polytungstate of density 3g/cm$^3$. After a settling time of 1 d, during which the ambient conditions were maintained to prevent any significant change of the density of the medium, the sinks, the floats, and the suspended material have been separated and labelled according to their density. The density separates were thoroughly cleaned by ultrasonication before loading for mass spectrometry. Scanning electron microscopy (SEM) analysis of the >3g/cm$^3$ fraction (>90% of the total mass) indicated it to be predominantly orthopyroxene, while the suspended material (~3g/cm$^3$ fraction; ~5% of total mass) is dominantly silicate with a small admixture (<5%; 2 out of 35 grains analysed) of a feldspathic component (maskelynite?). We did not characterize the float (<3g/cm$^3$ fraction) that yielded a very small sample amount. Noble gas studies of the various density fractions were attempted with the hope that differences in elemental composition among these separates will lead to identifiable changes in cosmogenic Ne and Ar as well as radiogenic $^{40}$Ar. The results obtained by us indicate that this expectation was only partly justified.

### Nuclear Track Studies

The samples analysed for track studies were gently crushed and individual pyroxene grains were handpicked and processed for revelation of nuclear tracks using standard procedures (Bhandari *et al.*, 1972). The etching was done in steps in a boiling 30N NaOH solution to monitor the state of the grains, most of which appeared to be shocked, and to ensure proper revelation of tracks. A large fraction of the pyroxenes was lost due to dissolution during the initial etching step, reflecting the shocked nature of the grains. We could find well-developed tracks after a total etch time of 60 min in pyroxenes from eight out of the nine samples analysed by us. The last sample did not yield any good pyroxene for track studies after the above etching treatment. Photomicrograph of well-developed nuclear tracks in a pyroxene grain from one of the near surface samples (#135) is shown in Fig. 2.

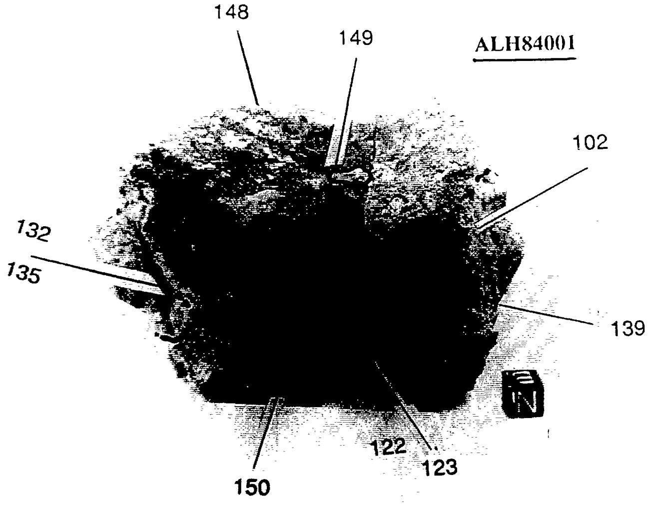

FIG. 1. Locations of ALH 84001 samples analyzed for nuclear track records. Samples 139, 148 and 150 were taken from surfaces and locations that are not directly visible in this photograph.

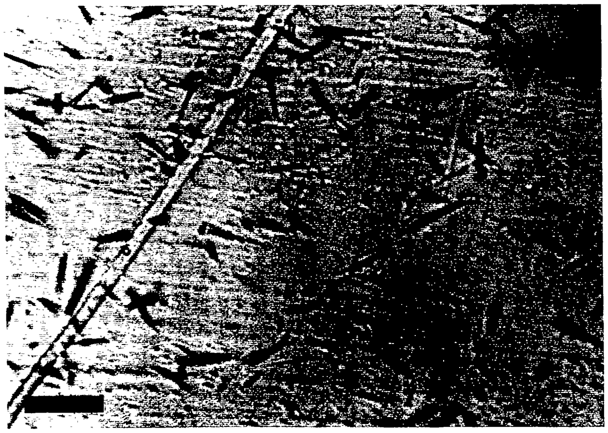

FIG. 2. Photomicrograph of nuclear tracks in a pyroxene grain from the sample ALH 84001,135. Scale bar is 10 $\mu$m.

