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The thermal and radiation exposure history of lunar meteorites

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Abstract–We have measured the natural and induced thermoluminescence (TL) of seven lunar meteorites in order to examine their crystallization, irradiation, and recent thermal histories. Lunar meteorites have induced TL properties similar to Apollo samples of the same provenance (highland or mare), indicating similar crystallization and metamorphic histories. MacAlpine Hills 88104/5 has experienced the greatest degree of impact/regolith processing among the highland-dominated meteorites. The basaltic breccia QUE 94281 is dominated by mare component but may also contain a significant highland component. For the mare-dominated meteorites, EET 87521 may have a significant highland impact-melt component, while Asuka 881757 and Y-793169 have been heavily shocked. The thermal history of Y-793169 included slow cooling, either during impact processing or during its initial crystallization. Our natural TL data indicate that most lunar meteorites have apparently been irradiated in space a few thousand years, with most <15,000 a. Elephant Moraine 87521 has the lowest irradiation exposure time, being <1,000 a. Either the natural TL of ALHA81005, Asuka 881757 and Y-82192 was only partially reset by lunar ejection or these meteorites were in small perihelia orbits (≤0.7 AU).

INTRODUCTION

The lunar meteorites offer new insights into the origin and evolution of the Moon, providing about a dozen new study localities possibly including the lunar farside (Warren and Kallemeyn, 1991). In this paper, we examine the thermal and irradiation history of lunar meteorites in comparison to Apollo samples using thermoluminescence.

Thermoluminescence is energy emitted as photons from a sample during heating. This energy is typically deposited by ionizing radiation. Natural thermoluminescence (natural TL) reflects recent thermal history and irradiation conditions (Hoyt *et al.*, 1971; Durrani *et al.*, 1977; Sears *et al.*, 1991a). In the case of lunar meteorites, natural TL is related primarily to preimpact depth in the regolith, duration of cosmic-ray irradiation, and temperatures experienced in space (Sutton, 1986; Sutton and Crozaz, 1983; Sears *et al.*, 1991a). Sutton (1986) and Sutton and Crozaz (1983) have examined the natural TL of ALHA81005 and Y-82192, suggesting that Y-82192 was in an orbit with a small perihelia and ALHA81005 was in space for only a few thousand years. The natural TL of lunar samples and meteorites is also affected by a process known as anomalous fading, which results in TL being lowered at rates much faster than predicted from thermal equilibria alone (Sears *et al.*, 1991a).

Induced thermoluminescence is the TL produced in a sample after removing the natural TL by momentary heating to ~500 °C followed by laboratory irradiation. Unlike natural TL, features in the induced TL glow curve directly reflect bulk properties of TL phosphors. The induced thermoluminescence intensity at peak emission (induced TL sensitivity) reflects the composition, structure and abundance of the phosphors, primarily feldspar (Sippel and Spencer, 1971; Geake *et al.*, 1977; Symes *et al.*, 1995). The peak temperature of the induced TL of feldspar is related to mineral structure, with ordered feldspar having significantly lower peak temperatures than disordered feldspar (Guimon *et al.*, 1985; Hartmetz and Sears, 1987). We have previously used induced TL properties to examine the metamorphic and brecciation histories of most meteorite classes and a wide variety of lunar samples (*e.g.*, Haq *et al.*, 1989; Sears *et al.*, 1991b; Batchelor and Sears, 1991; Guimon *et al.*, 1995).

In the present study, we summarize the natural and induced properties of seven lunar meteorites. We interpret the induced TL data in the context of crystallization and impact processing, and we interpret natural TL data in terms of recent irradiation and low-temperature thermal history.

METHODS

The samples, their sources, and simple descriptions are given in Table 1. Our samples were chips of ~300 mg. We crushed ~150 mg of each sample to 100 mesh using an agate mortar and placed three 4 mg aliquots in shallow Cu pans. Their natural TL was measured by heating in a N atmosphere to 500 °C at 7.5 °C/s using a Daybreak Nuclear and Medical Systems TL apparatus fitted with blue bandpass and IR filters (Corning 7-59 and 4-69). The induced TL was measured by the same procedure 5 min after exposure to a ~2 krad beta dose from a ^{90}Sr source. The Dhajala meteorite was used as a normalization standard and long-term check on the apparatus. We report TL sensitivity normalized to the Dhajala standard and peak temperatures. For natural TL data, we report equivalent dose at 250 °C and 400 °C in the glow curve (Sears and Hasan, 1986).

