THERMOLUMINESCENCE OF LUNAR METEORITES YAMATO-791197 AND ALHA81005

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Abstract: The thermoluminescence characteristics of lunar meteorites Yamato-791197 and ALHA81005 are remarkably similar although not identical. Natural TL glow curves peak at a much higher temperature than the artificial glow curves, 350°C *vs.* 150°C. The absence of low temperature natural TL is interpreted as resulting from shock heating during lunar ejection. The corresponding shock temperature is estimated to be 470 ± 70°C (1 ms shock time) and the subsequent Earth transit times must have been less than 19000 and 2500 years for Y-791197 and ALHA81005, respectively. The principal difference between the two lunar meteorites is that the pre-ejection TL level of Y-791197 is a factor of 7 greater than that of ALHA81005 indicating that Y-791197 resided at a shallower, more heavily irradiated depth. Irradiation of both objects in the uppermost meters of lunar regolith with a vertical separation of meters would explain the results.

1. Introduction

The first recognized meteorite from the Moon, ALHA81005, produced unusually low natural thermoluminescence (TL), the TL measured for the "as received" material, compared to that of other Antarctic meteorites (SUTTON and CROZAZ, 1983). Two effects were required to satisfactorily explain this observation. First, the TL at all glow curve temperatures was reduced by anomalous fading, an athermal TL instability phenomenon (WINTLE, 1977). Second, the low temperature TL was reduced even further by thermal decay. Three plausible thermal events could have caused the observed low temperature TL loss, a) a near-sun orbit, b) atmospheric entry heating, and/or c) shock heating during impact ejection from the lunar regolith. The last alternative was considered the most likely based on the results of natural TL studies on chondrite falls that show near-sun orbits are rare (MELCHER, 1981a) and that atmospheric heating effects are restricted to within a few millimeters of fusion crust (MELCHER, 1979; SEARS, 1975; VAZ, 1972) (the measured sample contained no fusion crust). If the impact heating interpretation is correct, the subsequent transit time to Earth must have been less than 2500 years, the cosmic radiation exposure time required to reaccumulate the lost TL.

Reported here are the results of similar TL measurements on a second lunar meteorite, Yamato-791197. The basic result of this work is that the TL characteristics of Y-791197 are remarkably similar but not identical to those of ALHA81005. The principal difference is the greater natural TL intensity exhibited by Y-791197. This difference

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indicates that Y-791197 resided at a shallower depth in the lunar regolith prior to ejection.

2. Experimental Procedure

The material analyzed derived from Y-791197,89, an interior allocation containing both clast and matrix material and lacking fusion crust. The majority of Y-791197,89 was used for INAA and electron microprobe studies (LINDSTROM *et al.*, 1986). Twenty milligrams of predominantly submillimeter grains were randomly selected for track (CROZAZ, 1985) and TL studies. The entire TL allocation (about 15 mg) was ground gently in a mortar and measurements were made on two aliquots of the resulting powder (3 mg each, grain size less than about 300 microns).

The TL apparatus has been described in detail elsewhere (MELCHER, 1981a). Heating was performed at a rate of 2°C s^{-1}. The light detection system consisted of an EMI-9635 photomultiplier equipped with a blue-transmitting filter (Corning 5–60). A $^{90}Sr/^{90}Y$ beta particle source was used for laboratory irradiations and was calibrated by comparison with a well-calibrated ^{60}Co radiotherapy unit (SUTTON, 1985b).

Two measurements were obtained on each of the aliquots, the natural TL and the artificial TL measured after draining the natural TL and irradiating the aliquot. Natural TL intensities were expressed in terms of equivalent dose (ED), the laboratory dose required to obtain an artificial TL intensity equivalent to that of the natural TL. ED effectively normalizes the natural TL by the sample's TL sensitivity and is therefore useful in comparing the irradiation and thermal histories of materials with different TL phosphors. The two aliquots differed by less than 10% in natural TL, artificial TL and equivalent doses. The results reported below represent average values.