### Mass Spectrometry

We have carried out simultaneous measurement of noble gases and N using a VG1200 mass spectrometer following the procedures described by Murty and Goswami (1992). Briefly, each sample was first combusted in 2 torr $O_2$ at 400 °C to liberate surficial contaminants. Subsequent gas extractions were carried out by pyrolysis by RF heating in a predegassed molybdenum crucible. Sample and blank runs were carried out in an identical fashion. Air standards were run after each sample to assess sensitivity and mass discrimination. The isotopic data reported in this paper are corrected for blanks and mass discrimination. The blank corrections are up to a maximum of 5% in the highest temperature fraction and much less at all the other temperature steps. Additionally, the Ne data have been corrected for interferences from $^{40}Ar^{++}$(at $^{20}Ne$ ) and $CO_2^{++}$(at $^{22}Ne$), though such corrections are mostly <1%.

## RESULTS AND DATA ANALYSIS

The results obtained from nuclear track studies are shown in Table 1. Only samples that yielded track data are included in the table. The errors in the track density represent statistical uncertainty based on the number of tracks observed in each sample. The sample location details in Fig.1 and Table 1 are based on data supplied by the curator of Antarctic Meteorites at Johnson Space Center, Houston, Texas. The shielding depth of each of the analysed sample is deduced following the approach of Bhattacharya *et al.*, (1973) and is also given in Table 1. The well-developed nature of nuclear tracks in the near crust samples (see, *e.g.*, Fig.2) rule out the possibility of partial annealing of tracks in samples taken from close (<5 mm) to the fusion crust. It may be noted that experimental studies of track annealing during atmospheric ablation for a dozen meteorites belonging to different classes (Jha, 1984) have shown that the zone of total to partial annealing of tracks extends only up to ~1 mm from the fusion crust. At distances of 1.5 to 2 mm, the tracks are completely unaffected.

TABLE 1. Nuclear track data in ALH 84001.

| Sample | Location | Track Density (#/cm$^2$) × $10^6$ | Shielding Depth (cm) |
|---|---|---|---|
| #102 | ~1cm from f.c.* | 2.7 ± 0.5 | 6.3 |
| #122<br>#123 | <0.5 cm from f.c. | 4.2 ± 0.4 | 5.1 |
| #132<br>#135 | <0.5 cm from f.c. | 3.7 ± 0.2 | 5.5 |
| #139 | West face† | 3.3 ± 0.5 | 5.7 |
| #149 | Bottom face† | 2.7 ± 0.7 | 6.3 |
| #150 | Top face† | 4.6 ± 0.4 | 4.8 |

*f.c. = fusion crust.
†Sample close to recovered surface; surfaces are marked following the labelled block in Fig.1.

The stepwise heating data for the Ne and Ar for the bulk sample as well as the density separates are shown in Table 2. Data for Kr, Xe, and N isotopic composition will be reported elsewhere. The deduced values of the cosmogenic, radiogenic and trapped components for each sample are given in Table 3. For decomposing the Ar data, we used the martian atmospheric (trapped) values of ($^{36}Ar/^{38}Ar$) = 4.1 ± 0.2 and ($^{40}Ar/^{36}Ar$) = 2400 ± 200, measured in lithology C of EETA 79001 (Wiens *et al.*, 1986).

## DISCUSSION

The nuclear track and noble gas (Ne and Ar) data for the different samples of ALH 84001 (Tables 1–3) are analysed to determine the cosmic-ray exposure duration of this meteorite, its preatmosperic size and mass ablation, nature of its fall (single/multiple), its formation age, and signatures of trapped martian atmospheric component.

