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The Natural Thermoluminescence of Meteorites

II. Meteorite Orbits and Orbital Evolution

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Natural thermoluminescence (TL) data for 26 meteorites for which orbital elements have been estimated are reported. Calculations of equilibrium natural TL level in ordinary chondrites suggest that TL should be a sensitive indicator of perihelion. Meteorites with perihelia <0.85 AU should have very low levels of natural TL (<5 krad at 250°C in the glow curve), while meteorites with perihelia >0.85 AU should show a range of natural TL (>5 krad) with significant scatter as a result of slight variations in dose rate (shielding) and albedo. The data presented here generally agree with the theory and suggest an effective dose rate of ~3 rad/year for most meteorites. Comparison with cosmic ray exposure ages indicates that natural TL level is also partly related to exposure age. Meteorites with high (>20 Ma) exposure ages generally have a lower and more constrained (10–30 krad) range of natural TL than meteorites with ages <20 Ma ages (10–>90 krad). We suggest that this reflects orbital evolution, since mature meteorite orbits evolve to lower perihelia.

The data presented here confirm the earlier observations that only a very small proportion of meteorites have experienced orbits with low perihelia within the last 10^5 years. The data suggest that <15% of ordinary chondrites have been in recent orbits with perihelia <0.85 AU. The reheating of these meteorites is independently confirmed by their generally low $^3He/^{21}Ne$ ratios.

INTRODUCTION

Thermoluminescence (TL) is an extremely useful technique for studying the metamorphism and recent histories of meteorites (Sears 1988). The induced TL of meteorites is predominantly controlled by the type and abundance of feldspar present, while the level of natural TL (TL of the sample "as received") is determined by the thermal and radiation history of the sample. The history of an "average" ordinary chondrite in terms of its natural TL is shown schematically in Fig. 1. The natural TL level of a meteorite is initially very low because of shielding from cosmic radiation by its parent body. After the impact which actually produces the meteorite-sized body (meter-diameter or less), natural TL levels build up relatively rapidly, reaching a state of "equilibrium" within about 10^5 years (Sears 1988). The level of natural TL, at least in the lower temperature and less thermally stable portion of the glow curve, is then in a state of dynamic equilibrium, varying slightly during each orbit as the TL drains slightly at the higher temperatures of perihelion which it regains at aphelion. The level of TL in the higher temperature and more thermally stable portion of the glow curve is, however, relatively unaffected by orbital temperature variations and may reach saturation level if exposed to cosmic rays for a sufficiently long period of time. The average level of low-temperature equilibrium TL can vary over the time span of 10^6–10^7 years if the meteoroid experiences changes in its long-term orbital parameters (i.e., between "equilibrium" and "equilibrium 2" in Fig. 1). After impact with the earth, natural TL levels gradually decrease to lower values ("equilibrium 3" in Fig. 1) as a result of the higher terrestrial temperatures and lower dose rates (Sears and Mills 1974, Melcher 1981a, McKeever 1982). Thermoluminescence levels are also lowered by heating during atmospheric entry, but this only affects a thin (≲5 mm in thickness) outer rim of the meteorite (Lalou *et al.* 1970, Sears 1975). Except for all but the smallest meteorites (≲20 g), this drained zone can be avoided during TL measurement by careful sampling.

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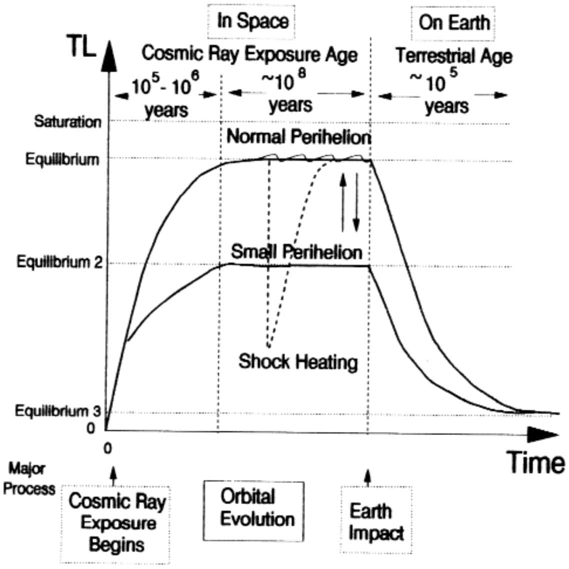

FIG. 1. Schematic of the natural thermoluminescence history of a typical ordinary chondrite. Arrows between the two higher equilibrium levels indicate that "equilibrium" level is controlled by perihelion, which can change throughout the meteoroid's orbital evolution. The wave function superimposed on the "normal perihelion" line shows the TL level increase and decrease over the course of individual orbits.

In this paper we examine the natural TL of three meteorites with known orbits (Pribram, Innisfree, and Lost City) and 23 meteorites (including 20 ordinary chondrites) for which orbits were derived from visual observations. The relationship between orbit and natural TL has been considered previously by Melcher (1981b) and McKeever and Sears (1980). In this paper we examine the relationship of natural TL to cosmogenic isotope abundances which are additional indicators of orbital history. We also identify a number of meteorites which we suspect have had unusual recent histories involving close passage to the sun and compare their abundance to that expected from visual observations (Simonenko 1975) and fireball data. These data are of particular interest in light of recent attempts to link certain meteorites with meteorite "streams" identified by fireball observations (Halliday 1987, Steel *et al.* 1991).

THEORY OF NATURAL TL AS A FUNCTION OF ORBIT

Using the Garlick and Gibson (1948) model of TL production, the TL intensity can be expressed in terms of the release of electrons from localized energy levels (traps) in the luminescent material (predominantly feldspar, in the case of meteorites). In this model, E is interpreted as a trap depth (below the conduction band) and the degree of trap filling can be expressed by

$$n/N = [(sR\exp(-E/kT)/\ln(2)r + 1]^{-1}, \qquad (1)$$

where n = the number of filled traps (proportional to the TL intensity), N = the total number of traps, R = the radiation dose required to fill half of the total traps, k = Boltzmann's constant, T = temperature, and r = the dose rate (Sears 1988). It has been found experimentally (McKeever and Sears 1979, McKeever 1980) that TL decay is a second-order process, in which case, the frequency factor, s, is a function of the number of filled traps, n, the relationship being

$$s = s_1 n/N, \qquad (2)$$

where s_1 is equal to the first-order frequency factor. Equation (1) can then be solved by iteration, if temperature and dose rate (degree of shielding) are known.

In order to consider TL levels over an entire orbital period, we can define an effective irradiation temperature as the temperature at which the amount of TL removed equals that gained over an entire orbit. Since TL draining is proportional to $\exp(E/kT)$, the TL level of a meteorite in space is determined mainly by the highest temperature of its orbit, namely at perihelion (Melcher 1981b, McKeever and Sears 1980). Thus, as a first approximation, T can be set equal to T_p, the perihelion temperature, which, for a sphere, is found by

$$T_p = [A0.25H/(\varepsilon\sigma X^2)]^{1/4}, \qquad (3)$$

where A = absorptivity, H = the solar constant at 1 AU, ε = emissivity, σ = the Stefan–Boltzmann constant, and X = distance from the sun in astronomical units (AU). By substitution of accepted values for the constants, this becomes

$$T_p = 278(\gamma/X^2)^{1/4}, \qquad (4)$$

where $\gamma = (1 - \alpha)/\varepsilon$, and α = average albedo. The natural TL level can thus be described by the combination of Eqs. (1) and (4). For any given trap E and R can be considered constant and s will vary in a predictable fashion. Thus, the main source of natural TL variability among a group of meteorites which have similar traps and which have been exposed to cosmic rays long enough to reach a state of dynamic equilibrium will be dose rate (r), irradiation temperature ($\sim T_p$, which is defined by orbit), and albedo (α), which is proportional to γ.

McKeever (1980) has determined that, although there are minor variations, the natural TL of ordinary chondrites is dominated by a few traps. As a first approximation, the TL glow curve can be modeled by the behavior of two of these traps, namely, a low-temperature peak (at ~250°C) and a high-temperature peak (at ~400°C). Using trap parameters determined from the Lost City meteorite (McKeever 1980), the glow curve can be modeled by the behavior of traps with $E = 1.31$ eV and $s = 9.2 \times 10^{12}$ $\sec^{-1}$ for the low temperature peak, $E = 1.51$ eV and $s = 1.6 \times 10^{10}$ $\sec^{-1}$ for the high temperature peak, and $R = 4.5 \times 10^5$ rad for both traps.

