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A recent meteorite shower in Antarctica with an unusual orbital history

P.H. Benoit, D.W.G. Sears

Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701, USA

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Abstract

The Antarctic meteorite collection has proved to be a source of many important discoveries, including a number of previously unknown or very rare meteorite types. A thermoluminescence (TL) survey of meteorite samples recovered by the 1988/89 European expedition and pre-1988 American expeditions to the Allan Hills Main blue ice field resulted in the discovery of 15 meteorites with very high TL levels (> 100 krad at 250°C in the glow curve). It is likely that these samples are fragments of a single meteoroid body which: (1) fell very recently and (2) experienced a decrease in orbital perihelia from $\geqslant 1.1$ AU to 1 AU within the last 10^5 yr. Carbon-14 data for two of the samples confirm their young terrestrial age compared to most Antarctic meteorites. Studies of the cosmogenic isotopes in at least one non-Antarctic meteorite which also has very high natural TL, Jilin, indicate that the meteorite experienced a multi-stage irradiation history, the most recent stage being 0.4 Ma in duration following a major break-up of the object. These meteorites, and the few equivalent modern falls, are the only documented samples from bodies which were recently in Earth-approaching (Amor) orbits (i.e., with perihelion > 1.0 AU), as opposed to the Earth-crossing (Apollo) orbits which are the source of most other meteorites. Their rarity indicates that such rapid orbit changes are unusual for meteoroid bodies and may be the result of isolated, large break-up events.

1. Introduction

Meteorites have been found in great numbers in the Antarctic over the last several decades, with over 14,000 samples having been recovered by American, Japanese, and European expeditions [1]. While there is some question as to how many actual meteorites this massive collection represents (because meteorites fragment in the atmosphere and in the Antarctic ice) [2], the Antarctic meteorites have made significant contributions to meteorite studies, including the first discovery of meteorites from the Moon [3], many new types of iron meteorites [4] and large numbers of primitive meteorites [5]. It has been shown that most Antarctic meteorites have been on earth for at least 10,000 yr and some have terrestrial ages of up to 1.5 million yr [6]. The discovery of a major recent (~ 1000 yr terrestrial age) meteorite shower in Antarctica with an unusual orbital history is described here.

On January 14–15, 1989, a field party from the European Meteorite Recovery expedition (EUROMET) discovered 59 meteorites in an area of the Allan Hills Main blue ice field (159°20′W,

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searched with negative results [7]. The day was unseasonably warm (~ -5°C) and many of the meteorites were found halfway buried in the ice. It was concluded that all these meteorites had "weathered" out of the ice during a rare period of rapid ice ablation. This discovery was very unusual in that, with only two exceptions [1], all previously recovered Antarctic meteorites have been found fully exposed on the ice surface some unknown period of time after their release from the ice sheet. The discovery of such a large number of samples was largely fortuitous; many are very small (< 20 g) and would probably have been blown away from the discovery site shortly after full exposure on the ice surface by the virtually constant strong winds of the region [7]. A single, possibly related sample, ALH85110, was found by an American ANSMET expedition 3 years earlier.

Natural thermoluminescence (TL) measurements were made on 49 of these meteorites as part of their initial characterization in order to study their radiation and thermal histories and to identify samples which were originally part of the same pre-terrestrial meteoroid bodies. Natural TL levels in meteorites reflect their radiation and thermal histories in space [8] and, in the case of meteorite finds, the decay of natural TL levels from high pre-terrestrial levels can be used as an indicator of terrestrial age [9].

2. Experimental procedure

The apparatus and procedure for measuring the TL of meteorites has been described in detail elsewhere [10]. During initial curation, by Dr. L. Schultz (Max Planck Institut für Chemie) [11,12], approximately 50 mg of material was taken from the interior of a 250 mg chip of each meteorite obtained. The 50 mg sample was then crushed in an agate mortar and metal removed using a hand magnet. No mineral separation procedures, such as are common in archeological TL studies [13], were used because the thermoluminescence of ordinary chondrites is dominated by a single bright phosphor, albitic feldspar [10]. Both natural and induced TL levels were determined for three aliquots of each meteorite and the natural TL level determined using the average peak height ratio converted to units of equivalent dose using a laboratory calibration [10]. Although weathering reduces the absolute intensity of both the natural and induced TL, the present procedure corrects for this using internal normalization. Previous work has shown that removal of weathering products by acid washing significantly increases the intensity of TL in meteorite finds, but does not change the calculated natural TL level [14].