### Cosmic-Ray Exposure Duration

In the absence of exact chemical composition of the mineral separates analysed by us, we use the data for cosmogenic Ne and Ar in the bulk sample of ALH 84001 to determine its cosmic-ray exposure duration, based on the bulk chemical composition given by Dreibus *et al.* (1994) and Mittlefehldt (1994a), and the procedure proposed by Eugster and Michel (1995) for obtaining shielding-dependent production rates for cosmogenic nuclides in SNC meteorites. We obtain a Ne exposure age of 19 Ma for a P($^{21}$Ne) value of 0.23 × $10^{-8}$ ccSTP(g.Ma)$^{-1}$ and an Ar exposure age of 14.4 Ma for a P($^{38}$Ar) value of 0.042 × $10^{-8}$ ccSTP(g.Ma)$^{-1}$. The mean cosmic-ray exposure age of 16.7 ± 1.7 Ma based on these two values is similar to those reported earlier by Eugster (1994), Swindle *et al.* (1995), and Miura *et al.* (1995). As has already been noted by these authors, the cosmic-ray exposure age for ALH 84001 is the highest among all the SNC meteorites for which exposure age estimates are available at present and which cluster around the values of 0.5, 2.5, and 9–12 Ma. If we consider ALH 84001 to have a simple exposure history, its high cosmic-ray exposure age would imply an additional break-up of a large martian meteoroid in space or an impact on the martian surface leading to the ejection of ALH 84001 as a small object in space ~16 Ma ago. The distinctly different and older formation age of this meteorite (see discussion below) tends to support the latter possibility.

The cosmogenic $^{22}Ne/^{21}Ne$ ratio of 1.22 for the bulk sample of ALH 84001 is rather high and is consistent with the earlier results of Welten *et al.* (1994), Swindle *et al.* (1995), and Miura *et al.* (1995). An even higher value of this ratio (1.32) was found in one of the density separates (Table 3). These values, however, are not a result of lower shielding of the analysed samples, as the nuclear track data suggest a high mass ablation for this meteorite and shielding depths of ~5–6 cm for all the analysed samples (see below). Further, unlike some of the shergottites that have high cosmogenic $^{22}Ne/^{21}Ne$ ratios and distinct signatures of solar cosmic ray (SCR) produced $^{21}$Ne (Garrison *et al.*, 1995), the ALH 84001 data do not show any sign of SCR-produced neon. Absence of SCR-produced radionuclides in ALH 84001 has also been reported by Nishiizumi *et al.*

TABLE 2. Neon and argon in ALH 84001.