Using these parameters, it is possible to explore the effects of the three major variables on natural TL levels. Figure 2a shows the variation of natural TL for the two major peaks for a meteorite of average albedo ($\gamma = 0.78$) as its perihelion evolves from the asteroid belt to Earth-crossing *assuming* that this occurs at a slow rate (and with no short-term radical perturbations of orbital parameters) so that dynamic equilibrium is maintained. As a result of the exponential increase of temperature in the inner Solar System, each trap is rapidly emptied in Earth- and Venus-crossing orbits. In fact, the level of TL in the low-temperature trap is highly sensitive to perihelia between 0.6 and 1.0 AU. Considering only the low-temperature peak, it is clear that variations in dose rate (Fig. 2b) merely shift this effect slightly in terms of perihelion. It has been suggested that lunar meteorites, which are small relative to modern falls, probably had dose rates of very close to 10 rad/year (Sutton and Crozaz 1983). The range of dose rates, with zero shielding, has been calculated to vary between 8 and 25 krad, based on measurements during the lunar missions (Wilkinson and Curtis 1972) and measured galatic particle flux components (Hoyt 1973). As is apparent from Fig. 2b, the differences in natural TL as a result of variations in dose rate over two orders of magnitude is small. Albedo, on the other hand, is known to vary considerably (γ between 0.68 and 0.9) among meteorites (Chapman and Salisbury 1973). Figure 2c shows the effect of varying γ between 0.68 and 0.90, assuming a constant dose rate of 1 rad/year. Clearly, γ (and hence albedo) should have a strong effect on natural TL of meteorites in Earth-crossing orbits.

In summary, the theoretical studies suggest that natural TL levels should be a sensitive indicator of meteorite orbit, especially at low glow curve temperatures. However, differences in albedo and dose rate should also produce significant variation in natural TL from meteorite to meteorite. This analysis is subject to the assumptions that orbital evolution occurs slow enough that dynamic TL equilibrium is maintained and that orbital evolution is a gradational process.

EXPERIMENTAL

Samples were taken from 26 meteorites for this study. For Pribram, Innisfree, and Lost City orbital parameters have been determined by photographic networks (Ceplecha 1961, McCrosky *et al.* 1971, Halliday *et al.* 1978). For the others, orbital parameters have been determined by Simonenko (1975) from visual observations. The calculation of the perihelion requires knowledge of the geocentric velocity, which is unknown for the visually observed falls. We have determined perihelia for velocities of 13, 16, 19, and 22 km/sec from the plots of Simonenko (1975). Except for the smallest perihelia, the uncertainties introduced by assumed velocities are fairly small.

Two chips were obtained from each meteorite and ground and sieved to approximately 100 mesh, the metal being removed with a hand magnet. Three 4-mg portions of each sample were placed in copper pans and the natural TL was measured. The induced TL of each sample was then measured.

Thermoluminescence (natural and induced) was measured by heating each pan on a nichrome strip in a nitrogen atmosphere at a controlled linear heating rate of 7.5°C/sec. The TL emitted was measured by a photomultiplier tube (PMT) which, by use of a specially designed light shutter, was kept at constant voltage throughout the experiments. A heat filter and blue filter (Corning 469 and 759, respectively) were placed between the samples and the PMT to reduce red blackbody radiation, and an acetate sheet, previously found to be insensitive to wavelength in its absorption properties, was used to protect the filters from emitted volatiles. All data were collected and stored by a dedicated computer system. After measuring the natural TL, each aliquot of the sample was irradiated with a ^{90}Sr source and the induced TL was measured. At the beginning and end of each day, samples of the Dhajala H3.8 chondrite were run as a normalization standard and system check. Further details on laboratory procedures and instrumentation may be found in Sears and Hasan (1986) and Sears (1988). The laboratory procedures used here are an improvement on the original TL work done on these meteorites and the present data supercede the earlier values (Hasan and Sears 1987).

Natural TL data may be quoted as the "peak-height ratio," the intensity of the low-temperature peak compared to that of the high-temperature peak (see Sears 1988 for review), or "equivalent dose," the intensity at a given glow curve temperature divided by the intensity of the induced TL at that temperature per unit of irradiation (Sears 1988, Melcher 1981b). The peak-height ratio has the disadvantage of not being applicable to achondrites. Equivalent dose has the disadvantage of being subject to significant errors as a result of slight thermal lags between the natural and the induced curves. In this study we follow the procedure of Hasan *et al.* (1989), which is to report natural TL data for ordinary chondrites

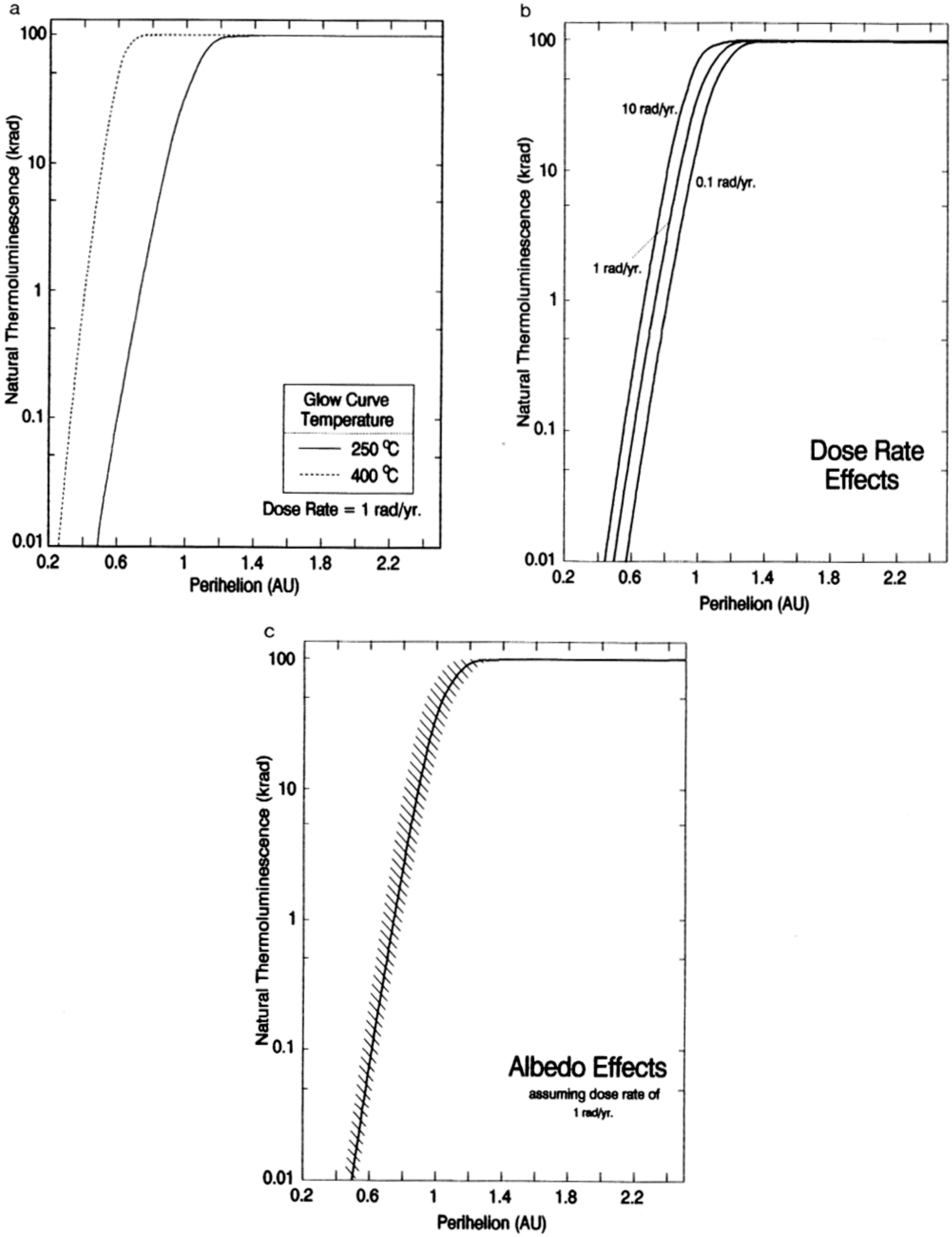

FIG. 2. (a) Calculated natural TL remaining at 250 and 400°C in the glow curve as a function of perihelion distance for an ordinary chondrite using the TL parameters of the Lost City meteorite (McKeever 1980). A value of $\gamma = 0.78$ (albedo = 0.22) and a natural TL level of 100 krad at 2.5 AU is assumed. (b) Calculated variation in 250°C curve from Fig. 2a as a result of dose rate variations. (c) Curve from Fig. 2b showing range produced by varying albedo between 0.32 and 0.1 ($0.68 < \gamma < 0.9$).

which have been derived from the peak height ratios using

$$\log(\text{nat. TL}) = 1.2903 * \log(\text{LT/HT}) + 1.0890 \quad (5)$$

for ordinary chondrites with a LT/HT > 0.5. For other samples, the natural TL value quoted is the equivalent dose. The natural TL values have the units of dose (krad) and are measured at 250°C in the glow curve.

