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Rapid changes in the nature of the H chondrites falling to Earth

P. H. BENOIT* AND D. W. G. SEARS

Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701, USA
*Correspondence author's e-mail address: cosmo@uafsysb.uark.edu

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Abstract–We have previously identified a subgroup of Antarctic H chondrites that are significantly different from H chondrites among the modern falls in terms of induced thermoluminescence (TL), metallographic cooling rate, and cosmogenic inert gas contents. Here we examine their terrestrial and thermal history as apparent in their natural TL and radioactive cosmogenic isotope abundances. These meteorites have a tendency towards high ^{26}Al activities and fairly short ^{14}C and ^{36}Cl terrestrial ages (generally <100 ka). They also sometimes exhibit unusually high natural TL levels, which we have previously interpreted as indicating orbital evolution from perihelia >1.2 AU to ~1 AU within the last <10^5 years. We suggest that the nature of the meteorites falling to Earth is not independent of time but depends on stochastic events, such as the breakup of parent bodies and recent variations in orbit.

INTRODUCTION

Comparisons of falls and finds have suggested that the nature of the meteorites falling to Earth may have changed over the past few hundred thousand years (*e.g.*, Dennison and Lipschutz, 1987; Koeberl and Cassidy, 1990; Cassidy and Harvey, 1991; Wasson, 1991; Benoit and Sears, 1992; Wolf and Lipschutz, 1995). These changes are thought to reflect the stochastic breakup of larger bodies in the asteroid belt (Greenberg and Nolan, 1989). Many of these studies have concentrated on H chondrites, which form about one-third of the modern meteorite flux. Differences between Antarctic H chondrites and modern falls have been noted in volatile trace-element abundance data (Dennison and Lipschutz, 1987; Lipschutz and Samuels, 1991; Wolf and Lipschutz, 1995) but are not noted in cosmic-ray exposure age distributions (Schultz *et al.*, 1991) or bulk composition data (Kallemeyn *et al.*, 1993). The interpretation of potential differences is complicated by weathering and by collection inefficiencies under the unique field conditions in Antarctica (*e.g.*, Huss, 1991; Lipschutz and Samuels, 1991; Schultz *et al.*, 1991; Kallemeyn *et al.*, 1993).

We have reported the existence of a large subgroup of H chondrites in the Antarctic meteorite collection, which has no equivalent among the modern falls (Benoit and Sears, 1992, 1993a). We will hereafter refer to these as the "unusual" H chondrites. These meteorites have high induced thermoluminescence (TL) peak temperatures relative to their peak widths, high metallographic cooling rates compared to modern falls, cosmic-ray exposure ages of ~8 Ma, and large ^{3}He/^{21}Ne and ^{22}Ne/^{21}Ne ratios. The abundance of these meteorites appears to decrease as a function of decreasing terrestrial age.

In this paper, we examine the radiation and thermal history of these meteorites using their ^{26}Al, terrestrial age (^{14}C and ^{36}Cl), and natural TL distributions. Although the data are sometimes limited, we find some evidence for differences among these groups, which suggests a particular time-orbit history for the newly recognized but now extinct subgroup of H chondrites.

METHODS

The methodologies for induced TL and natural TL measurements are those described previously (Benoit *et al.*, 1991; Benoit and Sears, 1993a). Cosmogenic noble-gas data are from the compilations of Schultz and Kruse (1989) and from Schultz *et al.* (1991); ^{26}Al data are from Evans and Reeves (1987) and Grossman (1994). The ^{14}C and ^{36}Cl data are from the compilations of Nishiizumi (1987 and pers. comm.), Nishiizumi *et al.* (1989), and Michlovich *et al.* (1995).

Metallographic cooling rates for selected H4 chondrites were determined using Ni profiles in taenite grains (Wood, 1967). Nickel concentrations were measured at intervals of between 3 μm to 5 μm across taenite grains using the Cameca Camebax electron microprobe at Johnson Space Center, Houston, Texas. Iron, Ni, and Co alloys were used as standards. The sizes of the grains were estimated from the backscattered electron images, and essentially all taenite grains in each section were analyzed. We rejected data for grains that did not exhibit a well-defined U-shaped Ni profile.