The anomalous fading characteristics of the highland meteorite Y-82192, the mare basalt EET 87521, and QUE 94281 were determined using a 4 mg sample which had been drained, irradiated, and stored in opaque containers in a dessicator in a temperature-controlled room for up to several weeks. The fading properties of ALHA76008 (H6) and highland soil 61501 were determined in the same way.

RESULTS

Our data are summarized in Table 1. Analytical uncertainties on both natural and induced TL data are quite small (generally <5%) despite the generally low levels, which in the case of EET 87521 and Asuka 881757 approach detection limits. The reproducibility of the data for the ALHA81005 and EET 87521 splits is well within analytical uncertainties. The data for MAC 88104 and MAC 88105 differ by more than the experimental uncertainties, although they are paired. As discussed below, these differences reflect real heterogeneities in the meteorite. We did not have duplicate chips of the remaining meteorites and cannot comment on possible heterogenities, but our conclusions are generally consistent with those based

TABLE 1. Induced and natural thermoluminescence properties of lunar meteorites.

Meteorite*	Mass (mg)	Induced TL Sensitivity (Dhajala = 1)	Peak Temp.(°C)	Natural TL (krad) at 250 °C	at 400 °C	Terrestrial Age (ka)‡	Description§
ALHA81005,83	62	0.22 ± 0.02	167 ± 6	0.10 ± 0.02	5 ± 1	15 ± 6	Anorthositic regolith breccia–Highland
ALHA81005,84	56	0.24 ± 0.04	169 ± 6	0.11 ± 0.02	9 ± 1		
A881757,70	403	0.003 ± 0.002	195 ± 5	~0	~20	25 ± 25	Unbrecciated gabbro–Mare
EET 87521,36	25	0.038 ± 0.003	218 ± 4	0.11 ± 0.02	~0.5	20 ± 20	Basaltic breccia–Mare
EET 87521,40	51	0.040 ± 0.003	210 ± 3	0.13 ± 0.01	0.6 ± 0.1		
MAC 88104,2†	326	0.137 ± 0.004	197 ± 4	2.5 ± 0.3	7.1 ± 0.2	230 ± 70	Anorthositic regolith breccia–Highland
MAC 88105,4†	270	0.128 ± 0.009	172 ± 4	1.1 ± 0.1	11 ± 2	230 ± 70	
QUE 94281,13	102	0.056 ± 0.004	171 ± 2	0.21 ± 0.01	1.0 ± 0.1		Basalt-rich breccia
Y793169,56	21	0.0050 ± 0.0003	171 ± 6	1.4 ± 0.2	4 ± 2	25 ± 25	Unbrecciated diabase–Mare
Y82192,64	214	0.27 ± 0.02	164 ± 3	3.6 ± 0.9	20 ± 7	80 ± 20	Anorthositic fragmental breccia–Highland

Uncertainties are the standard deviations shown by replicate measurements of a single aliquot.
*Asuka and Yamato samples were obtained from K. Yanai (Nat. Institute Polar Research, Japan). All others from the Meteorite Working Group of NASA, Johnson Space Center. Abbreviations: ALHA = Allan Hills; A = Asuka; EET = Elephant Moraine; MAC = MacAlpine Hills; QUE = Queen Alexandra Range; Y = Yamato.
†MAC 88104 and MAC 88105 are probably paired (Lindstrom, 1989).
‡From Nishiizumi (per. comm.).
§From Yanai and Kojima (1991) and Mason (1995).

on petrographic data, suggesting that heterogenity is not a major problem.

We compare the induced TL data for lunar meteorites with data for Apollo samples in Fig. 1a. The Apollo data from Batchelor (1992) are shown as fields. The lunar meteorites have a smaller range of induced TL peak temperature than Apollo lunar samples, with no lunar meteorites having peak temperatures <160 °C. Also, the lunar meteorites have TL sensitivities comparable to Apollo samples. The lunar highland meteorites have TL sensitivity levels similar to those of Apollo highland samples while the lunar mare meteorites have sensitivities similar to the Apollo mare samples.

The natural TL levels of lunar meteorites are best compared to basaltic meteorites rather than Apollo samples, since the Apollo samples were not irradiated in 4π geometry and therefore experienced a lower radiation dose rate. The basaltic meteorites have luminescence properties very similar to lunar meteorites, including the presence of anomalous fading. The lunar meteorites have low TL levels compared to most Antarctic basaltic meteorites at 250 and 400 °C in the glow curve (Fig. 2a,b). Both lunar and basaltic meteorites have TL levels lower than those of most ordinary chondrites by a factor of ten or more.