In addition to the new measurements reported here, we have sought to expand the available natural TL database by expressing the data of McKeever and Sears (1980) and Melcher (1981b) in terms of krad at 250°C. As noted by Strain *et al.* (1985), interlaboratory comparisons of natural TL data are intrinsically difficult because differences in filters and irradiation sources result in large, and sometimes nonlinear, differences in reported equivalent doses. However, these problems can be at least partly overcome by careful interlaboratory comparison of common samples. We have attempted to convert the literature data to the present units by assuming linear differences in absolute equivalent dose and determining conversion factors from samples common to all studies (Table II). The conversion is based on 16 of 39 samples from McKeever and Sears (1980) and 7 of 45 samples from Melcher (1981b). It should be noted that the original data from these studies were based on single TL measurements and thus are susceptible to undetermined instrumentation or sample heterogeneity effects. Also, Melcher (1981b) reports data for equivalent doses at 200 and 300°C and these have been converted to 250°C for the purposes of this study by averaging the two measurements. Since the glow curve is most sensitive to thermal decay in the 250°C region, it is likely that this averaging procedure results in underestimation of actual relative variations between samples. We stress that this conversion process gives only a rough approximation of the true value for any given meteorite. Because of these problems, we have used recently obtained data, reduced using the procedures explained at the beginning of this section, rather than the older data whenever possible.

RESULTS

Natural TL data for the present samples are given in Table I, with a laboratory description of the original chip. The range of TL data for the ordinary chondrites is from 8 to 70 krad at 250°C, with an average value of 30 krad, which is typical of non-Antarctic ordinary chondrites (Sears 1988). Table II gives the calculated perihelia distances (in AU, as read from the charts of Simonenko 1975) of each meteorite which are based on assumed initial velocities of 13, 16, 19, and 22 km/s in the case of the non-photographed falls.

Data from McKeever and Sears (1980) and Melcher (1981b), converted to krad at 250°C in the manner discussed above, are compared in Table III. In several cases we have obtained new data and these are also listed, with 1σ uncertainties based on triplicate measurements. In general, data from the three sources are in reasonable agreement where comparison is possible. In the case of Bjurbole and Lost City, differences between TL data from the different laboratories may be the result of sample heterogeneities, given the large variation exhibited by two chips in this study (Table I). This may also be the case for Holbrook, which shows a range of 21 krad among the three data sources. In a few cases, we suspect problems with the older data. The value for Dhajala reported by McKeever and Sears (1980) may be in error. Data for Jilin (Kirin) are so radically different between two sources that we suspect that the sample of Melcher (1981b) may have been heated during transport since a recent measurement by Wagner (1985) agrees with the higher value reported by McKeever and Sears (1980). The suggested value for the natural TL at 250°C in Table III is the average, except where an individual value is suspect, and is used throughout this paper.

DISCUSSION

We will discuss the factors which we suspect have had the greatest effect on natural TL levels of non-Antarctic meteorites in relation to the present data. We will first consider the effect of terrestrial age on natural TL levels, since TL decay under terrestrial conditions is initially very rapid (Fig. 1). We will show that, in most cases, terrestrial age of non-Antarctic falls has little influence on natural TL levels relative to other factors. We will then consider the effect of meteorite orbit on natural TL levels. We show that data for observed falls conform to the distribution expected from theory, with a few notable exceptions. We will then show that these exceptions may be explained by comparison with cosmic ray exposure ages; the relationship between these two phenomena probably reflects long-term orbital evolution. We will also show that data for other non-Antarctic meteorites support these conclusions.

Natural Thermoluminescence and Terrestrial Age

The decay of natural thermoluminescence under terrestrial conditions has been studied previously by Sears and Mills (1974), Melcher (1981a), and McKeever (1982). The rate of this decay is high enough, over long periods of time, to allow relative dating of the terrestrial ages of Antarctic meteorites (McKeever 1982, Hasan *et al.* 1987). The rate of decay is initially very rapid (e.g., Fig. 1), and before the effect of other factors on thermoluminescence can be considered, it is helpful to examine the degree to

TABLE I

Natural TL Levels of Observed Falls

Meteorite	Class-type	Source/Cat.[a]	Age[b] (years)	Natural TL at 250°C (krad)[c]			Per.[d]	Chip descr.[e]
				Chip A	Chip B	Average		
Appley Bridge	LL6	BM 1920, 40	76	42.6 ± 0.4	46.9 ± 0.2	45 ± 3	0.9	M
Bjurbole	L4	USNM 695, 2672	91	75.5 ± 5.6	51.1 ± 0.3	63 ± 17	0.99	Lg
Chicora	LL6	USNM 1326	52	29.4 ± 0.2	32.3 ± 0.1	31 ± 2	0.95	g
Forest City	H5	USNM 3316	100	20.6 ± 0.1	20.8 ± 0.4	21 ± 1	0.71	g
Homestead	L5	FMNH 313	115	32.1 ± 0.3	29.3 ± 0.2	31 ± 2	0.93	g
Innisfree	LL5	CGS	13	28.5 ± 0.3	18.4 ± 0.1	24 ± 7	0.986	Lg
Kendleton	L4	UCLA	51	55.3 ± 0.3	62.7 ± 0.3	59 ± 5	0.92	Dg
Knyahinya	L5	BM	124	18.3 ± 0.2	18.0 ± 0.1	18 ± 1	0.97	g
Kunashak	L6	ASU 741	41	26.2 ± 0.3	25.6 ± 0.2	26 ± 1	0.99	Dg
Lost City	H5	USNM 4848	20	33.8 ± 0.5	59.6 ± 0.1	47 ± 18	0.967	Lg
Nikolskoe	L4	USNM 1732	36	23.3 ± 0.1	20.1 ± 0.1	22 ± 2	0.91	Lg
Norton County	AUB	UNM	42	46.2 ± 1.8	25.1 ± 0.0	36 ± 15	0.88	W
Paragould	LL5	FMNH 2135	60	19.8 ± 0.2	—	20 ± 1	0.9	g
Pasamonte	EUC	USNM 897	57	1.8 ± 0.1	—	1.8 ± 0.1	0.7	Lg
Peace River	L6	USNM 2314	27	7.4 ± 0.1	7.8 ± 0.1	7.6 ± 0.3	0.84	Lg
Pervomaisky	L6	USNM 1424	57	23.7 ± 0.2	22.9 ± 0.2	23 ± 1	0.94	W
Pesyanoe	En-A	USNM 1425	57	24.6 ± 1.4	34.8 ± 0.5	30 ± 7	0.48	W
Pribram	H5	USNM 4840	33	23.3 ± 0.1	20.3 ± 0.1	22 ± 2	0.8	Lg
Rochester	H6	USNM 1125	114	7.3 ± 0.1	5.5 ± 0.1	6 ± 1	0.92	W
Simmern	H	ASU 591.1	70	11.1 ± 0.1	13.2 ± 0.1	12 ± 1	0.94	Lg
Stalldalen	H5	BM 1958, 713	114	61.6 ± 0.3	67.9 ± 2.0	65 ± 4	0.98	Dg
Strathmore	L	BM 1976, M.6	73	46.5 ± 0.3	48.5 ± 2.0	48 ± 1	0.95	Lg
St. Mitchel	L6	BM 1913, 145	80	32.2 ± 0.1	30.5 ± 0.3	31 ± 1	0.95	g
Tilden	L6	USNM 832	63	18.5 ± 0.1	16.3 ± 0.1	17 ± 1	0.92	W
Vengorovo	H5	USNM 1728	40	55.6 ± 0.3	58.6 ± 0.7	57 ± 2	0.75	Lg
Zemaitkiemis	L6	BM 1939, 247	57	16.8 ± 0.2	22.1 ± 0.2	19 ± 4	0.9	Lg

Note. Natural TL values are given for seperate chips and as an average value for each meteorite. Perihelia are based on visual estimates except for photographed falls (italized).