RESULTS AND DISCUSSION

The H4 and H6 Chondrites

In Fig. 1a,b, we show our previous induced TL data for a group of Antarctic H chondrites and modern falls. The unusual Antarctic chondrites produce a cluster with relatively high induced TL peak temperatures (~190 °C) at a peak width of ~140 °C (Fig. 1a). These meteorites have a narrow range of cosmic-ray exposure (CRE) ages; all have cosmic-ray exposure ages <18 Ma, and most have ages of ~8 Ma. Hereafter, we refer to these meteorites simply as the unusual H chondrites. Their absence is conspicuous in the data for modern falls (Fig. 1b). In our original study, all members of the unusual subgroup were petrologic type 5 (Benoit and Sears, 1992), but Benoit and Sears (1993a) noted the presence of H4 and H6 chondrites in the unusual subgroup, although cosmic-ray exposure data were not available.

New induced TL data for Antarctic H4 and H6 chondrites are shown in Fig. 1c,d and listed in Table 1. The H6 chondrites are similar to our earlier suite of H chondrites, which was dominated by H5 chondrites (Fig. 1a). ALHA81037 is the only H6 chondrite with normal induced TL but with a cosmic-ray exposure age of ~8 Ma. ALHA76008 has a cosmic-ray exposure age of ~2 Ma but normal induced TL. It also has an unusual multistage irradiation history with the total exposure history being >100 Ma (Nishiizumi *et al.*, 1979).

The H4 chondrites also generally resemble the H5 chondrites in their TL properties although data are meager (Fig. 1c). Two H4 chondrites with cosmic-ray exposure ages of >18 Ma plot on or near the trend line for modern falls, as do five modern falls of various cosmic-ray exposure ages (Fig. 1b). With the exception of ALHA77004, the remainder of the Antarctic H4 chondrites in this study have cosmic-ray exposure ages <18 Ma and plot above the modern fall trend line. However, the unusual H4 chondrites extend to lower induced TL peak temperatures, overlapping with the normal H5 and H6 chondrites.

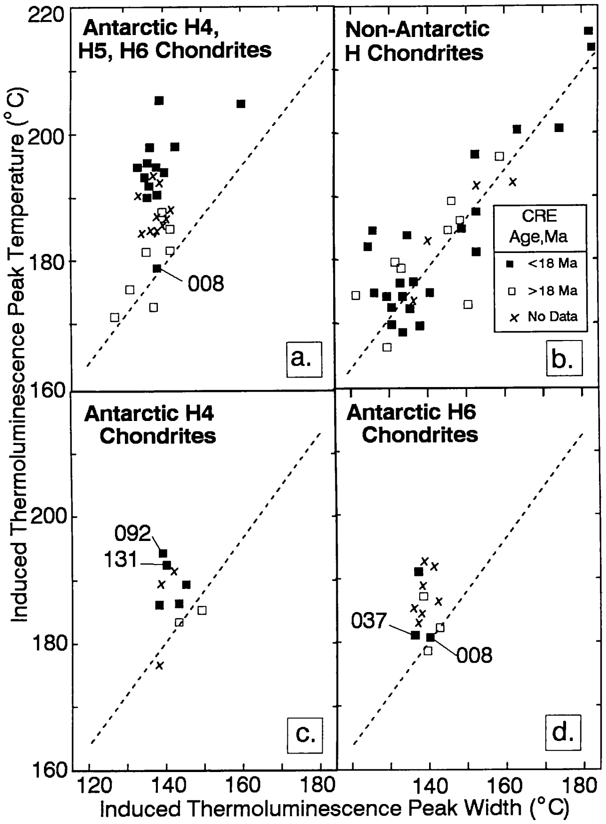

FIG. 1. Induced thermoluminescence peak temperatures *vs.* peak widths for H chondrites: (a) a group of Antarctic meteorites composed predominantly of H5 chondrites; (b) modern falls; (c) Antarctic H4 chondrites; and (d) Antarctic H6 chondrites. These data are keyed for cosmic-ray exposure age, based on ^{3}He, ^{21}Ne, and ^{38}Ar abundances (Schultz and Kruse, 1989; Schultz *et al.*, 1991). Abbreviations for samples: 008 = ALHA76008; 037 = ALHA81037; 092 = ALHA81092; 131 = ALHA80131.