The results of the anomalous fading experiments are shown in Fig. 3. The intensity of TL at three temperatures in the glow curve are normalized to the TL level at the same glow curve temperatures measured five minutes after irradiation. The two lunar meteorites and the highland soil sample exhibit anomalous fading. They also have the same fading rates, within the experimental uncertainties, as is evidenced by the variation between replicates. The ordinary chondrite does not display anomalous fading, the loss of signal occurring at the lowest glow curve temperatures and the longest time periods being due to normal thermal fading, in accord with models of TL thermal decay (McKeever, 1980). The rates of fading for the lunar samples are similar to those noted for ALHA81005 (Sutton and Crozaz, 1983) and terrestrial feldspars (Wintle, 1973).

DISCUSSION

Induced TL Properties of Lunar Meteorites

The induced TL of most lunar samples can be interpreted in terms of mixtures of pristine highland material, highland impact melt rocks, and mare material (Symes *et al.*, 1995; Fig. 1b) and in
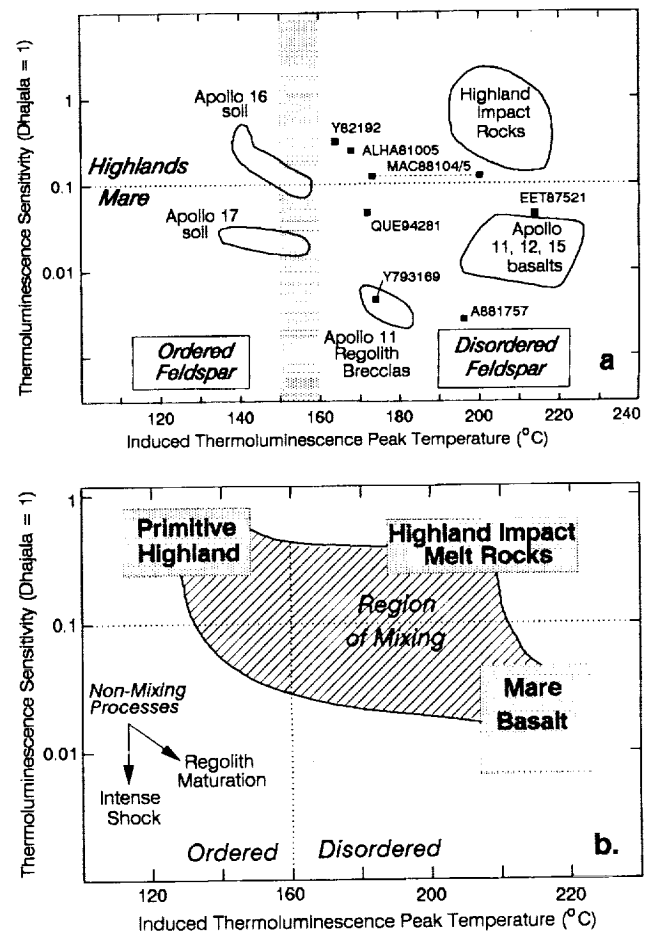