[a] Source and catalog number(s). ASU, Center for Meteorite Studies, Arizona State University; BM, British Museum; CGS, Canadian Geological Survey; FMNH, Field Museum of Natural History, Chicago; UCLA, University of California, Los Angeles; UNM, Institute of Meteoritics, University of New Mexico; USNM, United States Natural History Museum.

[b] Terrestrial age (in years) at time of measurement.

[c] Uncertainties are one-sigma for triplicate measurement of a single aliquot.

[d] Perihelia based on visual estimates (Simonenko 1975). Values given here based on assumed initial velocity of 16 km/sec. See Table II for estimates based on other velocities. Perihelia for Pribram, Innisfree, and Lost City are from photographic networks (Ceplecha 1961, McCrosky *et al.* 1971, Halliday *et al.* 1978).

[e] Naked eye description of chip. Dg, dark grey; g, grey; M, mixture; Lg, light grey; W, white.

which the data have been affected by decay of the natural TL on Earth.

Figure 3 shows the natural TL level at 250°C in the glow curve of all the ordinary chondrites in Tables I and III as a function of terrestrial age at the time of measurement. Since several samples have been measured more than once over the last 15 years, they are represented by multiple points. The terrestrial ages of these meteorites range from 0.5 to 488 years, although most are less than 150 years. The dashed line is a least squares fit through all the samples with natural TL >5 krad, which is a conservative boundary for the equilibrium level ("Equilibrium 3" in Fig. 1) of very old meteorites, as shown by Antarctic meteorites (Hasan *et al.* 1987). As is apparent from Fig. 3, this line is not statistically significant, but its slope is intermediate between those found by Melcher (1981b) for the natural TL at 200 and 300°C in the glow curve.

The shallowness of the slope of the fitted line in Fig. 3, in addition to its very poor statistical correlation, shows that terrestrial age is not the major factor determining natural TL levels in observed falls. Only the oldest of the studied meteorites, Ensisheim, may have a low natural TL solely as a result of terrestrial thermal decay. It should be noted, however, that Ensisheim also has a poorly documented history and may have been subjected to nonnatural heating (Melcher 1981b). Considering all the data (including those meteorites with TL levels <10 krad) renders even this possible exception rather doubtful.

TABLE II
Perihelia of the Meteorites of Table I Calculated for Different Initial Geocentric Velocities

Meteorite	Initial geocentric velocity (km/sec):	Perihelion (AU)			
		13	16	19	22
Appley Bridge		0.92	0.9	0.88	—
Bjurbole		1.0	0.99	—	—
Chicora		0.95	0.95	—	—
Forest City		<0.7	0.71	0.70	0.7
Homestead		0.91	0.93	0.94	0.95
Kendleton		0.9	0.92	0.93	0.93
Knyahinya		0.96	0.97	0.97	—
Kunashak		0.98	0.99	0.99	~1.0
Nikolskoe		0.91	0.9	0.89	<0.89
Norton County		0.90	0.88	0.85	<0.85
Paragould		0.91	0.91	~0.91	~0.91
Pasamonte		0.8	0.7	0.55	0.5
Peace River		0.9	0.84	0.8	0.75
Pervomaisky		0.95	0.94	—	—
Pesyanoe		0.65	0.48	<0.5	<0.4
Rochester		0.91	0.92	—	—
Simmern		0.98	0.94	>0.9	—
Stalldalen		0.99	0.98	0.95	—
Strathmore		0.96	0.95	0.94	—
St. Michel		0.95	0.95	0.94	—
Tilden		0.94	0.92	≥0.9	—
Vengorovo		0.83	0.75	0.71	0.68
Zemaitkiemis		0.9	0.9	0.88	0.85

Note. Data from the charts of Simonenko (1975). Blanks indicate that perihelia could not be calculated for the given velocity.

The TL decay of achondrites is complicated by the process of anomalous fading (Hasan *et al.* 1986, Sears *et al.* 1991), which reduces natural TL at all glow curve temperatures by 50% or more, though the effect can be stronger at lower glow curve temperatures in some meteorites (Sears *et al.* 1991). Anomalous fading may explain, or at least be partially responsible for, the extremely low levels of natural TL in Pasamonte.

Natural Thermoluminescence as a Function of Orbit

Figure 4 is a comparison of natural TL and Simonenko's (1975) calculated perihelia. As has been noted elsewhere (Wetherill 1985), most meteorites for which we have orbital information had perihelia between 0.9 and 1.0 AU, and such samples have a very wide range of natural TL (between 1 and 70 krad). Superimposed on the data in Fig. 4 is the calculated curve for a typical ordinary chondrite, based on the TL parameters for Lost City (McKeever 1980) and a γ of 0.78 (an average based on the albedo values quoted by Chapman and Salisbury 1973) and three different dose rates. Most of the data are consistent with these curves, but scatter for the reasons discussed below.

TABLE III
Comparison of Natural TL Levels of Non-Antarctic Falls

Meteorite	Class-type	Natural TL (krad at 250°C)						Suggested TL value
		Melcher (1981b)		Sears and McKeever (1980)		Present work		
		TL	T_{age}	TL	T_{age}	TL	T_{age}	
Aldsworth	LL5			0.4	138			0.4
Alfianello	L6	25.1	97					25
Allegan	H5			16.3	77	26.6	89	27
Alta'ameem	LL6			29.2	0.5			29
Ambapur Nagla	H5			13.6	81	5.3	95	10
Appley Bridge	LL6			31.9	64	45 ± 3	76	40
Ausson	L5	17.8	122					18
Barwell	L5			46.7	7.5	46.3	23	46
Beaver Creek	H4			11.9	83			12
Bjurbole	L4	31.0	81			63 ± 17	91	60
Bremevorde	H3			0.4	121	0.20 ± 0.01	136	0.4
Bruderheim	L6	52.9	20	27.6	13	26.0	30	27
Butsura	H6			40.7	112	31.4	129	35
Charsonville	H6	20.3	170			14 ± 1	181	14
Crumlin	L5			13.3	71			13
Cumberland Falls	AUB	27.5	61					28
Cynthiana	L4	29.5	103					30
Dandapur	L6	25.6	102					26
Dhajala	H3	24.1	4	41.9	2	22.9	14	23
Dhurmsala	LL6			0.6	113			0.6
Djati-Pengilon	H6	20.2	96					20
Drake Creek	L6	23.0	153					23
Durala	L6			16.3	158			16
Elenovka	L5	29.4	29					29
Ensisheim	LL6	10.8	488					11
Farmington	L5	20.1	90	19.7	88	22 ± 1	101	20
Farmville	H4	22.1	46					22
Fisher	L6	28.2	86					28
Forest City	H5			23.2	89	21 ± 1	100	22
Gambat	L6			1.8	76			2
Girgenti	L6	21.0	127					21
Guarena	H6	30.0	88					30
Guibga	L5	42.2	8					42
Hallingeberg	L3	20.7	36					21
Hamlet	LL4	31.7	21					32
Harleton	L6	29.7	19					30
Hessle	H5	24.7	111					25
Holbrook	L6	27.4	68	13.2	65	6.1	78	10
Homestead	L5	27.6	105			31.0	115	30
Idutywa	H5	24.9	24					25
Innisfree	L4	20.5	3			24 ± 7	13	21
Jelica	LL	21.6	91	14.7	83			18
Jilin (Kirin)	H4	37.2	4	292.6	3			290
Kandahar	L6	27.8	21					28
Kervouve	H6	20.4	111	30.1	107	32.0	121	31
Kesen	H4	27.8	130			52 ± 1	141	52
Khanpur	LL5			5.6	21			6
Langhalsen	L6	33.3	33					33
Lillaverke	H5	34.3	50					34
Limerick	H			4.4	160	1.9	177	2
Lixna	H4	29.9	160					30
Lost City	H5	27.9	10	22.9	7	47 ± 18	20	40
Lundsgard	L6	34.8	91					35
Malakal	L5	7.3	10	0.2	8			0.2
Mangwendi	LL6			30.7	39	12 ± 1	57	12
Marion	L6	22.2	133					22
Mauerkirchen	L6			0.6	205			0.6
Maziba	L6	25.0	38					25
Monroe	H4			31.9	130	34.7	141	33
Ochansk	H4	21.8	93			41 ± 3	104	41
Ogi	H6			26.5	232			27
Olivenza	LL5			1.4	49	0.5	66	1
Parnallee	LL3			19.7	121			20
Pribram	H5	23.8	21			22 ± 2	33	22
Quenggouk	H4			54.5	119			54
Richardton	H5	23.8	62			32 ± 1	73	24
Saratov	L4			80.2	55	79.1	70	80