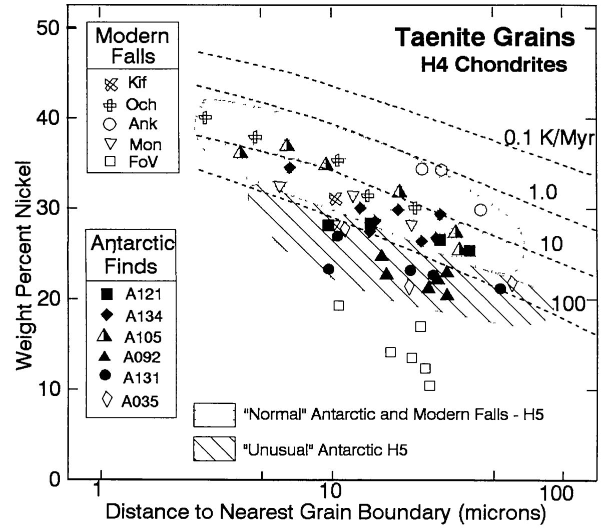

FIG. 2. Metallographic cooling rate data for H4 chondrites. Ranges for H5 chondrites are also shown (Benoit and Sears, 1993a). Calibration lines are from Willis and Goldstein (1981). Abbreviations for samples: Ank = Ankober (thin section USNM 3399-1); FoV = Forest Vale (USNM 2319-2); Kif = Kiffa (USNM 5490-3); Mon = Monroe (USNM 1086-2); Och = Ochansk (USNM 1788-1); A035 = ALHA79035; A092 = ALHA81092; A105 = ALHA81105; A121 = ALHA80121; A131 = ALHA80131; A134 = ALHA78134.

Our metallographic cooling rate estimates for H4 chondrites are shown in Table 1 and in Fig. 2. All the modern H4 falls we examined had cooling rates between ~10 K/Ma to 50 K/Ma, which is at the upper end of the range observed for modern falls and normal Antarctic H5 chondrites (Benoit and Sears, 1993a). Two exceptions are Forest Vale and Kesen, the latter of which has an irregular Ni profile distribution that is probably due to shock metamorphism. The data for Forest Vale agree with those obtained by Noonan *et al.* (1972) and Pellas *et al.* (1987). The two Antarctic H4 chondrites with the highest TL peak temperatures relative to their widths (ALHA80131 and ALHA81092) have high metallographic cooling rates that are similar to those observed for unusual H5 chondrites. The remaining four meteorites have metallographic cooling rates between 10 K/Ma–100 K/Ma with no separation between normal and unusual meteorites.

Aluminium-26 Activity of H Chondrites.

The ^{26}Al data for our present samples are listed in Table 2, and histograms are shown in Fig. 3. The normal Antarctic H chondrites have an ^{26}Al distribution that is similar to that of the modern falls; perhaps there is a slight skew to low ^{26}Al activities, reflecting high terrestrial ages (Evans and Reeves, 1987). However, the unusual Antarctic H chondrites have a distribution that is skewed to high ^{26}Al activities and extends above the modern falls.