3. TL Glow Curves

Artificial glow curves for Y-791197 and ALHA81005 are shown in Fig. 1. Both

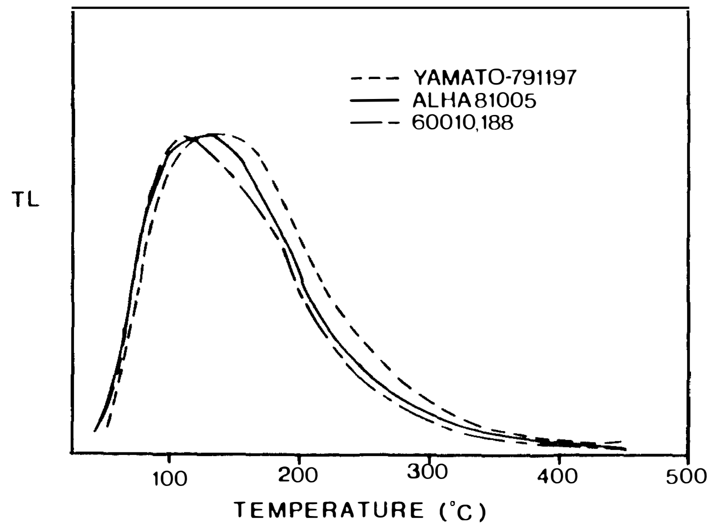

Fig. 1. Artificial glow curves (50 krads) for Y-791197, ALHA81005 and Apollo 16 lunar core sample 60010,188 (30 cm depth) (peak height normalized).

curves peak at a low temperature (~150°C) and their overall shapes are remarkably similar although not identical. The small difference between these curves, comparable to the aliquot-to-aliquot variation observed in ALHA81005 (SUTTON and CROZAZ, 1983), indicates that the plagioclase component of the two objects (the dominant TL phosphor in lunar material; see *e.g.*, HOYT *et al.*, 1971) possesses similar electron trapping and luminescence centers.

Artificial glow curves for lunar fines returned by the Apollo astronauts are shown in Figs. 1 and 2 for comparison. Curves for highland samples such as those from Apollo 16 (Fig. 1) also possess only a low temperature peak and the glow curve temperatures of these peaks are close to those of the two lunar meteorites. In contrast, non-highland samples (Fig. 2) exhibit substantial TL emission at all glow curve temperatures. These observations are consistent with a lunar highland origin for both meteorites.

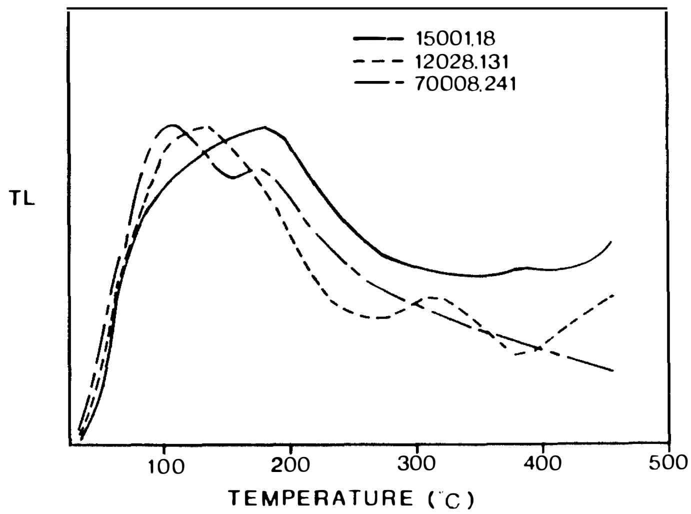

Fig. 2. Artificial glow curves for three lunar core samples from Apollo 12 (12028,131; 36 cm), 15 (15001,18; 2.4 m) and 17 (70008,241; 36 cm) (peak height normalized).

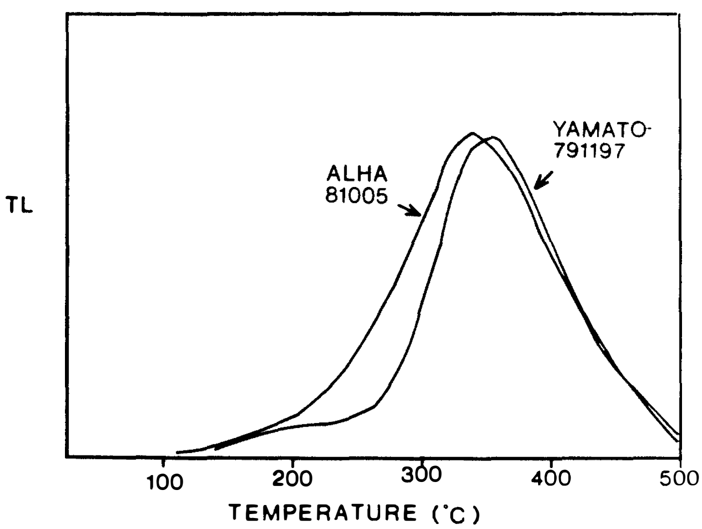

Fig. 3. Natural TL glow curves for Y-791197 and ALHA81005 (peak height normalized).