TABLE III—*Continued*

Meteorite	Class-type	Natural TL (krad at 250°C): Melcher (1981b) TL	Melcher (1981b) T_{age}	Sears and McKeever (1980) TL	Sears and McKeever (1980) T_{age}	Present work TL	Present work T_{age}	Suggested TL value
Soko Banja	LL4			58.6	96	36 ± 1	114	36
Tenham	L6			10.7	99	14 ± 4	112	11
Tennasilm [Tns]	H4			70.5	101	46 ± 1	119	46
Tieschitz	H3			7.0	100			7
Ucera	H5	20.4	10			66 ± 2	21	66
Vouille	L	30.5	149					31
Wold Cottage	L6			19.7	178	19.6	192	20
Zomba	L6			10.0	80	6.8	89	8

Note. Values from Melcher (1981b) and Sears and McKeever (1980) have been converted for direct comparison with the present data (including Table I), using overlapping samples as guides. T_{age} is terrestrial age in years of samples at time of measurement.

One source of the scatter in Fig. 4 is the uncertainty in the orbital parameters, Lost City, Pribram, and Innisfree apart. We think that this is particularly the case for two of the most discrepant meteorites, Vengorovo and Pesyanoe. The gas-rich character of Pesyanoe (Murty and Marti 1990) is independent evident against the extremely low perihelion determined by Simonenko (1975). Additionally, uncertainties in a few meteorite orbits as a result of geocentric velocities can account for some of the scatter. Thus, the data suggest that Appley Bridge, Peace River, and Vengorovo may have had geocentric velocities close to 13 km/sec and Kunashak may have had a velocity close to 22 km/sec. However, in most cases, uncertainties in perihelia due to geocentric velocities are relatively small (about the size of the symbols) and do not explain all the scatter in the present data.

Another important determinant of natural TL levels, as suggested by Fig. 4, is dose rate. It appears that most of the meteorites with fairly well constrained orbital parameters fall fairly close to a calculated line with a dose rate between 1 and 10 rad/year. The 10 rad/year dose rate suggested by Sutton and Crozaz (1983) seems to be too high relative to most of the data. This is probably because the 10 rad/year estimate is based on relatively *unshielded* conditions (i.e., very small meteorites). It is known that natural TL levels can vary up to a factor of three as a function of depth in a meteorite (Sears 1988). This factor,

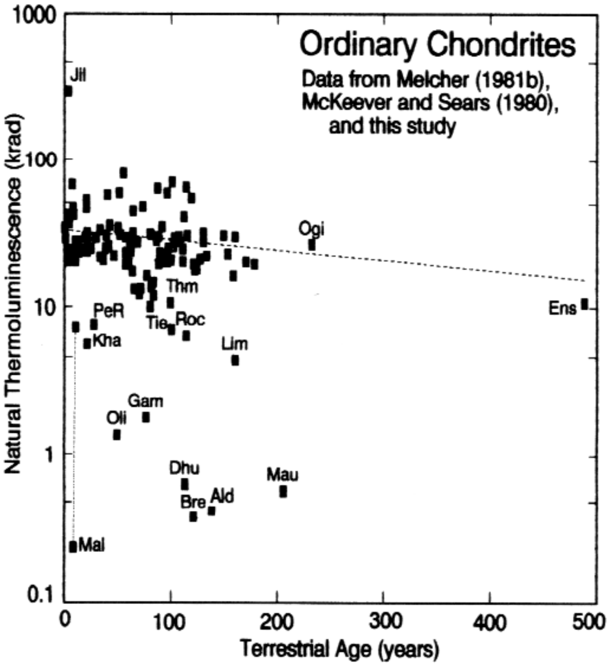

FIG. 3. Natural TL levels at 250°C in the glow curve verses terrestrial age for observed falls (Tables 1 and 3). Some samples have been measured several times during their history and hence are shown by multiple symbols. Dashed line is a nonstatistically significant least squares fit through all points with natural TL >5 krad.

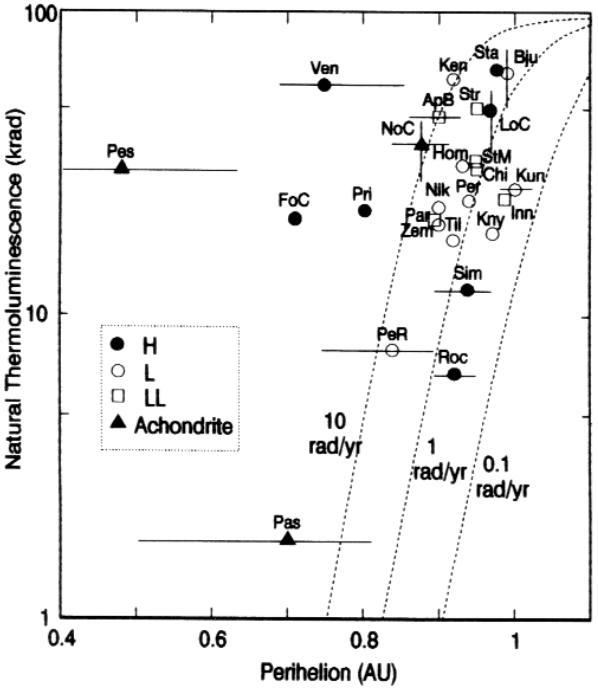

FIG. 4. Natural TL level verses calculated perihelion distance for observed falls. Unless otherwise indicated, uncertainties in perihelia as a result of assumed geocentric velocities are within the size of the symbols (see Table 2). Uncertainties for natural TL data are 1σ based on triplicate measurements of a single aliquot and are also within the size of the symbols unless otherwise indicated. Dashed lines are theoretical curves from Fig. 2b for a meteorite of average albedo and different dose rates.

however, includes a significant contribution from heating during atmospheric entry, which affects only a thin (~5 mm in thickness) rim of the meteorite. Clearly, TL studies on cores of large meteorites, analogous to those done for cosmogenic isotopes (Graf *et al.* 1990), are needed before the effects of shielding on natural TL can be evaluated quantitatively. Such studies are currently in progress. In the meantime, the current data seem to suggest that most meteorites have been significantly shielded in that their TL level is about a factor of three lower than expected (i.e., they have experienced dose rates about one-third that expected from unshielded measurements).

If we accept a dose rate of ~3 rad/year as a rough approximation for most meteorites, it is possible to identify a number of meteorites which may have experienced unusual histories. Figure 4 shows two candidates, Pribram and Forest City, both with well constrained orbits, which may have experienced dose rates greater than 10 rad/year. Their high natural TL, relative to their low perihelion orbits, suggests that either they were less shielded than most meteorites or else they failed to reach thermal equilibrium prior to earth impact. Kendleton, Appley Bridge, and perhaps Vengorovo and Norton County are also candidates for somewhat higher dose rates.