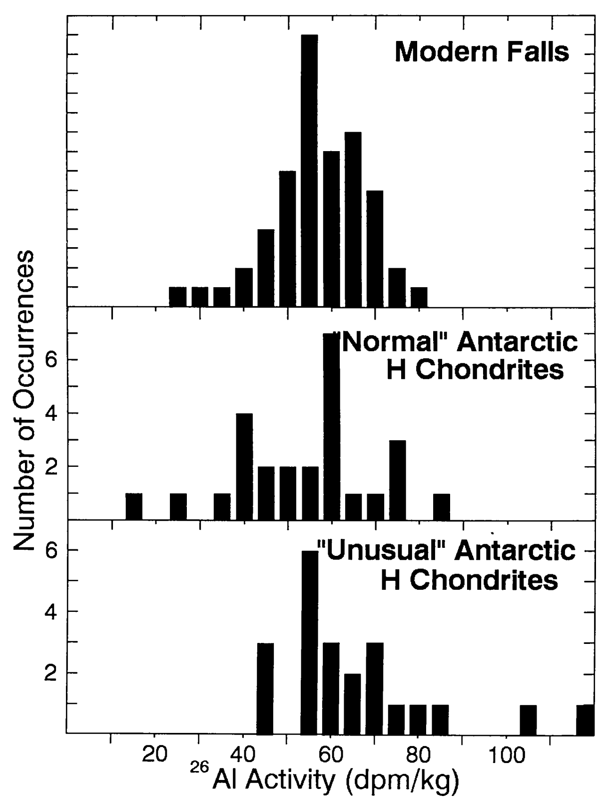

FIG. 3. Histograms of ^{26}Al activities of Antarctic H chondrites. A normalized plot for modern falls is also shown. Data from Evans and Reeves (1987) and Grossman (1994).

TABLE 1. Induced TL, metallographic cooling rate, natural TL, and cosmic-ray exposure age data for H4 and H6 chondrites.

Meteorite	Class	Induced TL Peak Temp., °C	Induced TL Peak Width, °C	Metallo-graphic Cooling Rate, K/Ma	Group#	Natural TL, krad	Cosmic-Ray Exposure Age, Ma†
ALHA77004	H4	177 ± 2	138 ± 3		A	36	
ALHA77262	H4	187 ± 3	143 ± 2		B	65	8
ALHA78084	H4	186 ± 4	149 ± 2		A	73	30
ALHA78134	H4	190 ± 1	139 ± 2	50	B	88	
ALHA79035	H4	184 ± 1	143 ± 3	100	A	17	26*
ALHA79039	H4	190 ± 1	145 ± 2		B	11	9
ALHA80121	H4	187 ± 1	138 ± 3	50	B	8	8
ALHA80131	H4	193 ± 4	140 ± 1	150	B	160	4*
ALHA81092	H4	195 ±11	139 ± 7	130	B	5.5	5*
ALHA81105	H4	192 ± 1	142 ± 2	10	A	3.4	
ALHA76008	H6	180 ± 2	140 ± 2		A	8.5	2**
ALHA77111	H6	185 ± 2	136 ± 1		A	5	
ALHA77258	H6	187 ± 2	138 ± 1		A	37	40
ALHA77271	H6	184 ± 4	138 ± 1		A	46	
ALHA78076	H6	182 ± 2	142 ± 3		A	12	53
ALHA78115	H6	179 ± 2	139 ± 1		A	44	53
ALHA79002	H6	186 ± 1	142 ± 1		A	59	
ALHA80126	H6	191 ± 2	137 ± 3		B	3.9	5*
ALHA81037	H6	181 ± 1	136 ± 3		C	66	9
ALHA81093	H6	183 ± 1	137 ± 1		A	15	
MBRA76001	H6	192 ± 2	141 ± 3		B	12	
META76006	H6	187 ± 5	139 ± 2		A		
META78019	H6	192 ± 2	139 ± 2		B	0	

\# Group based on induced TL peak temperatures and width. A = "normal" H chondrite; B = "unusual" H chondrite; C = "normal" H chondrite with cosmic-ray exposure age of <18 Ma.
† Calculated using the production rate and shielding corrections of Eugster (1988) and noble-gas data compiled in Schultz and Kruse (1989) and Schultz *et al.* (1991). Based on average of ^{3}He, ^{21}Ne, and ^{38}Ar cosmic-ray exposure ages.
* Solar gas-containing samples. ^{3}He cosmic-ray exposure ages can not be calculated for these samples and their cosmic-ray exposure ages are estimated only from ^{21}Ne and ^{38}Ar, using an assumed $^{22}Ne/^{21}Ne$ ratio of 1.11 (see Schultz *et al.*, 1991).
** ALHA76008 has a multistage irradiation history; an earlier stage has a cosmic-ray exposure age of >100 Ma (Nishiizumi *et al.*, 1979).