Because TL is a thermally sensitive phenomenon, it is common to obtain samples for TL measurements by chipping fragments from interior portions of meteorites. In the case of the present samples, however, samples were obtained by cutting with a proponal lubricated saw during curatorial processing. This probably resulted in heating of the samples to various degrees, which may have lowered measured TL levels. However, an important observation can be made, namely, that while it is possible to artificially lower a meteorite sample's natural TL level by heating in the laboratory it is very difficult to raise its level without exposing the meteorite to large amounts of high energy radiation, which did not occur in the present case.

3. Results and discussion

While 33 of the samples recovered by the EUROMET field party had natural TL levels typical of meteorite finds from the Allan Hills region (10–100 krad), a group of 14 H-chondrite samples had very high natural TL levels (> 100 krad) (Fig. 1). One of these samples, ALH88020, is sufficiently distinctive in terms of its petrographic properties that it is clearly not related to the other samples and is not discussed further here. The remainder of the samples are listed in Table 1. The high natural TL levels exhibited by these samples are not only unusual by Antarctic meteorite standards but are higher than all but a very few non-Antarctic observed falls (Fig. 1; Table 2).

Table 1
Thermoluminescence (TL) data for 15 unusual ordinary chondrites recovered by the 1988/89 EUROMET expedition and ALH85110 recovered earlier by a US expedition. All samples bear the designation ALH and are from the Main icefield. Quoted uncertainties on TL data are for one standard deviation based on triplicate measurements of a single aliquot

Sample	Class*	Mass (g)	Natural TL (krad at 250°C)	----------- Induced TL ----------			Olivine* Fa (mol %)	Pairing+
				Sensitivity (Dhajala=1.0)	Peak Temp(°C)	Peak Width(°C)		
85110	H5	22.2	148 ± 2	1.3 ± 0.2	180 ± 5	139 ± 3	17.0	A
88017	H4	70.4	130 ± 1	0.45 ± 0.06	182 ± 3	137 ± 1	18.6	
88018	H6	67.1	108 ± 1	0.43 ± 0.05	183 ± 6	138 ± 3	19.0	B
88021	H6	51.0	170 ± 1	1.1 ± 0.1	178 ± 1	136 ± 1	18.8	
88026	H5	37.1	127 ± 1	0.55 ± 0.05	184 ± 5	138 ± 2	18.8	C
88027	H5	31.6	177 ± 1	1.02 ± 0.11	180 ± 4	135 ± 1	18.9	A
88029	H5	29.1	226 ± 2	1.5 ± 0.1	196 ± 8	141 ± 5	18.8	D
88030	H5	28.5	120 ± 3	0.50 ± 0.05	186 ± 2	138 ± 1	19.3	C
88031	H4-5	27.8	160 ± 1	1.1 ± 0.1	196 ± 10	142 ± 1	19.2	A
88033	H5	27.3	118 ± 1	0.79 ± 0.09	187 ± 3	138 ± 2	19.0	C
88035	H5	26.6	123 ± 4	0.52 ± 0.03	173 ± 2	151 ± 10	19.9	C
88039	H5	24.9	145 ± 1	0.99 ± 0.09	190 ± 1	138 ± 1	18.8	A
88042	H5	22.6	238 ± 1	1.16 ± 0.06	192 ± 2	142 ± 2	19.0	D
88047	H6	20.6	109 ± 1	1.9 ± 0.2	191 ± 3	137 ± 2	19.2	B
88049	H5	20.1	225 ± 4	0.8 ± 0.2	194 ± 9	138 ± 2	19.5	D

* Classifications, weights and fayalite contents of olivine for ALH88 meteorites from Meteoritical Bulletins 69 and 70 [11,12].

\+ Letter indicates assignment to groups of meteorite fragments thought to have been pieces of the same body immediately prior to fall. Grouping is on the basis of compositional and TL properties; the criteria are conservative and it is likely that most of these samples are fragments of a single meteorite fall.

Table 2
Non-Antarctic modern observed falls with very high natural TL levels. Date of fall and approximate mass after impact are also shown

Meteorite*	Source/ Catalog Number	Class	Mass (kg)	Date of Fall	Natural TL (krad)**
Bo Xian	USTC	LL4	13	1977Oct20	207±1
Jilin	CAS	H5	~4000	1976Mar08	290±15
Qidong	UCLA	L5	1.3	1982Jul02	125±1
Saratov	BM1956,169	L4	328	1918Sep06	130±7
Tennasilm	BM1913,218	L4	28.5	1872Jun28	120±6

* Sources of samples: BM = British Museum; CAS = Chinese Academy of Sciences; USTC = Chen Jiang Feng, University of Science and Technology of China; UCLA = J. Wasson, University of California, Los Angeles.