FIG. 1. (a) Induced TL sensitivity *vs.* peak temperature for lunar meteorites and Apollo samples. Lunar meteorites generally resemble their closest petrographic analogs in the Apollo collection, highland-dominated samples having high TL sensitivity and mare-dominated samples having low TL sensitivity and high TL peak temperatures. Fields for Apollo samples based on data of Batchelor (1992). (b) Schematic diagram of the luminescent "components" in lunar samples and possible mixing curves. Thermoluminescence sensitivity reflects the abundance and crystallinity of feldspar while TL peak temperature reflect its degree of structural order. Arrows indicate the effects of processes other than mixing in this diagram.
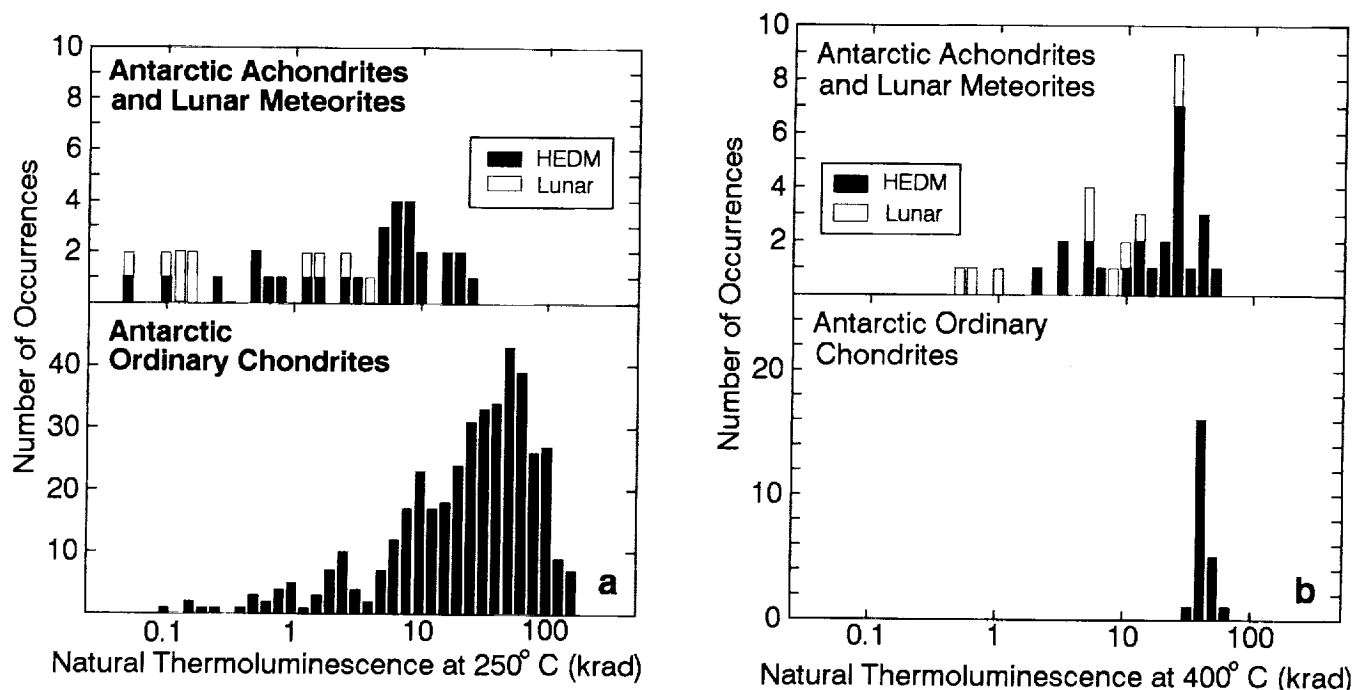
FIG. 2. Natural TL levels of lunar meteorites, basaltic achondrites (HEDM: howardites, eucrites, diogenites, and mesosiderites), and ordinary chondrites at (a) 250 °C and (b) 400 °C in the glow curve. Lunar meteorites and basaltic meteorites generally have lower natural TL levels than ordinary chondrites, and lunar meteorites have TL levels in the low TL tail of the distribution.

terms of thermal processes. Intense shock lowers TL sensitivity considerably by fusing the feldspar while regolith processing results in slightly lower TL sensitivity and moderate increases in induced TL peak temperature.

Mare Basalts–Elephant Moraine 87521 has induced TL peak temperatures very similar to those of Apollo mare samples, especially Apollo 12 and 15 basalts (Fig. 1a). It is possible that its slightly greater TL sensitivity compared to most Apollo mare samples reflects the presence of a highland component. At least one small highland impact melt clast has been observed in EET 87521 (Warren and Kallemeyn, 1989). Asuka 881757 also has a TL peak temperature similar to those of Apollo mare basalts, but a lower TL sensitivity, perhaps suggesting that this meteorite was heavily shocked and then rapidly cooled. Consistent with this, the feldspar is maskelynized in Asuka 881757 (Yanai and Kojima, 1991), and only traces of crystalline feldspar would account for the TL sensitivity. The impact that produced the low TL sensitivity might have been the same event that ejected the meteorite from the Moon. The low induced TL sensitivity of Y-793169 could also be interpreted in terms of shock, although petrographically it is an unbrecciated diabase (Yanai and Kojima, 1991). Distinctive plagioclase textures were thought by these authors to indicate recrystallization after maskelynization, but this process must have been minimal or the TL sensitivity would be much higher. Takeda et al. (1993) have described this meteorite as partially maskelynitzed. The TL peak temperature for Y-793169 indicates partially ordered feldspar and thus slower cooling than experienced by the mare basalts. Therefore, either Y-793169 experienced slower cooling in a lava flow than most mare rocks, or it experienced at least a two stage excavation history, involving a large shock event that resulted in immediate burial and slow cooling followed by a large impact event that ejected it from the surface.