The natural TL glow curves of Y-791197 and ALHA81005 peak at a glow curve temperature of about 350°C (Fig. 3). The fact that the natural glow curves peak at a much higher temperature than do the artificial glow curves indicates that both objects have experienced low temperature TL loss by thermal decay. This interpretation is supported by the observation that artificial glow curves measured after irradiation and preheating in the TL apparatus up to 300°C, closely reproduce the natural glow curves.

4. Equivalent Dose Curves and Terrestrial Thermal Decay

A comparison of equivalent dose curves for Antarctic meteorites demonstrates that the low temperature thermal decay experienced by the lunar meteorites occurred prior to their arrival on Earth. The ED curves of Antarctic chondrites with short radiometrically-determined terrestrial ages are relatively flat above a glow curve temperature of about 200°C while those with long terrestrial ages (*e.g.*, ALHA77272; NISHIIZUMI *et al.*, 1981), begin to reach a plateau at a higher glow curve temperature of 275°C (Fig. 4 and SUTTON and CROZAZ, 1983). It is concluded that TL below a glow curve temperature of 275°C can be thermally drained at Antarctic storage temperatures while the TL at greater glow curve temperatures is thermally stable. In contrast, the ED curves of the lunar meteorites fail to reach a plateau until a glow curve temperature in excess of 325°C (Fig. 4) indicating that they have experienced thermal decay in excess of that produced by Antarctic residence.

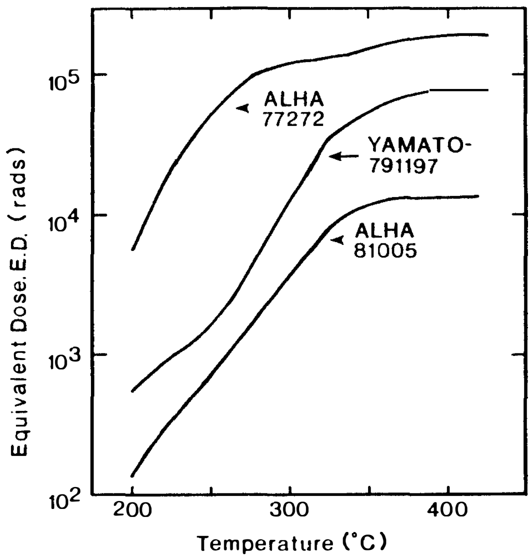

Fig. 4. Equivalent dose, ED, curves for Y-791197, ALHA81005 and Antarctic chondrite ALHA77272 (terrestrial age =0.54 Ma; NISHIIZUMI et al., 1981).

The low temperature TL loss experienced by Y-791197 and ALHA81005 prior to arrival in Antarctica has three plausible interpretations, a) heating in a near-sun orbit, b) heating during atmospheric entry and/or, c) shock heating during impact ejection from the Moon. The latter alternative is considered the most likely since near-sun orbits are rare and atmospheric entry heating effects are restricted to within a few millimeters of the fusion crust (our allocations of both objects were interior fragments lacking fusion crust).

5. Earth Transit Times

If the shock heating interpretation is correct, the total radiation dose received by the lunar fragments after lunar ejection must have been less than that required to reaccumulate the lost TL. The Earth transit times are therefore, constrained by the pre-ejection TL levels and the galactic cosmic radiation dose-rate.

Upper limits to the transit times were obtained by assuming that prior to shock heating the ED curves of both objects were flat at values equivalent to the observed ED plateau levels, 10^4 and 7×10^4 rads for ALHA81005 and Y-791197, respectively. If the estimated minimum galactic radiation dose-rate of 10 rads y^{-1} (HOYT *et al.*, 1971) and observed anomalous fading rates (see below) are taken into account, the maximum space exposure times are 2500 and 19000 years, respectively. Both objects have, therefore, spent short times in space and the TL data are consistent with their transit times being the same.