| Temp. (°C) | $^{22}$Ne ($10^{-8}$cc STP/g) | $^{20}$Ne/$^{22}$Ne | $^{21}$Ne/$^{22}$Ne | $^{36}$Ar ($10^{-8}$cc STP/g) | $^{38}$Ar/$^{36}$Ar | $^{40}$Ar/$^{36}$Ar |
|---|---|---|---|---|---|---|
| **Bulk (692.4 mg)** | | | | | | |
| 400 Combst.* | <0.005 | – | – | 0.002 | 0.2275 | 466.3 |
| | | | | | ±.0032 | 2.5 |
| 1000 | 2.02 | 0.9200 | 0.8130 | 0.109 | 0.6493 | 5535 |
| | | .0038 | .0050 | | .0012 | 18 |
| 1200 | 2.75 | 0.8673 | 0.8041 | 0.223 | 1.2575 | 1131 |
| | | .0027 | .0050 | | .0032 | 4 |
| 1400 | 0.73 | 1.3424 | 0.7838 | 0.206 | 1.3565 | 247.3 |
| | | .1265 | .0062 | | .0022 | 0.8 |
| 1600 | <0.004 | – | – | 0.006 | 0.9723 | 174.4 |
| | | | | | .0074 | 2.5 |
| Total | 5.51 | 0.9547 | 0.8043 | 0.547 | 1.1662 | 1662 |
| | | .0195 | .0051 | | .0024 | 5 |
| **>3g/cc (670 mg)** | | | | | | |
| 400 Combst.* | <0.004 | – | – | 0.001 | 0.2937 | 2736 |
| | | | | | .0025 | 38 |
| 1000 | 2.139 | 0.8924 | 0.8076 | 0.153 | 0.5793 | 4629 |
| | | .0027 | .0050 | | .0020 | 15 |
| 1200 | 3.596 | 0.8337 | 0.8228 | 0.331 | 1.2669 | 495.9 |
| | | .0022 | .0068 | | .0043 | 1.6 |
| 1400 | 0.365 | 1.4346 | 0.7620 | 0.160 | 1.3108 | 204.5 |
| | | .2050 | .0065 | | .0019 | 0.6 |
| 1600 | <0.002 | – | – | 0.013 | 0.8023 | 195.6 |
| | | | | | .0025 | 0.9 |
| Total | 6.106 | 0.8894 | 0.8138 | 0.658 | 1.1076 | 1385 |
| | | .0061 | .0061 | | .0031 | 4 |
| **~3g/cc (42.2 mg)†** | | | | | | |
| 1000 | 1.96 | 0.7456 | 0.7662 | 0.279 | 0.5205 | 10106 |
| | | .0142 | .0050 | | .0043 | 33 |
| 1600 | 3.02 | 0.9029 | 0.7549 | 0.746 | 0.7641 | 1985 |
| | | .0714 | .0130 | | .0019 | 6 |
| Total | 4.98 | 0.8406 | 0.7590 | 1.025 | 0.6977 | 4198 |
| | | .0489 | .0098 | | .0025 | 13 |
| **<3g/cc (20.7 mg)†** | | | | | | |
| 800 | 0.922 | 4.9616 | 0.4788 | 0.057 | 0.4786 | 8583 |
| | | .0175 | .0060 | | .0023 | 47 |
| 1600 | 2.476 | 1.1025 | 0.7884 | 0.422 | 0.8854 | 5018 |
| | | .0037 | .0084 | | .0019 | 14 |
| Total | 3.398 | 2.1498 | 0.7044 | 0.479 | 0.8372 | 5441 |
| | | .0075 | .0081 | | .0020 | 18 |

*Combustion in 2 torr $O_2$.

†The 400 °C combustion step has yielded only blank levels of noble gases. Errors in isotopic ratios represent 95% C.L. Errors in concentration are ±10%.

(1994), which is again consistent with the high shielding values of the near surface samples inferred from the track data. As pointed out by Garrison *et al.* (1995), the high $^{22}$Ne/$^{21}$Ne cosmogenic ratio is most probably a reflection of the chemical composition of ALH 84001, characterized by a Mg/(Al+Si) ratio lower than the chondritic value. The higher value of 1.32 for cosmogenic $^{22}$Ne/$^{21}$Ne measured in one of the density separate that also contains a small amount of Na-rich feldspathic component (maskelynite?) most probably reflects the higher Na content in this sample that resulted in an additional component of higher than normal $^{22}$Ne/$^{21}$Ne and low $^{20}$Ne/$^{22}$Ne typical of Na spallation (see *e.g.*, Smith and Huneke, 1975). It may be noted that this density separate is characterized also by higher K content as evident from the high value of radiogenic $^{40}$Ar for this sample.