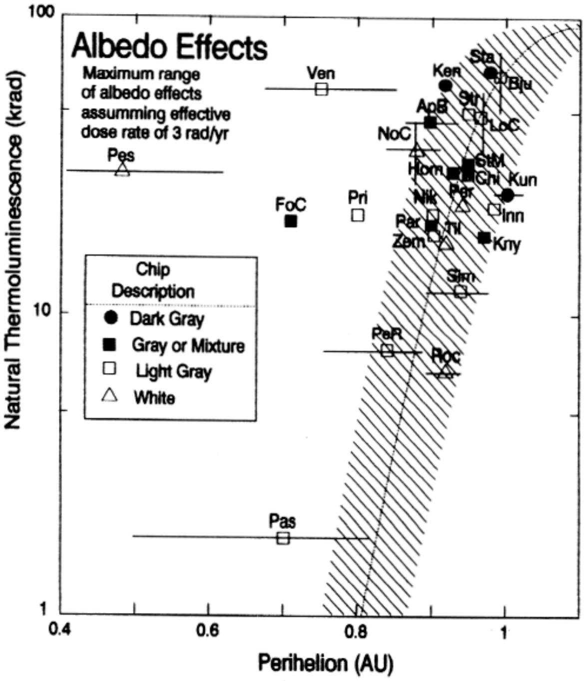

FIG. 5. Natural TL level verses calculated perihelion distance for ordinary chondrites. Symbols are coded according to relative color of the sample, as noted in our laboratory. Uncertainties are as described in caption for Fig. 4. Hatching shows range of TL expected for meteorites with albedo between 0.1 and 0.32 and an effective dose rate of 3 rad/year.

While dose rate (shielding) is undoubtedly important in determining natural TL levels, another factor, meteorite albedo, is similarly important. Unfortunately, albedos are not known for these samples but it is possible to treat this factor qualitatively. In Fig. 5 the data are coded according to relative darkness of the sample as received in our laboratory and as estimated by eye. Also shown is the calculated range of natural TL expected for a dose rate of 3 rad/year and a reasonable range of albedo (γ between 0.68 and 0.9). One would expect dark meteorites to approach the lower (right hand) curve whereas light colored meteorites should approach the upper (left hand) curve. The data scatter within the range suggested for albedo but a separation by color is poorly developed. This is not, perhaps, surprising since slight differences in dose rate will blur the albedo effect and, in any case, it is likely that most meteorites have fairly similar *surface* (as opposed to interior) albedoes in space due to reworking of their surfaces and it is this surface albedo which controls the amount of heat absorbed by the meteorite. In addition, the sample descriptions used here are not necessarily applicable to the entire meteorite. For instance, our sample of Pervomaisky is "white" whereas the meteorite as a whole is composed of dark and light colored regions (Britt and Pieters 1990). The analysis presented here does, however, identify a number of unusual meteorites. Thus, the low natural TL of Kunashak and Knyahinya, relative to their ~1 AU perihelion, may be due to their low albedo. The high natural TL of Kendleton, considering its low albedo, emphasizes the suggestion that it has experienced a higher dose rate. Innisfree has a low natural TL, considering its high relative albedo and orbit. While this may also be an effect of dose rate (shielding), we will present evidence that this may be the result of reheating (i.e., by a smaller perihelion) prior to earth impact.

Natural TL calculations suggest that ordinary chondrites with extremely low TL have experienced orbits with perihelia <0.85 AU (Fig. 2). If this is true, one would expect to see thermal draining of some of the lighter noble gases (i.e., a low ^{3}He/^{21}Ne ratio) in these meteorites as well since gas diffusion rates are analogous to TL decay rates (Goles *et al.* 1960, Melcher and Walker 1977). Figure 6 shows that this is the case for some of the meteorites with unusually low natural TL. A boundary of <15 krad is used for the lowest TL category in Fig. 6 so as to separate both candidates for low perihelia orbits *and* large terrestrial ages from the larger "normal" group. Ensisheim falls on the ordinary chondrite line in Fig. 6, despite its low natural TL, suggesting that its thermal history is much like that of most ordinary chondrites and that its low TL is a result of its longer terrestrial age. Malakal, Limerick, and Dhurmsala, however, all have ^{3}He/^{21}Ne ratios less than 4.0, as do also some of the borderline cases (natural TL >5 krad but <10 krad) such as Zomba

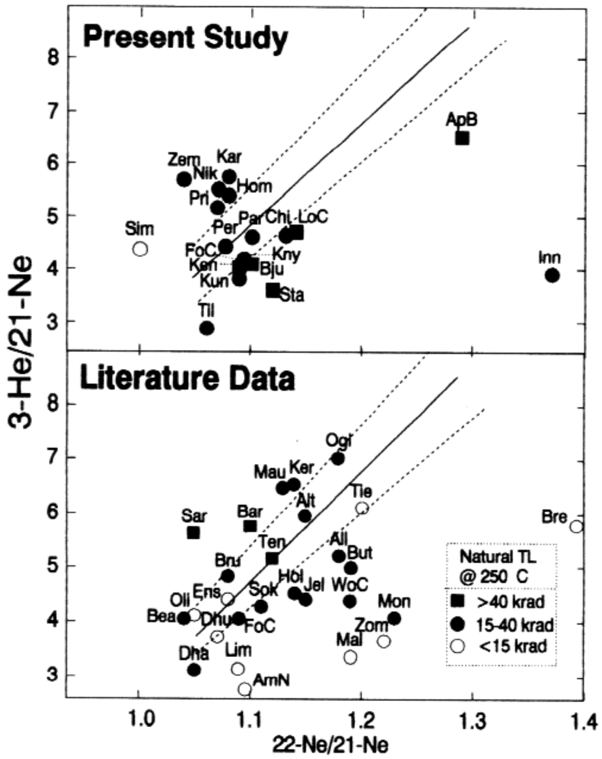

FIG. 6. ^{3}He/^{21}Ne verses ^{22}Ne/^{21}Ne for ordinary chondrites listed in Tables 1 and 3. Meteorites with natural TL at 250°C of <15 krad are shown as open symbols. With the exception of Tieschitz and Bremervorde, all the low TL meteorites have low ^{3}He/^{21}Ne ratios, which is independent evidence for reheating. Dashed lines show the best fit for non-Antarctic H-chondrites and the ±10% band determined by Nishiizumi *et al.* (1980).

and Ambapur Nagla. The only exceptions are Tieschitz and Bremevorde, which are both type 3's (3.6 and 3.9, respectively) and hence unusual in their TL properties (Sears *et al.* 1980). Along the same lines, one would also expect that meteorites which have experienced low perihelion orbits should have ^{3}He exposure ages which are lower than their ^{21}Ne exposure ages. Malakal has a (^{21}Ne–^{3}He) age difference of 2.4 Ma, while Limerick, Dhurmsala, Zomba, Ambapur Nagla, Tieschitz, and Bremevorde have age differences of 3.1, 0.7, 15.0, 7.5, 4.6, 14.4 Ma, respectively. Appendix 1 gives cosmic ray exposure ages for many of the meteorites listed in Tables I and III derived from ^{3}He, ^{21}Ne, and ^{38}Ar contents using the production rates of Eugster (1988). While there are some notable exceptions in Appendix 1 (e.g., Dhajala), most of the meteorites having natural TL >15 krad have ^{3}He exposure ages which are very close to, or even slightly exceed, their ^{21}Ne exposure ages. This relationship seems to be independent evidence for the low perihelia suggested by natural TL, though we admit the current database of helium and neon abundances for such samples is small (6 out of 12 possible, not counting the type 3's) and often based on older analyses (see Schultz and Kruse 1989, for references). We recommend that most of the samples exhibiting low TL (<10 krad) in Tables I and III should be analyzed, or reanalyzed, in the near future.

Another candidate for reheating is Innisfree, mentioned above as having a low natural TL relative to its measured orbit and relative albedo. Innisfree has one of the largest cosmic ray exposure ages of the meteorites of the present study (~35 Ma), and is similar in natural TL level to Knyahinya and Nikolskoe (Fig. 5). This would suggest that it had the opportunity to evolve to a low perihelion orbit if the CRE age is not caused by exposure in the asteroid belt. The low ^{3}He/^{22}Ne ratio of Innisfree relative to the chondrite trend (Fig. 6), which is also shown by its large (^{3}He–^{22}Ne) cosmic age difference of −50 Ma, also suggests a reheating event. If this is the case, the intermediate natural TL level of Innisfree would suggest that the event occurred about 10^{4}–10^{5} years ago so that TL levels have had time to build up after having been at least partly drained. Monroe may also have been reheated (−10 Ma age difference), but, if so, it has had sufficient time in an orbit with perihelion >0.8 AU to return to a fairly normal natural TL level.