6. Shock Temperature

The extent of thermal decay is sensitive to heating time and temperature. Since the natural peaks for Y-791197 and ALHA81005 occur at nearly the same glow curve temperature, the objects must have experienced similar thermal histories during the event(s) which resulted in the low temperature TL loss. If the shock heating interpretation is correct, the glow curve temperature of the natural TL peak can be used to estimate the shock temperature experienced during lunar ejection since samples exposed to greater shock are heated to higher temperatures and suffer TL loss to higher glow curve temperatures (SUTTON, 1985a). The temperature estimate is based on the observation that the TL loss during shock heating was equivalent to that produced by a 300°C preheating in the TL apparatus for about 1 s. The actual shock temperature T(moon) will be greater than the appropriate laboratory preheating temperature T(lab) since the shock heating time t(moon) will be less than the laboratory heating time t(lab). Using the RANDALL and WILKINS (1945) description of TL decay, T(moon) can be calculated from T(lab), the corresponding heating times and the associated electron trap depth E

$$T(\text{moon})=\frac{ET(\text{lab})}{E+kT(\text{lab})\ln[t(\text{moon})/t(\text{lab})]},$$

where k=Boltzmann's constant. Since the position of the natural glow curve peak is controlled by thermal decay at a glow curve temperature of ~300°C, a sufficiently accurate value for E in this case is 1.5 eV (MELCHER, 1981b; HOYT *et al.*, 1971). The shock temperature calculated in this manner assuming a shock heating time of 1 ms (KIEFFER, 1971; SHOEMAKER, 1963) is 470°C±70°C. The uncertainty (70°C) in the shock temperature of 470°C is that calculated from the following estimated one standard deviations: $E=1.5\pm0.3$ eV, $T(\text{lab})=300\pm10$°C, $\ln(t(\text{moon}))=-6.9\pm1.0$ (*i.e.*, 0.4–3 ms) and $\ln(t(\text{lab}))=0\pm1$ (*i.e.*, 0.4–3 s).

7. Lunar Burial Depths

Y-791197 yields an ED plateau value greater than that of ALHA81005 by about a factor of 7, 7×10^4 rads compared to 1×10^4 rads (Fig. 4). Since this high temperature TL has been unaffected by the thermal event described above, the dose difference reflects a difference in the pre-ejection TL level of the two fragments. The TL of lunar regolith samples at glow curve temperatures below 500°C is in thermal equilibrium between accumulation by galactic cosmic radiation exposure and depletion by two processes, thermal decay due to storage at the subsurface regolith temperature of about 240 K and anomalous (athermal) fading (HOYT *et al.*, 1971). Equilibrium differences due to anomalous fading are expected to be small since the observed rate of this instability was equivalent in the two meteorites. (At 400°C glow curve temperature, Y-791197 artificial TL shows $15\pm7\%$ loss after 10 days storage at room temperature compared to $25\pm6\%$ for ALHA81005. Assuming this anomalous TL loss obeys a power law time dependence (SUTTON and CROZAZ, 1983), this phenomenon could account for, at most, a factor of 2 difference in equilibrium level.) The greater high temperature equilibrium ED level exhibited by Y-791197 therefore indicates that this meteorite resided in a more heavily irradiated, cooler region of the regolith, *i.e.*, nearer to the surface, than did ALHA81005. Since the lunar thermal gradient is small (about 1 K m^{-1}; HOYT *et al.*, 1971), the depth dependence of TL in the lunar regolith is controlled primarily by the attenuation of galactic cosmic rays. (The combined effect of solar flare irradiation and the diurnal heat wave within the top few centimeters of regolith is negligible for TL at the high glow curve temperatures considered here; HOYT *et al.*, 1971.) Attenuation of galactic protons by a factor of 7 requires shielding on the order of meters (REEDY and ARNOLD, 1972) representing the magnitude of the burial depth difference between the two objects.

The absolute burial depth of each fragment is difficult to estimate from their TL levels primarily because the long term effects of anomalous fading cannot be accurately quantified. If a power law extrapolation of the laboratory fading results is assumed, fading would have reduced the TL by a factor of about 2 and the ED plateaus would correspond to 1.4×10^5 and 2×10^4 rads for Y-791197 and ALHA81005, respectively. Since the equilibrium time of the natural TL associated with the ED plateau is on the order of 10^4 y, these doses correspond roughly to a dose-rate of several rads per year, similar in magnitude to the surface dose-rate (HOYT *et al.*, 1971). These results indicate that both objects derive from the uppermost meters of the lunar regolith.

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