Queen Alexandra Range 94281–This meteorite has been described as a basalt-rich breccia, with a composition intermediate to EET 87521 and Calcalong Creek and very similar to Y-793274 (Mason, 1995). The induced TL properties of QUE 94281 are different from other lunar meteorites, this meteorite having a fairly low induced TL peak temperature but a moderate TL sensitivity (Fig. 1a). These data may indicate that this meteorite has a significant "pristine" highland component (Fig. 1b). Alternatively, this meteorite may have experienced a significant heating event, with peak temperatures of ~800 °C (Symes et al., 1995) followed by slow cooling, which is analogous to the inferred history of Y-793169. Unlike Y-793169, however, the feldspar of QUE 94281 was not maskelynized to a significant degree, as evidenced by the relatively high TL sensitivity of this meteorite. In support of the TL data reflecting a highland component, petrographic and bulk chemical composition seem to indicate that ~30% of this meteorite may be derived from highland components (Jolliff et al., 1996; Kring et al., 1996; Lindstrom et al., 1996).

Highland Rocks–The highland lunar meteorites have homogeneous induced TL properties that are consistent with their being uniform mixtures of highland impact melt rock and primitive highland material (TL properties defined from lunar soil and pristine rocks by Benoit et al., 1994,). These meteorites have a significant amount of impact glass and heavily shocked fragments (Delaney, 1990; Yanai and Kojima, 1991). The TL data suggest that MAC 88104/5 is the most mature highland lunar meteorite, having a low TL sensitivity and one split with high induced TL peak temperature. The latter split is probably dominated by the recrystallized melt breccia clasts that are common in this rock (Koeberl et al., 1991). MacAlpine Hills 88105 is thought to be a less mature regolith breccia than ALHA81005 and QUE 93069 (Warren et al., 1983; Koeberl et al., 1991; Warren and Kallemeyn, 1995), but induced TL

Fraction Thermoluminescence Remaining

○	250 C
●	300 C
▲	400 C

ALHA76008
- Ordinary Chondrite -

Y82192
- Highland meteorite -

EET87521
- Mare meteorite -

QUE94281
- Lunar Meteorite -

Lunar Highland
Soil 61601
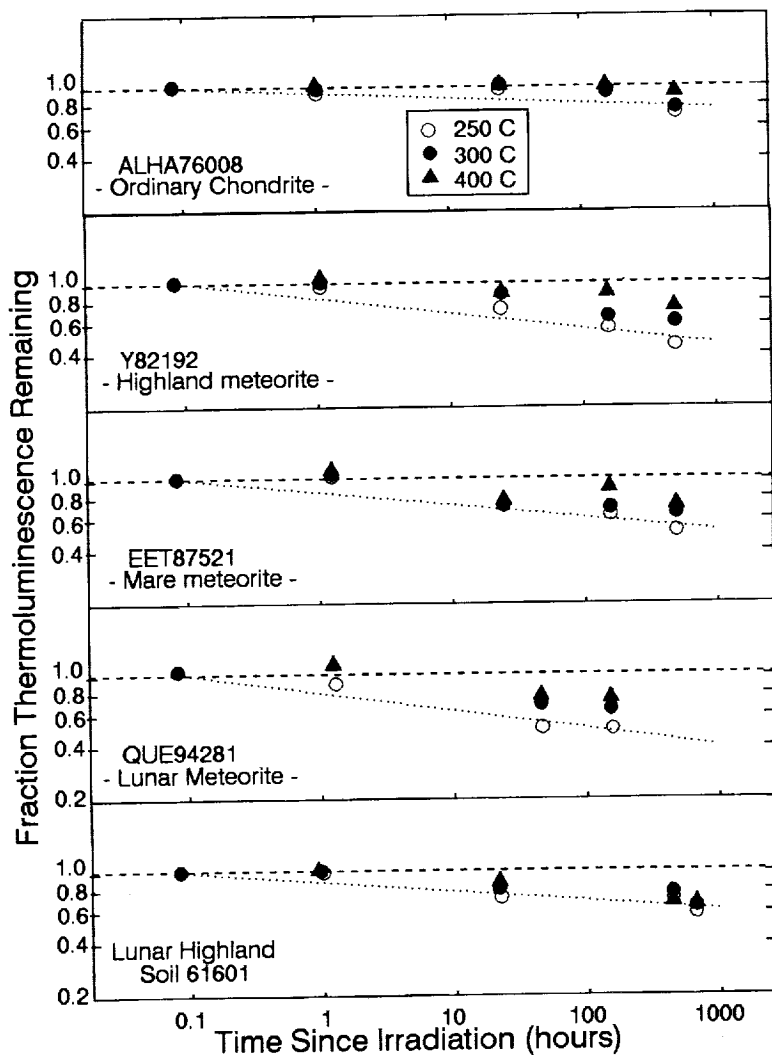
Time Since Irradiation (hours)