** Data for Jilin, Saratov, and Tennasilm from [8]; others are from the present work.

Natural and induced TL data, as well as petrographic data, can be used to examine the relationship of these samples with each other [15]. The somewhat conservative criteria for recognizing fragments of a single fall described in [15] result in seven groups of samples, four of which have multiple members (Table 1). In fact, the highly unusual natural TL levels of these meteorites, the geographic and temporal conditions of their recovery and their common classification as H-chondrites (although possibly of different types in some cases) suggest that most of them are from a single unusual meteorite. Our calculations (Fig. 2), based on lunar core TL profiles, indicate that the range of natural TL observed in this group of meteorites is greater than that expected in even a large meteorite, but we suspect at least part of this variation is a result of heating during sampling. With this bias in mind, the natural TL values must be interpreted as *lower* limits of the true TL levels of these samples and there is no reason to expect that all the samples would have been heated to exactly the same degree during processing.

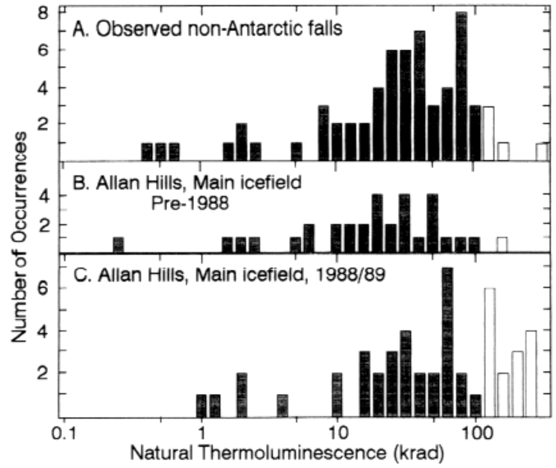

Fig. 1. Histograms of natural thermoluminescence (TL) levels for: (a) observed non-Antarctic falls of ordinary chondrites, the most common meteorite class; and for meteorites recovered in the Allan Hills Main ice field area (b) prior to 1988 and (c) during the 1988/89 EUROMET field expedition. A large number of meteorites with very high natural TL levels (> 100 krad, shown as open boxes) were recovered during the 1988/89 expedition, while only a few observed falls have such high levels of natural TL and only one was found in previous years at Allan Hills.

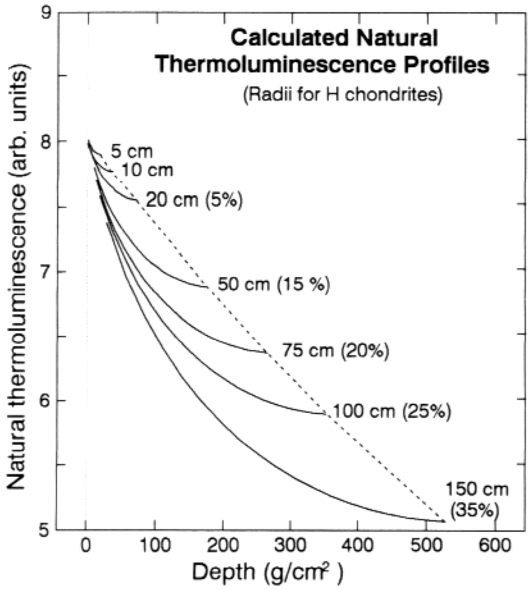

Fig. 2. Calculated relative TL depth profiles in meteroid bodies of various radii (R). The absolute relative maximum amount of variation expected in these bodies from these profiles is given in parentheses. In very large meteoroid bodies (150 cm radius) the variation over the TL profile is about 35%. In smaller bodies the variation is less and for a given depth the TL level is higher for a smaller body. These profiles are calculated from lunar core data [30] which have been corrected for irradiation geometry in meteoroid-sized bodies.

The apparent petrographic diversity of the samples presents an obstacle to grouping them all as a single meteorite shower. Meteorite breccias which include material ranging from type 4 to 6 are known [16] but not very common. However, re-evaluation of most of the sections of these meteorites suggests that the type 6 samples may actually be type 5 while the type 4 sample has yet to be re-examined (R. Hutchison, Pers. Commun., 1993). If this is the case, and in consideration of the potential for lowering of natural TL levels during sample processing, it is possible that all the samples are part of a single meteorite fall. In accordance with standard Antarctic meteorite nomenclature, we refer to this potential shower of meteorites collectively using the identification of the lowest numbered member, ALH85110. The total mass of the shower is nearly 0.5 kg and might be considerably more, since we have not examined all samples found in the vicinity and more samples may be awaiting discovery within the ice.