## Atmospheric Ablation, Preatmospheric Size and Nature of Fall

The extensive sampling of ALH 84001 for nuclear track studies (Fig.1) allowed us to reconstruct its preatmospheric size with confidence. We use the exposure age estimate of 16.7 Ma and follow the approach of Bhattacharya *et al.* (1973), to obtain shielding depths of the analysed samples, whose locations within the recovered meteorite are known within an accuracy of a couple of millimeters. We assume a single fall of this meteorite and a value of 1.97 kg for the recovered mass to obtain an approximate value of ~5 cm for the equivalent radius of the recovered meteorite. The recovered radius is not a very sensitive parameter in estimating shielding depths, and we also show later that ALH 84001 was indeed a single fall. The shielding depths for the different sampling points within the preatmospheric ALH 84001 are given in Table 1. The data indicate a nearly uniform ablation of all the analysed locations, with the extent of ablation being ~5 cm which in turn suggests an effective mass ablation of >85% in the case of ALH 84001. In Fig. 3, we show the track data in a plot of track production (TPM, #/cm$^2$-Ma) *vs.* shielding depth. The smooth trend in the data for the near surface samples as well as samples from interior region rules out the possibility of partial annealing of tracks in the near surface samples. As can be seen from the figure, even for the worst case uncertainty in our estimation of the recovered radius, the shielding depth estimates do not change by more than a centimeter. The most important point to note is that the shielding depths of all the sampling points, some of which are separated by up to 7 cm within the recovered meteorite, do not differ by more than 2 cm. This immediately suggests that the center of the original (preatmospheric) ALH 84001 meteoroid is contained within the recovered fragment and that the meteorite has suffered a nearly symmetrical atmospheric ablation. This fact and the extremely weak dependence of shielding depth on meteorite size therefore indicate that ALH 84001 must have been a single fall. Thus the track data suggest a preatmospheric radius of ~10 cm for ALH 84001, an effective ablation of >85%, and rule out the possibility of multiple fall of this meteorite.

## A Complex Exposure History for ALH 84001?

The transport of SNC meteorites from Mars can be a single stage or a multiple stage process. Wetherill (1984) has discussed two models involving either small size (~30 cm diameter) or a large size (>15m diameter) martian ejecta which may give rise to the martian meteorites. One of the results obtained from Monte Carlo simulation of transport of martian ejecta to Earth was that martian meteoroids should enter the atmosphere only slightly above the Earth's escape velocity and their ablation mass loss would be rather small, ~50%, compared to the value of >80% found for most other meteorite types (Bhandari *et al.*, 1980). A more recent study based on a numerical approach that follows orbital evolution of ejecta from terrestrial planets and their transfer to Earth (Gladman *et al.*, 1996) has also reached a similar conclusion. Our earlier study of the shergottites ALHA 77005, EETA 79001, and Shergotty tend to support this proposition (Bhandari *et al.*, 1986). This is also supported by the observation of solar cosmic-ray pro-

Table 3. Noble gas components* (in $10^{-8}$ ccSTP/g units) and ages.

| Sample | Cosmogenic | | | | | Radiogenic | | Trapped | |
|---|---|---|---|---|---|---|---|---|---|
| | $^{22}$Ne/$^{21}$Ne | $^{21}$Ne | $^{38}$Ar | $T_{21}$ (Ma) | $T_{38}$ | $^{40}$Ar | $T_{40}$ (Ga) | $^{20}$Ne | $^{36}$Ar |
| Bulk | 1.22 | 4.41 | 0.604 | 19.0 | 14.4 | 569 | 3.86† | 0.85 | 0.14 |
| | ±0.1 | .44 | .060 | 2.0 | 1.4 | 57 | | .10 | .02 |
| >3g/cc | 1.22 | 4.94 | 0.678 | – | – | 432 | – | 0.49 | 0.20 |
| | .01 | .50 | .068 | | | 43 | | .06 | .02 |
| ~3g/cc | 1.31 | 3.76 | 0.555 | – | – | 2731 | – | 0.43 | 0.66 |
| | .02 | .38 | .056 | | | 273 | | .05 | .08 |
| <3g/cc | 1.22 | 2.37 | 0.339 | – | – | 2003 | – | 4.93 | 0.25 |
| | .01 | .24 | .034 | | | 200 | | .60 | .03 |