FIG. 3. Thermoluminescence remaining as a function of storage time for EET 87521, Y-82192, QUE 94281, the equilibrated ordinary chondrite ALHA76008, and highland-dominated lunar soil 61501 at 250, 300, and 400 °C in the glow curve. Regression lines for the 250 °C data are shown as dotted lines. The loss of TL throughout the glow curve over laboratory timescales is indicative of similar degrees of anomalous fading for all samples except the ordinary chondrite ALHA76008. Ordinary chondrites do not display anomalous fading but only slow thermal fading at the longest duration.

reflects the lithification event(s) as well as the regolith history of the bulk sample. Alternatively, the relatively low TL sensitivity of MAC 88104/5 could reflect the presence of mare material, but this is unlikely as mare components are in very low abundance (Delaney, 1990; Koeberl *et al.*, 1991).

Natural TL.

Natural TL levels decrease by time- and temperature-dependent decay, and, in some cases, anomalous fading (Wintle, 1973; Sears *et al.*, 1991a), while the only mechanism for increasing natural TL levels is exposure to ionizing radiation. Equilibrium natural TL levels are reached after $\sim 10^5$ a in typical meteorites in the inner solar system (*e.g.*, Fig. 4). The low natural TL levels of lunar meteorites relative to the basaltic meteorites (Fig. 2a,b) can therefore reflect heating in space, long terrestrial ages, differences in anomalous fading, or short irradiation times. Most Antarctic achondrites appear to have terrestrial ages in excess of 50,000 a (Nishii-

zumi *et al.*, 1989), but of the present samples, only MAC 88104/5 has a terrestrial age significantly greater than this (Table 1). MacAlpine Hills 88104/5 also has higher natural TL levels than the other lunar meteorites. The anomalous fading characteristics of ALHA81005 (Sutton and Crozaz, 1983), MAC 88104/5 (Sears *et al.*, 1991a) and the basaltic meteorites are very similar to those of Y-2192, EET 87521, and QUE 94281 and highland-dominated lunar soil (Fig. 3), in contrast to the equilibrated ordinary chondrites like ALHA76008, that exhibit no anomalous fading. The experimental uncertainties on these data make extrapolation of anomalous fading to thousands of years difficult, but the relative rates of fading will not change. Thus, while anomalous fading is the likely cause of the low TL of basaltic achondrites compared to ordinary chondrites, neither anomalous fading nor terrestrial age can explain the low natural TL level of lunar meteorites compared to the basaltic meteorites.

The low natural TL values for lunar meteorites might reflect small perihelia orbits or short transit times. We have determined the TL parameters for the TL traps in ALHA81005 using a peak fitting approach (McKeever, 1980), and we have experimentally determined the dose-response for this meteorite (see Appendix). Allan Hills A81005 was used for this determination because of its relatively high TL sensitivity. However, limited measurements on Y-82192, EET 87521, and QUE 94281 indicate that these meteorites exhibit similar dose-reponse. From these data, we calculate the curves for build-up in natural TL at 250 and 400 °C in the glow curve allowing for anomalous fading (Fig. 4). These curves assume a "storage temperature" of 273 K and a radiation dose of 5 rad/a, the latter estimate appropriate for irradiation of a meter-sized body by galactic cosmic rays (Letaw *et al.*, 1988). Other temperatures and dose rates yield different final equilibrium TL level and time required to reach this level but do not radically change our results. From these curves, we determine the duration of irradiation for each meteorite from the 400 °C curve (Table 2). Assuming the meteorites were not exposed to radiation prior to lunar ejection, or that their TL levels were reset by the ejection events, these estimates equal transit times from the Moon to the Earth.