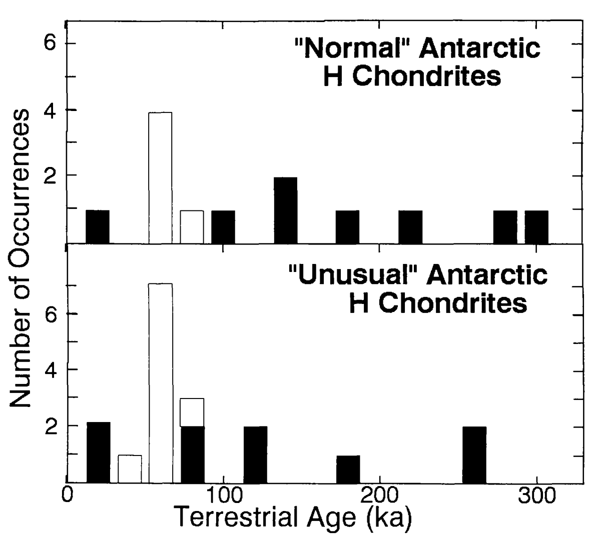

FIG. 4. Histograms of terrestrial ages for normal and unusual Antarctic H chondrites. Lower limits from ^{36}Cl measurements are shown as open symbols. As a group, the unusual H chondrites may have smaller average terrestrial ages than normal H chondrites. Data from Nishiizumi (1987 and pers. comm.), Nishiizumi *et al.* (1989), and Michlovich *et al.* (1995).

Terrestrial Ages of Antarctic H chondrites

Terrestrial ages, calculated from ^{14}C or ^{36}Cl, are listed in Table 2 and plotted in Fig. 4. The uncertainties of most of the terrestrial age measurements are greater than the width of the histogram bars, so some features of this figure may be analytical artifacts. The spike at ~80 ka reflects the lower limit of ^{36}Cl terrestrial age estimates, and members of this spike may actually be distributed among terrestrial ages <80 ka.

While the data are meager, it is possible that the unusual H chondrites include a higher proportion of small terrestrial ages than normal Antarctic H chondrites. About 70% (13 out of 18) of the unusual H chondrites have terrestrial ages <100 ka, compared to only ~50% (7 out of 13) for the normal Antarctic H chondrites. On the other hand, ~20% of the unusual H chondrites have terrestrial ages in excess of 150 ka, compared to ~45% of the normal H chondrites. The observed distributions are not simply the result of a few large meteorites dominating the data set since pairing has already been considered (*e.g.*, Haq *et al.*, 1988).

Additional terrestrial age data are needed before the terrestrial age distributions can be interpreted with confidence. However, these data are consistent with the more abundant ^{26}Al data in suggesting that the unusual H chondrites have small terrestrial ages relative to the others. Since most of ^{36}Cl terrestrial age estimates are limits, it is possible that most of the members of the unusual H chondrite group have terrestrial ages within or just outside the range for ^{14}C terrestrial age determinations, namely ≤40 ka (Jull *et al.*, 1993).

Natural Thermoluminescence and H Chondrites

In Fig. 5, we show histograms of natural TL levels for Antarctic H chondrites and modern falls. Normal Antarctic H chondrites cover a broad range between 100 krad and 10 krad with a tail toward the lower values. This distribution is very similar to that of the modern falls except for a tendency for the Antarctic H chondrites to have lower TL values, which reflect their high terrestrial ages and long-term exposure on the ice surface (Benoit *et al.*, 1994; Benoit, 1995). The natural TL distribution for the unusual Antarctic H chondrites has high natural TL levels, generally >50 krad and ranging up to ~200 krad.