*Trapped and cosmogenic ratios used in deriving these components are: $(36/38)_t = 4.1$; $(40/36)_t = 2400$; $(20/22)_t = 9.8$; $(21/22)_t = 0.029$; $(36/38)_C = 0.67$; $(20/22)_C = 0.8$.
†Using K = 108 ppm (Mittlefehldt, 1994b).

duced stable and radionuclides in ALHA 77005 (Nishiizumi *et al.*, 1986; Garrison *et al.*, 1995) that indicate ablation of less than a couple of centimeters in this case. However, our track data for ALH 84001 suggest a much higher ablation mass loss of ≥85% for a single stage cosmic-ray exposure age of 16.7 Ma. The only way we can lower the estimated mass ablation value will be if ALH 84001 had a two-stage exposure history, with a shorter exposure to cosmic rays during recent times, when the nuclear tracks were also formed. Beryllium-10 data for ALH 84001 tends to support such a scenario and is suggestive of a recent cosmic-ray exposure of 4–7 Ma for ALH 84001 as a small body in space (Nishiizumi *et al.*, 1994). Such exposure durations will reduce the mass ablation of this meteorite to ~55–70%, a value that may be consistent with the shergottites. However, if this was indeed true, the effect of an earlier epoch of cosmic-ray exposure, either in space or on Mars, for a significant length of time (≥10 Ma) under high shielding condition (>10 cm), so that effective track production can be neglected, should be reflected in the noble gas data and particularly in the cosmogenic $^{22}$Ne/$^{21}$Ne and $^{131}$Xe/$^{126}$Xe ratios. The high value of cosmogenic $^{22}$Ne/$^{21}$Ne ratio in our samples (1.22 ± .01), as well as in samples analysed by other workers (Welten *et al.*, 1994; Miura *et al.*, 1995; Swindle *et al.*, 1995), is attributable to a non-chondritic chemical composition and does not provide any indication for such an irradiation. In addition, the value of cosmogenic $^{131}$Xe/$^{126}$Xe ratio measured in our sample of ALH 84001 is rather low (2.5 ± 1.0), and this is also true for the noble gas data for this meteorite reported by Miura *et al.* (1995) and Swindle *et al.* (1995). Such low values for the $^{131}$Xe/$^{126}$Xe ratio preclude the possibility that ALH 84001 had experienced a long duration exposure under high shielding conditions (cf., Kaiser, 1977). The ALH 84001 therefore may have an orbit different from the shergottites and its velocity and angle of entry in to Earth's atmosphere must have been much different than those for shergottites. It is interesting to note that the calculations of Gladman *et al.* (1996) suggest that martian ejecta with orbital evolution time of >10 Ma have a large spread in their eccentricity. Thus, the possibility that martian meteorites with long cosmic-ray exposure ages (*e.g.*, ALH 84001) could have orbits much different from the shergottites that are characterized by lower exposure ages (≤2.5 Ma) and may enter the Earth's atmosphere at a much higher velocity than the shergottites cannot be ruled out. Different orbital parameters for the NC subgroup of the SNC meteorites, that have much higher cosmic-ray exposure ages compared to the shergottites, have also been advocated by Garrison *et al.* (1995) based on the absence of any solar cosmic-ray produced effects in this subgroup of meteorites as opposed to the shergottites.