If it is assumed that the decay calculations summarized in Fig. 2 are at least roughly correct and that meteorites with very low TL levels may have been in low perihelia orbits, then the number of such meteorites should give some indication to the proportion of meteoroid bodies in such orbits. Using a conservative boundary of 10 krad (i.e., just below the level which can reasonably be produced by long terrestrial ages), the data presented in this paper suggest that only 12% (11 out of 89, again not counting Tieschitz and Bremevorde) of ordinary chondrites may have experienced recent orbits with perihelia <0.85 AU. This number is actually an overestimate, since, as explained above, some of these meteorites might have relatively low albedos and thus had their natural TL drained to these levels at higher perihelia (Fig. 2c). Only 7% (6 out of 89) of the ordinary chondrites have natural TL levels < 5 krad and hence are very strong candidates for recent orbits with small perihelia. This low proportion is in accord with the observed proportions (Simonenko 1975), with orbital data on fireballs of chondritic affinity (Wetherill and ReVelle 1981), and with current calculations of asteroid orbital evolution, which suggest that only a very few meteoroids survive long enough to evolve to low perihelia (Wetherill 1985). This is at least partly because a significant proportion of the chondritic meteoroids that do survive long enough to evolve to low perihelia orbits are selectively destroyed during atmospheric passage because of their higher geocentric velocities (ReVelle 1979, Halliday and Griffin 1982, Bronshten 1983).

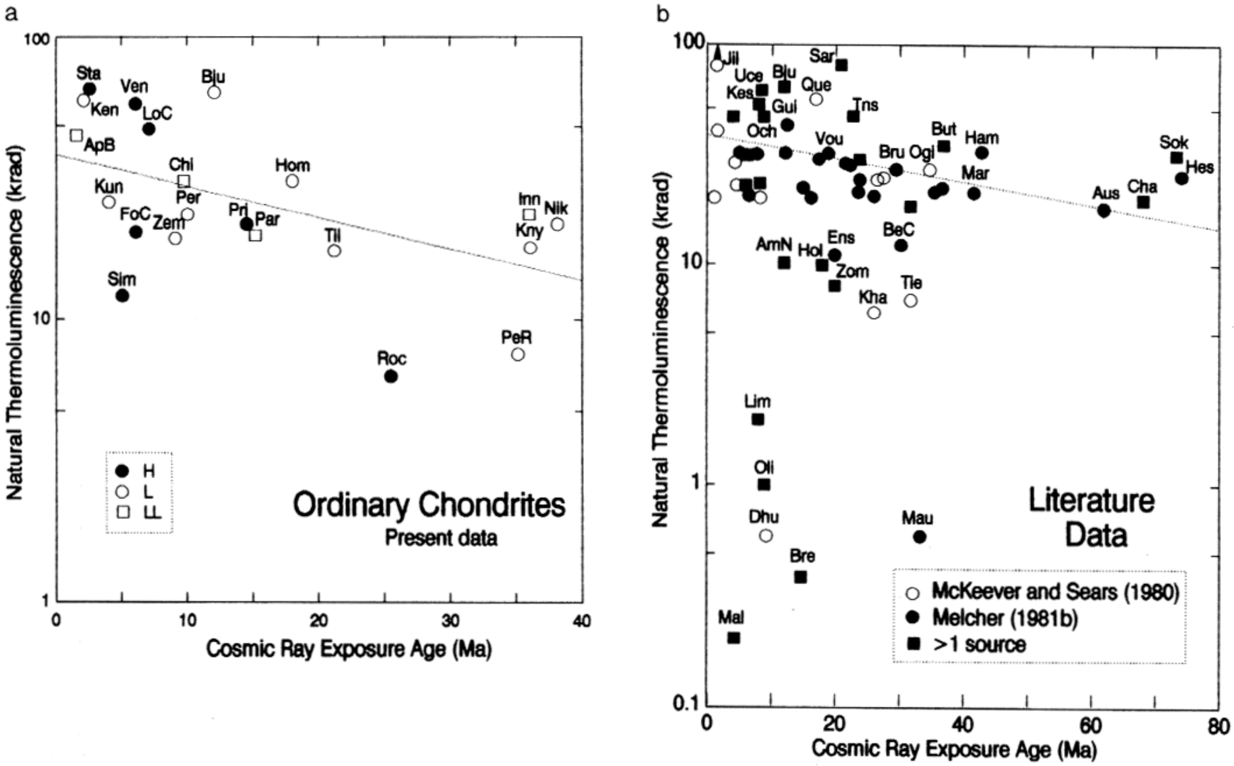

FIG. 7. (a) Natural TL levels verses calculated cosmic ray exposure (CRE) age for ordinary chondrites with known orbital parameters. Older meteorites have a smaller range of natural TL. Dotted line is a regression line through all the data. This regression line is not statistically significant because of the wide range of values at lower CRE ages. (b) Natural TL level verses calculated CRE age for ordinary chondrites from Table 3. Symbols are coded for the original source of the TL data. Dotted line is from Fig. 7a.

Natural TL and Cosmic Ray Exposure Age: Evidence of Evolution of Orbits

The amount of time spent in space is not usually considered a major factor in natural TL studies of non-Antarctic falls. In theory, after a short (~10^5 years) period of TL buildup after initial exposure to cosmic rays, natural TL in space should be a state of "equilibrium" (Fig. 1). Thus, one would expect there to be no relationship between natural TL and other exposure-dependent data, such as cosmic ray exposure age, except for meteorites with exposure ages <0.1 Ma (McKeever and Sears, 1980). However, contrary to these exceptions, the present data show a relationship between natural TL and cosmic ray exposure age. We calculated CRE ages using the method of Eugster (1988), which makes shielding corrections based on the ^{22}Ne/^{21}Ne ratio, and using the noble gas data of Schultz and Kruse (1989) (see Appendix 1). The results are shown in Fig. 7a. The natural TL of meteorites with exposure ages <20 Ma ranges between 10 and 70 krad. The natural TL of six meteorites with exposure ages >20 Ma, however, appears to be more constrained, ranging only between 10 and 30 krad. This relationship seems to also hold for the meteorites listed in Table II (Fig. 7b), though the spread in meteorites is not nearly as great in the Melcher (1981b) data, probably for the reasons explained above. There are a small number of exceptions to the general relationship. Butsura and Soko Banja are somewhat higher than would be expected (35 and 59 krad, respectively). There are also six meteorites with extremely low natural TL (≲5 krad), including Malakal, Limerick, and Olivenza.

The distribution of data in Fig. 7 can be explained in terms of orbital evolution. Meteorites with short cosmic ray exposure ages are constrained to orbits with perihelia near 1 AU, but evolution of their orbits eventually produces smaller perihelia (Wetherill 1985, 1988). Thus, one would expect older meteorites to have had smaller perihelia than younger meteorites and thus have lower levels of natural TL. Younger meteorites, however, should show a broad range of natural TL as a result of small differences in perihelia between 0.9 and 1.0 AU and differences in shielding an albedo. Implicit in this argument is the assumption that cosmic ray exposure ages are a good indicator of the time a meteoroid has spent evolving to an Earth-crossing orbit. It is, of course, possible that at least some of the meteorites with large CRE ages are "predosed" in the asteroid belt, being exposed to cosmic rays before beginning their orbital evolution (Wetherill 1980). This may be the origin of some of the high natural TL exceptions such as Soko Banja and Butsura. However, this cannot explain the low levels of natural TL (and hence high draining temperatures) of the majority of the older meteorites.

Of the three photographed falls, two have been studied in some detail in terms of their orbital evolution. Calculations have been completed for Lost City (Lowrey 1971, Williams 1975) and Innisfree (Galibina and Terent'eva 1987), although the results from these calculations are limited by uncertainties in the initial parameters which effectively prevent extension to very long time spans. In general, these calculations suggest that, while the various orbital parameters oscillate in both long- and short-term time frames, the orbits of both meteorites were "stable" in the sense that their perihelia (and other parameters) did not vary erratically since evolving to Earth-approaching and Earth-crossing orbits. It appears that Lost City impacted the Earth while still in an orbital series with perihelia generally ≥ 1 AU (Williams 1975) while Innisfree may have recently (within 10^5 years) been evolving from slightly less than 0.9 AU to its final perihelion ~ 1 AU (Galibina and Terent'eva 1987). These calculations are generally supported by the TL data, with the TL level of Lost City being relatively high and incompatible with a recent perihelion value significantly less than 1 AU and the TL level for Innisfree being very low, suggesting a recent perihelion of ~ 0.9 AU. We suggest that orbital evolution calculations for Pribram should show it to have a similar recent history to Innisfree, considering the similarity of their TL levels.