There are two possible interpretations of the differences in natural TL distributions. First, these could reflect differences in radiation dose, which most probably is due to size differences. In this case, the unusual H chondrite meteoroids would have been smaller than most modern falls, which is consistent with their relatively high $^{3}He/^{22}Ne$ and $^{21}Ne/^{22}Ne$ abundance ratios (Benoit and Sears, 1992). However, even very small modern falls do not exhibit such high levels of natural TL. Second, the differences may reflect the average orbital history for these meteorites since TL is dependent on temperature at perihelion (Benoit *et al.*, 1991). Natural TL levels >100 krad are consistent with TL equilibrium for meteorites with perihelia >1.2 AU. To reach Earth and still retain these levels, the meteorites must evolve to Earth-crossing orbits fairly rapidly. Time scales of <10^5 years are required. The

TABLE 2. Terrestrial age, ^{26}Al activities, and natural thermoluminescence of Antarctic H chondrites.

Meteorite	Class	Group*	Terrestrial Age (ka)+	^{26}Al (dpm/kg)†	Natural TL (krad, 250 °C)
ALHA76008	H6	A	100 ± 70	12	8.5
ALHA77004	H4	A	170 ± 70	56	35
ALHA77012	H5	A		83	15
ALHA77014	H5	A	60 ± 60	59	6.5
ALHA77111	H6	A	290 ± 70	21	5
ALHA77112	H5	A	50 ± 50	31	25
ALHA77177	H5	A		58	9
ALHA77182	H5	B	250 ± 80	44	0.6
ALHA77258	H6	A	270 ± 70	51	37
ALHA77259	H5	B	250 ± 70	52	10
ALHA77262	H4	B	18 ± 1	70	65
ALHA77271	H6	A	70 ± 70	42	46
ALHA77274	H5	B	120 ± 70	57	28
ALHA77294	H5	A	10 ± 1	67	32
ALHA78047	H5	A		35	1.2
ALHA78075	H5	B		52	11
ALHA78076	H6	A	130 ± 70	56	12
ALHA78084	H4	A	140 ± 70	54	73
ALHA78102	H5	A	220 ± 80	37	23
ALHA78108	H5	B	65 ± 65	59	61
ALHA78111	H5	A		57	0.8
ALHA78115	H6	A	45 ± 45	46	44
ALHA78134	H4	B	45 ± 45	65	88
ALHA79002	H6	A		36	60
ALHA79026	H5	B	55 ± 55	64	
ALHA79029	H5	B		52	67
ALHA79035	H4	A		73	17
ALHA79039	H4	B		45	11
ALHA79046	H5	B	50 ± 50	54	38
ALHA79054	H5	B	55 ± 55	67	165
ALHA80121	H4	B		71	8
ALHA80126	H6	B	70 ± 60	81	4
ALHA80131	H4	B	70 ± 60		163
ALHA80132	H5	B	110 ± 60	62	1.2
ALHA81015	H5	B	180 ± 70	52	35
ALHA81037	H6	C		60	66
ALHA81039	H5	B		60	2.5
ALHA81092	H4	B	55 ± 55		5.5
ALHA81093	H6	A			15
ALHA81105	H4	A		58	3.4
ALH82102	H5	B	11 ± 1	42	119
ALH84074	H5	A		35	29
ALH84139	H5	A		74	0.5
EET83208	H5	B		102	64
EETA79007	H5	B	60 ± 60	50	72
MBRA76001	H6	B	>39	78	12
META76006	H6	A		64	
META78010	H5	A	50 ± 50	60	
META78019	H6	B	40 ± 40	116	
RKPA79004	H5	A		48	35
RKPA80220	H5	B			130
RKPA80230	H5	B	55 ± 55		33
RKPA80233	H5	A		72	15

* See footnote to Table 1.
\+ Terrestrial ages based on ^{14}C and ^{36}Cl activities. Data from Nishiizumi (1987 and pers. comm.), Nishiizumi *et al.* (1989), and Michlovich *et al.* (1995).
† Data taken from Grossman (1994); adjusted upwards by 10% to allow for bulk chemistry effects (Evans and Reeves, 1987).