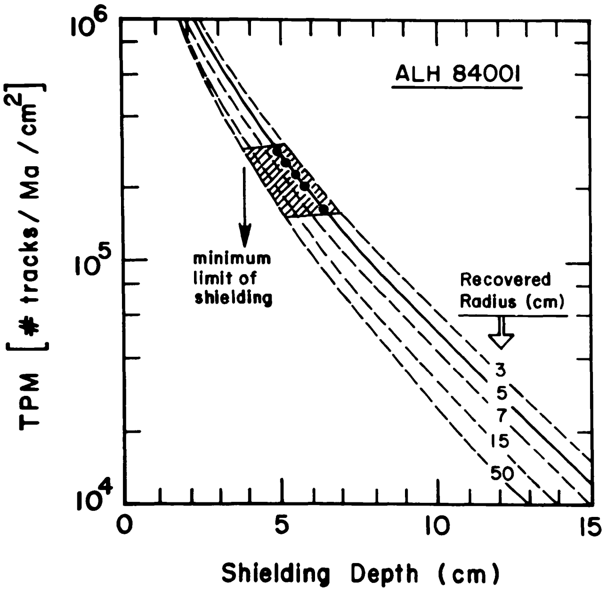

FIG. 3. Track production rate (TPM) *vs.* shielding depth profiles for meteorites with recovered radius between 3–50 cm based on Bhattacharya *et al.* (1973). The ALH 84001 data points, for an exposure age of 16.7 Ma, are plotted on the curve for a recovered radius of 5 cm. The TPM values for all the samples cluster within a narrow zone (the shaded area). Minimum shielding for a worst case uncertainty in the value of the recovered radius is indicated.

## Formation Age of ALH 84001

An earlier estimate of a K-Ar age of >5 Ga (Eugster, 1994) for ALH 84001 turned out to be erroneous due to the use of an incorrect value of K content reported originally that was subsequently revised (Mittlefehldt, 1994b). Using the revised value of K content of 108 ± 16 ppm and the radiogenic $^{40}$Ar measured by us, we can derive the K-Ar age for the bulk sample of ALH 84001, while this is not possible for the density separates in the absence of K measurements. The data shown in Table 3 indicate that all the samples have a small amount of trapped Ne and Ar. This trapped component could be either terrestrial (acquired by the meteorite during its residence in the Antarctic ice sheet) or martian atmospheric in origin. In deriving the radiogenic $^{40}$Ar content from the total $^{40}$Ar, we have to subtract trapped $^{40}$Ar, which can be done by assuming trapped Ar to be of terrestrial or martian in origin. If we consider a terrestrial origin, we can use $(^{40}Ar)_t = 295.5 \times (^{36}Ar)_t$ to get $(^{40}Ar)_r = 868 \times 10^{-8}$ ccSTP/g and a K-Ar age of 4.55 Ga. On the other hand, if we assume it to be of martian origin and use $(^{40}Ar)_t = 2400 \times (^{36}Ar)_t$, we get $(^{40}Ar)_r = 569 \times 10^{-8}$ ccSTP/g and a K-Ar age of 3.86 Ga, which may be considered as a lower limit as the value for trapped $^{40}Ar/^{36}Ar$ in the martian atmosphere 4 Ga ago is likely to be <2400. This age is also in good agreement with the Ar-Ar ages of 4.0±0.1 Ga for ALH 84001 reported recently by Ash *et al.* (1996). Therefore, we conclude that a small fraction of martian atmospheric Ar is indeed present in ALH 84001. Nitrogen and noble gas studies of ALH 84001 have clearly indicated the presence of N and Xe of martian atmospheric origin in this meteorite (Murty et al., 1995; Swindle et al., 1995; Miura et al., 1995). The older age of ALH 84001 thus confirms the earlier contention of Jagoutz *et al.* (1994) that ALH 84001 is a remnant of an ancient martian crust.