This raises the question of how quickly TL levels can adjust to new perihelia values. If, for example, a meteoroid's perihelion changed rapidly, as orbital calculations suggest is the case for certain existing Earth-crossing asteroids (Hahn and Lagerkvist 1988), would this be detectable in the TL levels of the final meteorite? The answer would seem that TL levels *should* reflect the smallest perihelion seen by the meteoroid during its recent evolution, regardless of how rapidly or irregular the evolution. Our calculations of thermal diffusion in a typical meteoroid-sized body, using the equations of Carslaw and Jaeger (1959), suggest that such small bodies thermally reequilibrate over a small portion of a single orbit after a perihelion change and TL will obtain a (lower) equilibrium state on the time scale of days or less. The theoretical curves of Fig. 2 are thus applicable even in cases where perihelion evolution is not a smooth function of time. In this respect, TL should be more sensitive to erratic orbital evolution than noble gas contents, which are more thermally stable except at very small perihelia orbits (as shown by diffusional calculations: Goles *et al.* 1960, Bogard and Hirsh 1980). It should be noted, however, that if a meteoroid evolves from a small to a larger perihelion orbit, as orbital calculations suggest does occur in at least some cases (Hahn and Lagerkvist 1988, Galibina and Terent'eva 1987), the TL level will gradually increase to reflect the new, cooler environment over a period of $\sim 10^5$ years. Thus a small perihelion (≤ 0.9 AU) incursion will only be detectable by TL if Earth impact occurs $<10^5$ years afterward (e.g., Innisfree).

CONCLUSIONS

(1) Calculations of the equilibrium natural TL level in ordinary chondrites suggest that natural TL is extremely sensitive to perihelia. In general, a meteorite with a natural TL level $>$ 30 krad cannot have had a perihelion of less than 0.9 AU within the last 10^5 years, and perihelia <0.8 AU should drain the natural TL to <5 krad. However, the calculations also suggest that natural TL for meteorites with perihelia between 0.9 and 1.0 AU will show a large spread in natural TL due to slight differences in perihelia, dose rate (shielding), and albedo.

(2) Natural TL data for 26 observed falls (including 23 ordinary chondrites), for which orbital elements have been determined, are consistent with the results of the calculations. Much of the scatter in the data is probably the result of differing albedo, based on the assumption that meteorite chip color (relative albedo) is analogous to meteoroid albedo in space, and the result of slight differences in the degree of shielding. There are, however, a number of meteorites (e.g., Innisfree) which have unusual TL levels even given these complications.

(3) There is a relationship between natural TL levels and cosmic ray exposure ages for the present samples. Meteorites with a CRE age <20 Ma show natural TL values between 10 and 70 krad (Fig. 7), while meteorites with a CRE age >20 Ma have a more restricted range (10–30 krad). The data of McKeever and Sears (1980) and Melcher (1981b), after conversion to the units used here, are consistent with this trend. These additional data extend the natural TL range for meteorites with low CRE ages to between 10 and >90 krad. The relationship between natural TL and CRE age can be understood in terms of orbital evolution. Meteorites with CRE ages <20 Ma are generally constrained to orbits with perihelia very close to 1.0 AU and hence their natural TL should be highly variable as a result of slight albedo and orbital differences, while meteorites with CRE ages >20 Ma evolve to orbits with small perihelia and hence low natural TL.

(4) Only 12% (11 of 89) of the ordinary chondrites have very low natural TL (<10 krad) and, with the exception of several type 3 ordinary chondrites, these meteorites also have low ^{3}He/^{21}Ne ratios. They also have low ^{3}He exposure ages, relative to ^{21}Ne ages, even after corrections for shielding. From these data, we suggest that <15% of the ordinary chondrites experienced orbits with perihelia less than 0.85 AU. If we take a more conservative view (natural TL < 5 krad), we find that ~7% of ordinary chondrites have been in recent (within 10^5 years) orbits with perihelia <0.8 AU.

APPENDIX 1

Cosmic Ray Exposure (CRE) Ages of Meteorites (in Ma)[a]

Meteorite	CRE based on			Estimated CRE[b]
	^{3}He	^{21}Ne	^{38}Ar	
Alfianello	28.2	26.3	27.4	27
Allegan	6.6	8.3	9.6	8
Alta'ameem	23.2	22.2	23.1	23
Ambapur Nagla	4.8	12.3	18.3	12
Appley Bridge	1.2	1.5	3.6	2
Ausson	62.7	59.6	64.4	62
Barwell	3.8	3.1	8.7	4
Beaver Creek	33.5	29.5		30
Bjurbole	11.1	12.9	23.9	12
Bremevorde	15.0	29.4	53.6	15
Bruderheim	31.2	27.6	33.9	30
Butsura	36.2	49.7	36.6	37
Charsonville	76.9	62.1	64.9	67
Chicora	9.1	10.3		10
Cynthiana	2.6	5.5	27.3	4
Dandapur	23.9	25.2	18.8	24
Dhajala	4.5	5.5	48.6	5
Dhurmsala	8.6	9.3	13.0	9
Djati-Pengilon	33.5	20.4		26
Drake Creek	40.8	32.7		36
Elenovka	24.3	19.5	23.0	22
Ensisheim	19.1	20.1	20.3	19
Farmington	0.7	1.6		1
Farmville	6.5	7.5	10.8	8
Fisher	21.4	17.4	17.8	19
Forest City	5.7	6.6	10.7	6
Girgenti	26.2	19.4		23
Guarena	6.0	4.4	71.0	5
Guibga	11.5	12.3	17.2	12
Hamlet	44.3	41.9	73.8	43
Harleton	43.7	39.6	42.1	42
Hessle	82.7	133.1	64.5	74
Holbrook	16.8	20.4	20.0	18
Homestead	18.6	14.6	17.8	18
Innisfree	35.9	88.5	96.1	36
Jelica	30.1	39.1	35.1	32
Jilin (Kirin)	0.8	1.9	5.3	1
Kandahar	25.0	24.5	26.8	25
Kendleton	2.0	2.3	21.2	2
Kervouve	4.8	4.2	8.0	4
Kesen	7.9	7.2	13.1	7
Knyahinya	35.5	38.4	36.0	36
Kunashak	3.3	3.8	5.7	4
Limerick	6.3	9.4	9.3	8
Lixna	7.5	8.0	12.3	7
Lost City	6.4	7.8	9.0	7
Malakal	2.9	5.3	7.9	4
Marion	44.7	35.6	44.1	41
Mauerkirchen	37.0	30.2	31.0	33
Maziba	29.9	27.1	28.0	28
Monroe	11.8	21.9	29.5	12
Nikolskoe	38.2	28.0	38.6	38
Ochansk	7.7	8.1	13.1	8
Ogi	34.3	32.3	35.0	35
Olivenza	8.6	7.5	8.9	9
Paragould	14.8	15.6	19.6	15
Parnallee	5.1	10.0	71.7	7
Peace River		37.0	32.6	35
Pervomaisky	10.7	10.0	12.8	10
Pribram	15.1	16.5	15.5	16
Quenggouk	16.1	18.4	16.1	17
Richardton	19.6	24.5	26.2	23
Rochester		25.2	25.7	25
Saratov	20.1	12.9	22.6	21
Simmern	6.2	3.8		5
Soko Banja	69.7	79.3	93.3	73
Stalldalen	2.3	3.3	10.6	3
Tennasilm	23.1	22.8	42.9	23
Tieschitz	30.3	34.9	103.5	32
Tilden	20.3	26.8		21
Ucera	6.3	16.8	10.6	8
Vengorovo	6.7	25.0	5.6	6
Vouille	22.7	17.3	18.0	19
Wold Cottage	15.8	23.3	15.3	16
Zemaitkiemis	9.4	5.6		9
Zomba	16.0	31.0	23.7	20

[a] Isotopic data from Schultz and Kruse (1989) and production rate equations from Eugster (1988).

[b] Best estimate of cosmic ray exposure age, used in this study.

ACKNOWLEDGMENTS

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