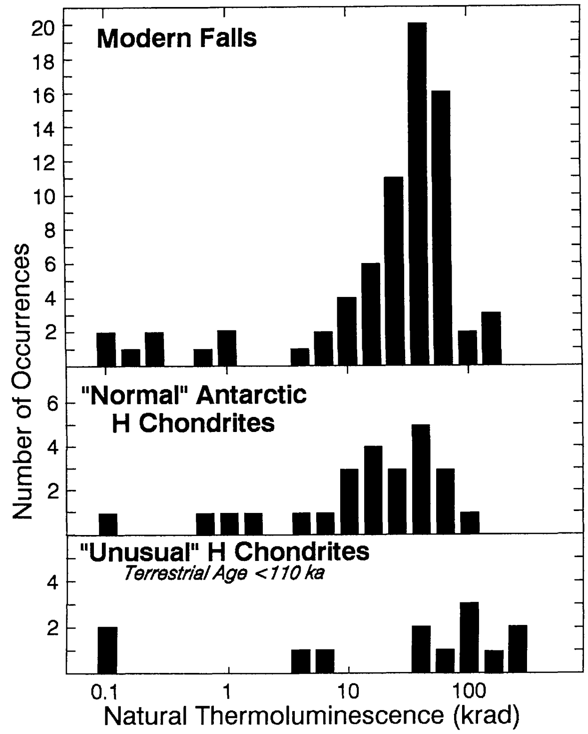

FIG. 5. Histograms of natural TL levels of Antarctic H chondrites and modern H chondrite falls. The unusual H chondrites have high TL levels (generally >50 krad) compared to the others. Data from Benoit *et al.* (1991), Grossman (1994), and the present study.

observed tail in natural TL levels could reflect continued orbital evolution to perihelia of ~0.8 AU.

Calculations of the long-term orbital evolution of known Earth-crossing asteroids indicate that such bodies can change their perihelia (and other orbital parameters) on a <10^5 time scale due to interaction with either planetary bodies or orbital resonances (*e.g.*, Galibina and Terent'eva, 1987; Ipatov, 1992; Farinella *et al.*, 1993). We have previously suggested a similar orbital history for a few other meteorites (Benoit and Sears, 1993b).

Because ^{26}Al can be produced by interaction of solar cosmic rays as well as galactic cosmic rays (*e.g.*, Welten *et al.*, 1992), the activity of ^{26}Al in meteorites can be indicative of meteoroid orbit (*e.g.*, Cressy and Rancitelli, 1974). In particular, ^{26}Al activities may be higher in meteorites that experience higher solar cosmic-ray flux while in orbits with low perihelia. In Fig. 6, we compare the ^{26}Al activities of the meteorites in this study with their natural TL data. Most H chondrites displaying unusual induced TL have somewhat high ^{26}Al activities (>50 dpm/kg) and moderate to high natural TL levels (>50 krad). Since the natural TL levels of these meteorites would be lowered considerably if they had been in orbits with perihelia <0.8 AU, it would appear that the source of the high ^{26}Al activities of these meteorites is not simply proximity to the Sun. Since it is unlikely these samples received large epithermal neutron irradiation in large bodies, it is at least possible that these bodies were irradiated in an unusual enviroment, such as in a high inclination orbit (*e.g.*, Cressy and Rancitelli, 1974). However, spacecraft observations of the cosmic-ray flux at high solar latitudes do not generally support this idea (McDonald *et al.*, 1992; Simpson *et al.*, 1995).