The calculated irradiation durations range from <1000 a to about >100,000 a (Table 2), but with most estimates <15,000 a. The natural TL of Asuka 881757 and Y-82192 could be at saturation, but it is also possible that the TL levels of these meteorites were not completely reset by their ejection events. To examine this issue further, we use the more thermally-sensitive 250 °C glow curve data. For EET 87521, MAC 88104/5, QUE 94281, and Y-793169, the irradiation times estimated from 250 °C in the glow curve agree well with those calculated from the 400 °C data, but for ALHA81005, Asuka 881757, and Y-82192 the irradiation times estimated from the natural TL at 250 °C in the glow curve are much less than those estimated from natural TL at 400 °C. Apparently, either the natural TL at 400 °C was only partially reset by ejection from the Moon, or these samples were heated in space. In the former case, it should be noted that the equilibrium natural TL level in lunar soils for glow curve temperatures in excess of ~200 °C is ~6 krad for samples between ~5 to 100 cm beneath the surface (Benoit and Chen, 1996). Samples from lesser and greater depths
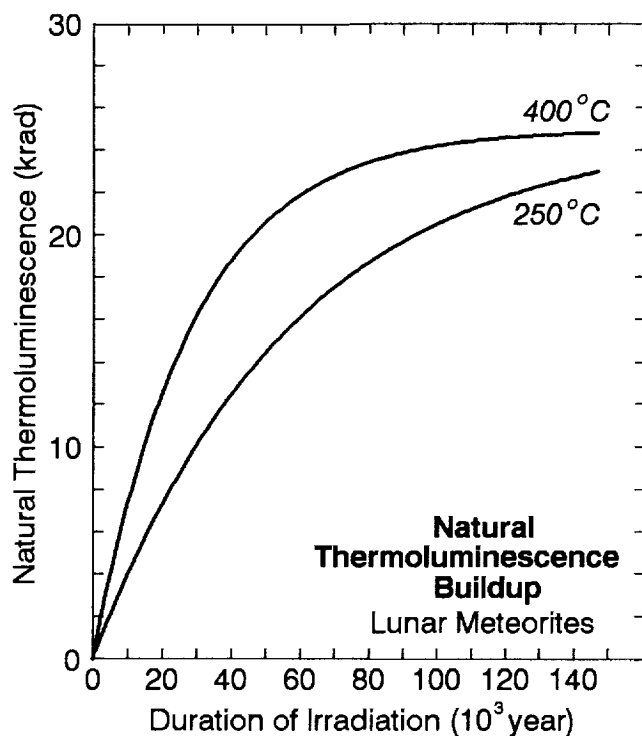
FIG. 4. Natural TL buildup at 250 and 400 °C in the glow curve as a function of time assuming no preexisting TL. This curve is calculated assuming a saturation TL level of 25 krad (Fig. 2), TL trap properties determined from glow curves (see Appendix), the observed rates of anomalous fading for lunar meteorites (Fig. 3), and a radiation dose of 5 rad/a.

exhibit lower natural TL levels, due to the diurnal heat pulse and radiation attenuation, respectively. Therefore, if the TL levels of these meteorites were not reset by the ejection event, they should have apparent exposure times of ~6,000 a, with any exposure in space increasing this apparent exposure time (Fig. 4). The apparently rapid transit times are generally consistent with the orbital calculations of Gladman et al. (1996). Their results indicate that meteorites from the Moon usually are captured by the Earth shortly after their production or break away from the Earth-Moon system and experience orbital evolution leading to ejection from the solar system or eventual impact with planets.

If some of these samples were heated in space, as indicated by discrepancies between irradiation duration estimates at different glow curve temperatures, the most likely heat source would be close approach to the Sun, as was suggested by Sutton (1986) for Y-82192. Using our experimentally derived parameters for TL at 250 °C, and a black body approximation for solar heating (e.g., Melcher, 1981), we estimate that ALHA81005 and Asuka 881757 would have had perihelia <0.5 AU, while Y-82192 had a perihelion of ~0.7 AU.

There are a number of basaltic achondrites that have natural TL levels similar to those of lunar meteorites (Fig. 3). We have previously interpreted the data for these basaltic achondrites as indicative of reheating (Sears et al., 1991a). This interpretation is supported by the cosmic-ray exposure ages of basaltic achondrites, which typically are >5 Ma and preclude short radation exposure (Eugster and Michel, 1995). Unlike lunar meteorites, the basaltic achondrites generally have been exposed to cosmic radiation in space long enough to reach equilibrium TL levels, and thus their TL levels reflect their thermal environment rather than irradiation duration.

TABLE 2. Transit times for lunar meteorites from cosmogenic nuclide abundances and thermoluminescence.