All but four of the samples of the ALH85110 group were found along a line near the ice escarpment along the west edge of the Allan Hills blue ice field (Fig. 3). The main cluster covers a region about 1.5 km wide and about 2 km long. The SE–NW trend of these samples may reflect concentration by wind in crevasses during previous periods of surface exposure [7]. Small meteorite fragments can be moved across the ice surface by wind until they are trapped in small crevasses, which are produced by the movement of the ice sheet. However, given the very short terrestrial age of these samples (as discussed below), it is also possible that the orientation of the fragments represents the true strewn field of a single meteorite fall. In this case, additional samples of this meteorite, perhaps including larger masses, may be found at one end of this trend line. The relatively small masses of the present samples (Table 1) and probably incomplete sampling make it impossible to observe the trends often seen in well-characterized strewn fields, whereby mass increases along the length of the field [17].

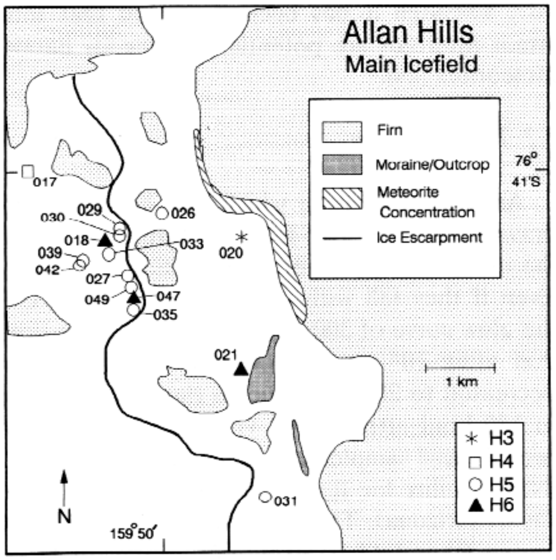

Fig. 3. Geographic find locations of the 15 samples listed in Table 1. Samples are labelled by the last three digits of their identification numbers. The samples lie close to a SE–NW line, which may reflect a preserved strewn field or possibly wind concentration of meteorites in crevasses.

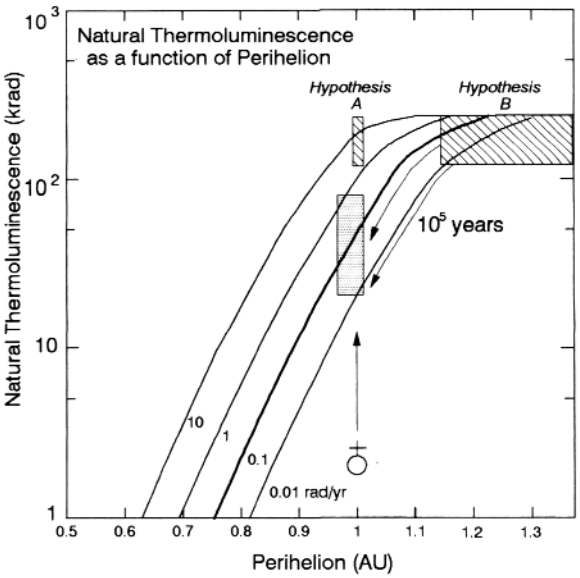

Fig. 4. Calculated natural thermoluminescence level as a function of perihelion for a meteroid body under various levels of irradiation intensity. Stippled box = the range of modern falls, which generally have perihelia between 0.95 and 1.0 AU [18]. Cross-hatched boxes = range of high TL samples; the high TL of these samples can be explained either by > 10X irradiation in perihelia of ~ 1 AU (Hypothesis A) or irradiation in perihelia > 1.1 AU (Hypothesis B). In the latter case, the time for TL to decay to equilibrium at 1 AU is ~ 10^5 yr.