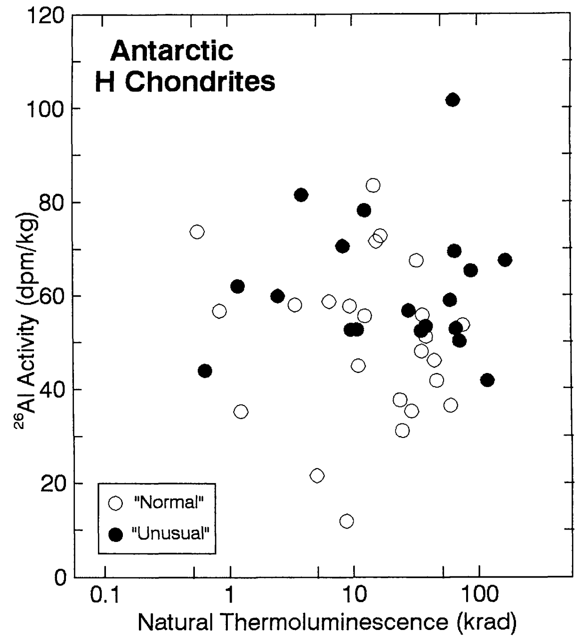

FIG. 6. Aluminum-26 activity *vs.* natural thermoluminescence levels for Antarctic H chondrites. In general the unusual meteorites exhibit high ^{26}Al activities and natural TL levels compared to normal H chondrites.

Another conclusion that can be drawn from the natural TL data is that these meteorites were not exposed on the ice surface of Antarctica for long periods of time. The natural TL levels of most of the unusual H chondrites are highly out of equilibrium, a value of ~10 krad is the final state for meteorites on the ice surface. In general, the high levels of natural TL and the spread of TL levels in the unusual H chondrites would indicate that these meteorites have been on the ice surface for <100,000 years (Benoit, 1995).

CONCLUSIONS

On the basis of the present study, we suggest a history for the H chondrites, as seen from the perspective of the Earth in Fig. 7. A group (or groups) of normal H chondrites began their history as meteoroid bodies >18 Ma ago and form a background in both the Antarctic collection and in the modern falls. We show their abundance as decreasing with time, but we stress that little is known about the history of these meteorites. It is equally possible that their abundance has been constant or has increased over this time interval. At ~8 Ma ago, however, a large number of H chondrite meteoroid bodies were generated. Some of these had normal H chondrite properties (induced TL, metallography, and trace-element compositions) and were of a typical meteoroid size (as indicated by cosmogenic noble-gas ratios), whereas some had unusual properties and were relatively small. Whether their unusual properties were produced during the 8 Ma event (perhaps by extensive shock metamorphism) or whether they were originally formed in a different region or even a separate parent body, is not yet certain. It is possible that these two groups were produced in separate bodies that collided. In any case, the unusual H chondrites evolved to Earth-crossing orbits more rapidly than the normal H chondrites from the 8 Ma event and first contributed to the Earth's meteorite flux before ~280 ka (Fig. 4). This group dominated the H chondrite portion of the meteorite flux by ~80 ka but then declined rapidly in abundance. The normal H chondrites from the 8 Ma event came to

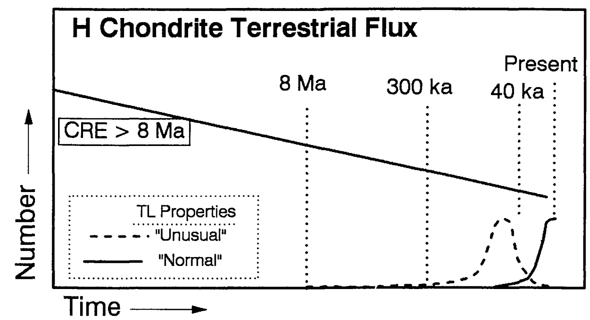

FIG. 7. A schematic history of the terrestrial H chondrite flux. Two different groups of meteoroids are generated in an event(s) at ~8 Ma. The unusual group reached Earth first, made a major contribution to the meteoroid flux from at least 280 ka to 80 ka or so, but declined rapidly in abundance thereafter. Sometime after 80 ka, this group was replaced by the normal H chondrites with cosmic-ray exposure ages of ~8 Ma.

dominate the H chondrite portion of the meteorite flux some time after 80 ka, although the time of their first arrival on Earth is still uncertain.

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