Meteorite	Cosmogenic "Transit" Time (Ka)*	Thermoluminescence "Transit" Time 400 °C (Ka)[†]	Ejection Time (Ka)[‡]
ALHA81005	<100	10 ± 5[§]	~25
A881757	900 ± 100	>100[§]	>125/~25
EET 87521	<100	<1	~20
MAC 88104/5[†]	<200	12 ± 3	~240
QUE 94281	–	1.0 ± 0.2	–
Y-793169	1,100 ± 200	6 ± 3	~30
Y-82192	10,800 +600/−5600	>45[§]	>120/~90

*Based on [10]Be and cosmogenic noble gas abundances. Data from Eugster (1989), Vogt et al. (1991), Thalmann and Eugster (1994), and Nishiizumi et al. (1995).
[†]Based on an irradiation temperature of 273 K and a radiation dose of 5 rad/a. Uncertainties are based on analytical precision.
[‡]Transit time (estimated from TL) + terrestrial age (Table 1).
[§]May reflect preejection irradiation. Apparent transit times based on 250 °C in the glow curve are <1,000 a for ALHA81005 and Asuka 881757 and 11 ± 2 for Y-82192.

The transit time estimates from natural TL for Asuka 881757, Y-793169, and Y-82192 are significantly smaller than those derived from cosmogenic nuclide abundances. Of course, both TL and cosmogenic transit time estimates are subject to many assumptions about the irradiation and thermal history of these meteorites, but the quoted uncertainties refer only to analytical precision. For instance, although Nishiizumi et al. (1992) suggested a transit time of 0.9 ± 0.1 Ma for Asuka 881757 based on cosmogenic nuclide abundances, they noted that a history involving 2 Ma of irradiation on the lunar surface and a transit time of <0.1 Ma was equally consistent with the data. Cosmogenic nuclide data for QUE 93069 can be interpreted likewise as reflecting a long transit time or a long lunar surface exposure history (Nishiizumi et al., 1995).

If we interpret the TL data for ALHA81005 and Asuka 881757 as reflecting short transit times and add the TL-derived transit times to the terrestrial ages for lunar meteorites (Table 1), we can calculate ages for the events that ejected them from the Moon (Table 2). Two meteorites, MAC 88104/5 and Y-82192, appear to have been produced during separate ejection events ~240 and 90 Ka, respectively, while the other meteorites were derived from events <50 Ka.

CONCLUSIONS

Our induced TL data indicate that, despite their rather extreme transport history, lunar meteorites had thermal histories very similar to those of Apollo lunar samples of similar petrography. The highland-dominated lunar meteorites, all breccias or regolith breccias, can be considered as mixtures of primitive highland material and local impact melt. These meteorites can be considered more thermally mature than "pristine" lunar samples and bulk highland-dominated soil, and MAC 88104/5 may be the most impact processed in this suite. Mare lunar meteorites share the fast cooling history of mare lunar samples, a possible exception being Y-793169 which may have had most of its feldspar destroyed during a large impact followed by some recrystallization under slow cooling conditions, or the sample may have cooled in a fairly thick lava flow.

Our natural TL data can be interpreted in terms of transit time for these meteorites. We find that most lunar meteorites have very short transit times, generally not more than a few thousand years

and <1,000 a in the case of EET 87521. Lunar meteorites EET 87521, MAC 88104/5 and Y-793169 appear to have had simple one stage irradiation histories but the TL of ALHA81005, Asuka 881757, and Y-82192 either reflects preserved irradiation on the lunar surface or a thermal event, such as small perihelia orbits.

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APPENDIX

The characteristics of the "trap" populations contributing to the natural TL of ALHA81005 were determined using a peak fitting procedure (McKeever, 1980). We find that the natural TL of ALHA81005 is dominated by two trap populations with maximum peak temperatures of 250 and 290 °C. There is some overlap of these traps, and the 290 °C trap population contributes to TL up to 400 °C in the glow curve. We estimate that the trap depths (E) and frequency factors (s) are 1.54 and 1.72 eV, and 1×10^{13} and 9×10^{12} (seconds)$^{-1}$ for the 250 and 290 °C traps, respectively. Uncertainties on these estimates are ~10%. In comparison, the natural TL of ordinary chondrites is dominated by two trap populations at glow curve temperatures of ~250 and 400 °C with trap depths of 1.3 and 1.5 eV and frequency factors of 9×10^{12} and 1.6×10^{10} (seconds)$^{-1}$ (McKeever, 1980).

In order to determine the TL build-up curve for the trap populations (e.g., Fig. 4), it is necessary to determine experimentally the radiation dose required to fill them to equilibrium levels. We irradiated a sample of ALHA81005 for times ranging from 5 min to 24 h in a ^{90}Sr beta cell and measured their TL. From these data, we find that the radiation dose necessary to achieve equilibrium TL levels in the laboratory is ~200 krad and 120 krad for the 250 and 290 °C traps, respectively. Note that these doses do not include inefficiencies in converting dose to TL, nor do they include the effects of anomalous fading and are thus not equivalent to measured saturation TL levels for lunar meteorites.