3.1 Origin of high thermoluminescence

As noted above, levels of natural TL as high as those observed in the present samples are very rarely found in meteorites. The explanation for these high TL levels must involve exposure to high radiation levels or unusually low temperatures while in space [8]. The temperature of meteoroid bodies in space is largely controlled by their distance from the sun, and the level of TL in such bodies is controlled by the highest temperature experienced during their orbits, that is, at perihelion, which must be $\leqslant 1$ AU for a body supplying meteorites to Earth. As shown in Fig. 4, most meteorites have perihelia of 0.95–1.0 AU [18] and have TL levels of 20–80 krad [8]. It is apparent from this figure that the meteorites with very high natural TL levels either must have (a) been exposed to radiation doses approximately ten times that of most meteorites or (b) were irradiated at approximately the same dose rate at a somewhat greater distance from the Sun ($\geqslant 1.1$ AU). In the latter case, the meteoroids did not have sufficient time to adjust their TL levels to the warmer environment at 1 AU prior to Earth impact.

It appears very unlikely that these meteorites where exposed to dose rates 10 times greater than that of most meteorites. Dose rate at a given point within a meteoroid body is dependent upon two independent factors; namely, the external cosmic ray flux and the depth of the point within the body, sometimes referred to as "shielding", in relation to the size of the body. However, our calculations indicate that shielding and parent body size alone cannot account for the very high natural TL levels observed in the present samples (Fig. 2). Our calculations indicate that: (a) the expected TL range in a large meteoroid body (100 cm diameter) would be about 25%, with smaller bodies showing smaller variations; and (b) smaller meteoroids will, at a given depth, have greater TL levels than larger ones. The latter conclusion is clearly not the case in modern falls with very high natural TL levels (Table 2).

Given that it does not appear possible to produce the high dose rates using shielding, a higher external flux must be considered. Solar cosmic rays associated with solar flares are too low in energy to contribute to the flux more than a few centimetres from the surface of a meteoroid body in space, material which is normally removed during atmospheric passage [19]. Another possibility is that these meteorites were in orbits which were at least partly outside the heliosphere [20,21]. However, data from the Pioneer and Voyager spacecraft indicate a cosmic ray flux outside the heliosphere which is a only a factor of two to three higher than at 1 AU [21], far less than the factor of ten or more needed to explain the high TL levels.

The remaining possibility is that the meteorites with high natural TL levels were irradiated while in perihelia $\geqslant 1.1$ AU and reached Earth without adjusting their TL levels to the warmer temperatures in space at 1 AU. Such a possibility is clearly dependent upon the kinetics of the TL decay process. Approximately 10^5 yr are required for TL levels to decay from an equilibrium level of 250 krad at $\geqslant 1.1$ AU to about 80 krad at 1 AU [9]. While this is a short period of time relative to the orbital evolution of most meteoroid bodies, orbital calculations indicate that, even without considering the effects of catastrophic collisions between bodies, rapid changes of perihelion are possible on the $< 10^4$ yr time scale [22]. The proportion of meteorites with very high TL levels relative to those with more typical TL levels should, in this case, reflect the number of meteoroid bodies undergoing such rapid evolution. Less than 5% of ordinary chondrites have such high TL levels (Fig. 1). It is quite possible that some of these meteorites had their orbits perturbed due to collisional events; the best characterized of these meteorites, Jilin, has a two-stage irradiation history in which the most recent stage was only about 0.4 Ma long [23], compared to > 5 Ma for most ordinary chondrites. These two irradiation stages are separated by a major event in which the meteoroid underwent considerable fragmentation and possibly changes in orbital parameters. In any case, if our interpretation of the origin of high TL in meteorites is correct, these rare meteorites are the only documented samples from meteoroid bodies which were recently in orbits similar to Earth-approaching (Amor) asteroids, which have perihelia > 1.0 AU, although it has been suggested that three Amor asteroids are potential sources for basaltic meteorites [24].

3.2 Terrestrial age

Another conclusion which may be confidently drawn from such high levels of natural TL is that the meteorites have not been on Earth very long. Even if they fell with saturation TL at 250°C in the glow curve of 300 krad, decay studies indicate that after 10^4 yr the level of TL would have decreased to 200 krad due to thermal decay and to 140 krad after $4 \cdot 10^4$ yr. The ^{14}C content of two of these samples was measured by A.J.T. Jull (NSF Facility for Radioisotope Analysis, University of Arizona). The levels of ^{14}C in ALH88047 (group B) and ALH88029 (group D) were 44.5 ± 0.5 and 35.3 ± 0.5 dpm/kg. These ^{14}C activities correspond to terrestrial ages of < 1300 and $2{,}300 \pm 1300$ yr, respectively, assuming a value of 46.5 dpm/kg at time of fall [25]. Given the uncertainties due to the unknown degree of shielding for these samples and also the uncertainties of the method, these data are very similar, and it is possible to say, on the basis of these data alone, that these samples could come from a single meteorite with a terrestrial age of about 1000 yr. This terrestrial age is extremely short by Antarctic meteorite standards: at the Allan Hill Main ice field most meteorites have terrestrial ages well in excess of 40,000 yr and are often in the order of 10^5 yr [6].