### Trapped Ne in ALH 84001

The Ne isotopic data for the different temperature steps of the samples (Table 2) indicate that Ne is mostly spallogenic, except for the high temperature steps for the bulk sample and the >3g/cm$^3$ separate as well as both 800 °C and 1600 °C steps of the <3g/cm$^3$ separate, which clearly show the presence of trapped Ne. We show the data for all the temperature steps in the standard Ne three isotope diagram in Fig. 4. Most of the data points seem to define a simple two component mixture, with one end member being the normal galactic cosmic rays (GCR) spallation and the other a trapped component, which is above the terrestrial (air) value. The two points belonging to the ~3g/cm$^3$ separate are purely spallogenic but fall away from the normal GCR end member. As already discussed above, the presence of a spallation component from excess Na in this density separate can explain this shift. The higher value of cosmogenic $^{22}Ne/^{21}Ne$ for this sample, compared to the rest, as well as its higher K contents (inferred from the higher $^{40}Ar/^{36}Ar$ ratio), are consistent with this possibility. From a least square fit through all the data points and for $(^{21}Ne/^{22}Ne)_t = 0.03$, we get a trapped $(^{20}Ne/^{22}Ne) = 10.8 \pm 0.2$, whereas this value is $10.5 \pm 0.2$ if we exclude the two points for the ~3g/cm$^3$ separate. In either case, the value is distinctly higher than the terrestrial value for this ratio (9.8). Bogard *et al.* (1984) have first suggested the possibility of a higher than terrestrial $^{20}Ne/^{22}Ne$ for the SNC meteorites and hence for the martian atmosphere. Trapped $^{20}Ne/^{22}Ne$ ratios of 10.6 ± 0.6 for lithology C of EETA 79001 (Swindle *et al.,*1986) and 10.8 for LEW 88516 (Ott and Löhr, 1992) also suggest that martian atmospheric Ne might be slightly enriched in $^{20}Ne$, compared to terrestrial Ne, though within errors the values overlap. Our data for trapped Ne in ALH 84001 is consistent with the proposed higher value of $^{20}Ne/^{22}Ne$ in martian atmosphere compared to the terrestrial value.

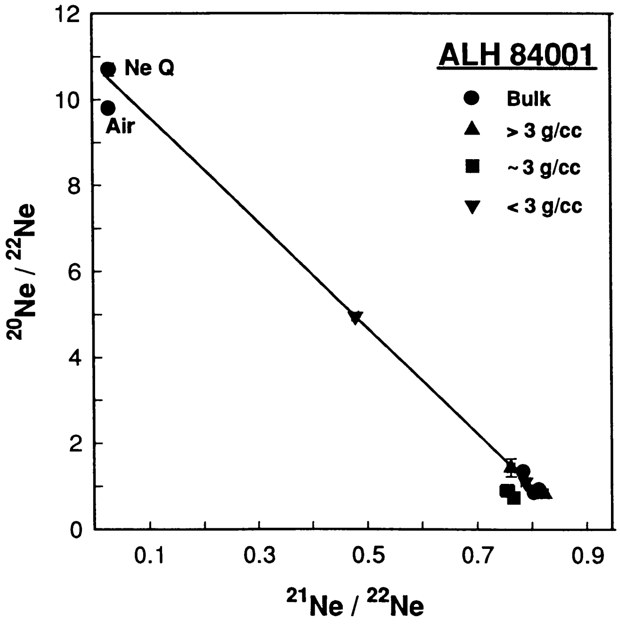

FIG. 4. Neon three isotope plot of the data for the different temperature steps of the bulk sample and the three density separates of ALH 84001.

## SUMMARY

A detailed study of cosmic-ray produced nuclear track and noble gas records in ALH 84001 has been carried out. The data obtained from this study suggest ALH 84001 to be a single fall that had a simple exposure to cosmic rays for a duration of 16.7 ± 1.7 Ma, the longest among the martian meteorites studied so far. It has also suffered a very high ablation mass loss of >85%, unlike the shergottites that are characterized by lower mass ablation loss of ~60%. It is possible that orbital parameters for ALH 84001 were much different and that it entered the Earth's atmosphere at a much higher velocity than the shergottites. The older K-Ar age of 3.9 Ga, coupled with the above facts, necessitate a separate impact event on Mars to deliver ALH 84001 to Earth. Signatures are present in the noble gas data for a trapped Ar component with martian atmospheric composition, and the trapped $^{20}Ne/^{22}Ne$ ratio is higher than the terrestrial (air) value and may represent a possible martian component.

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