3.3 Induced thermoluminescence

The induced TL peak temperatures of the high natural TL samples are generally < 190°C (Table 1) and are thus very similar to modern H-chondrite falls. They are clearly different from most H-chondrites from the Allan Hills Main ice field, many of which have induced TL peak temperatures > 190°C. This accords with the idea that the composition of the H-chondrite flux has changed over the last million years [26,27], with recently fallen H-chondrites, including ALH 85110, being very similar to each other but distinctly different in terms of thermal histories to many of those which fell > 100,000 yr ago [28].

As noted above, weathering can greatly lower the intensity of both the natural and induced TL signal. As shown in Fig. 5, the induced TL sensitivities of the meteorites of this study are less than those of modern falls of equivalent petrologic type by approximately a factor of ten. Acid-washing of these meteorites, using the procedure described in [14], removes the weathering products such that the induced TL sensitivities of the samples are brought within the range for modern falls. The difference in TL sensitivity between the normal and acid-washed samples is very similar to that observed in other Antarctic finds [14]. This emphasizes the rapidity at which meteorites weather on Earth, even in the cold desert conditions of Antarctica [29]. Within 1000 yr after fall, meteorites in the Antarctic are indistinguishable from those which fell approximately 0.6 million yr before, at least in terms of TL sensitivity. Within any given group of Antarctic ordinary chondrites, however, TL sensitivities ranging from the modern fall range to approximately 0.1 (relative to Dhajala) are observed [15]. This suggests that some Antarctic meteorites are more protected from weathering than others. One possible explanation for this is that only those meteorites exposed at or near the ice surface are subjected to heavy degrees of weathering whereas those buried deeper within the ice are more protected. If this is the case, TL sensitivity could be used to estimate the numbers of meteorites which have been recently exposed on the ice field surface, as opposed to meteorites which have fallen on the field or which were exposed in the more distant past. This would have implications for the study of meteorite concentration mechanisms on the blue ice fields of Antarctica.

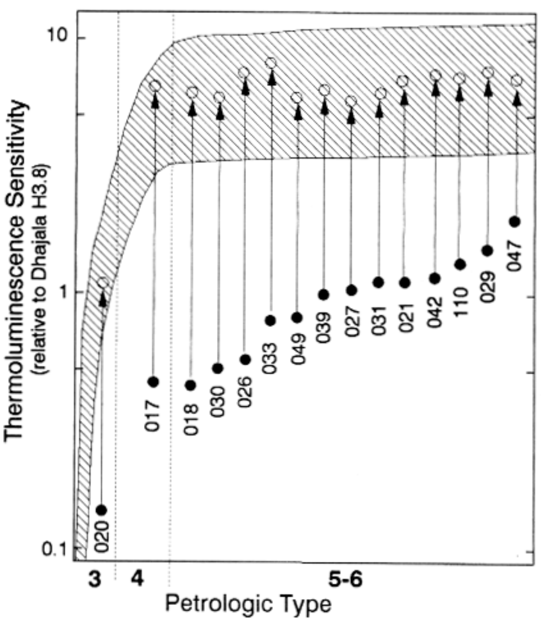

Fig. 5. Thermoluminescence sensitivity of the present samples relative to the Dhajala (H3.8) meteorite as a function of petrologic type. Untreated samples shown as dots, acid-washed samples shown as circles. After acid washing, all samples have sensitivities which are very similar to each other and which are within the range observed for modern falls [10].

4. Conclusions

In summary, we have identified a major Antarctic meteorite shower which has been on

Earth only ~ 1000 yr and which experienced a very unusual radiation/orbital history in space, probably involving a change of perihelion from ⩾ 1.1 Au to 1 Au within the last few hundred thousand years. Only a very small number of other meteorites have apparently had similar histories. This meteorite may be an H-chondrite breccia, incorporating material ranging from petrologic type 4 to 6. Most of the 15 samples of this meteorite lie along a geographic trend line, which might represent a preserved strewn field or reflect wind concentration of small meteorites in ice crevasses. The discovery of this meteorite is of interest in the study of irradiation histories and environments of meteorites, in linking the Antarctic finds to those found elsewhere in the world, and to the mechanics of ice movements in Antarctica.

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