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NATURAL THERMOLUMINESCENCE PROFILES IN LUNAR CORES AND IMPLICATIONS FOR METEORITES.

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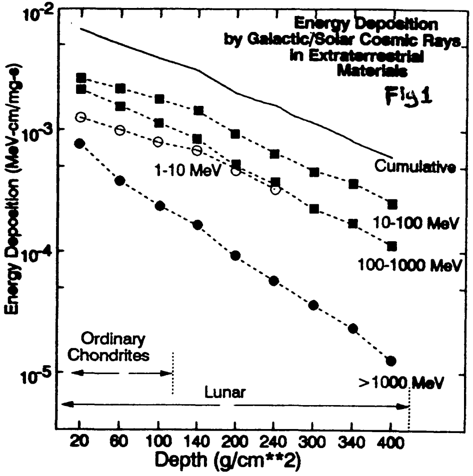
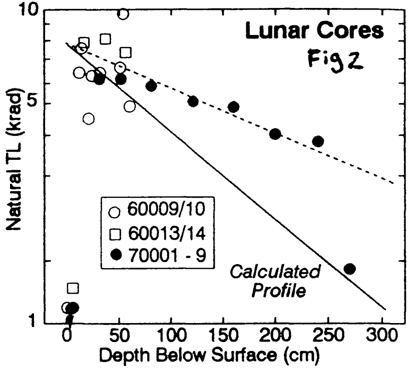
Meteorites and lunar samples have been irradiated by high energy cosmic rays, typically for millions of years. In addition to producing isotopic changes, the irradiation creates ionization which may be recorded in the form of stored thermoluminescence (TL) in certain minerals, the most important of which is feldspar. One aspect of interpreting the TL of these samples is the effect of "shielding" or depth control, which is particularly important for meteorites, since they have lost an unknown amount of mass during atmospheric entry. Here we report theoretical calculations which we compare with samples from lunar cores for which we have excellent stratigraphic control. We then discuss the implications for these results for the TL of meteorites, which have a different irradiation geometry. We find that, in general, calculated profiles are similar to those observed in lunar samples and meteorites. Additional effects, such as orbital (thermal) history and terrestrial age must also be considered in the case of meteorites.



Calculations: We use the calculated cosmic ray flux of Michel *et al.* [1] which is based on the flux on the Moon. This flux estimate is probably approximately correct for most meteorites but might be too low by a factor of 2-3 for meteorites in high inclination or large aphelion orbits [2]. The flux from Michel et al. [1] includes both primary *and* secondary protons. Thermoluminscence levels in materials are governed by the amount of energy deposited per unit volume rather than any specific nuclear reaction. Thus, we assume that only charged particles (i.e., largely protons) contribute to the TL build-up, as these are much more efficient at depositing energy in matter than are primary and secondary neutrons. We convert the cosmic ray energy spectrum to energy deposited using "stopping power" curves for a material near in atomic number to the samples [3]. These curves emphasize the importance of the lower energy cosmic rays (10 - 100 MeV) in TL build-up, especially the secondary particles. The shape of the TL profile can be estimated by finding the cumulative energy deposited as a function of depth. This calculated profile is fairly shallow on a log(energy) vs. depth plot, with a drop of about a factor of 5 over 400 g/cm^2 (Fig. 1). Additional calculations show that lower energy solar cosmic rays (<100 MeV primary particles)[4] will make a significant contribution to TL only in the first ~4 g/cm^2.



Lunar Cores. We have measured the natural TL of three lunar cores: 60009/10 (8 samples); 60013/14 (4 samples); and 70001-70009 (8 samples). These data are shown in Fig. 2. In all three cores the uppermost sample has a very low level of natural TL. This is because of the high temperatures experienced by the top 5-10 cm of lunar regolith due to diurnal heating [5]. The TL profiles reach a plateau of ~7 krad in all three cores in the interval of 10-100 cm, including the entire length of 60009/10 and 60013/14. It is, however, possible that the samples in the 10-40 cm range have also been affected by diurnal heating but to a much lesser degree than those in the uppermost 10 cm. These data are in accord with earlier TL studies of lunar cores [6].In the 70001-70009 core there is a gradual drop in TL from 100-250 cm. This decrease is linear on a log(TL) vs. depth plot (Fig. 2) and thus is qualitatively similar to the calculated profile for simple 2π geometry (Fig. 1). However, the TL profile in 70001-70009 is shallower than that predicted by the calculations, showing a range of only a factor of ~2 verses the expected factor of ~4. The deepest sample, at ~270 cm, has very low TL relative to the other samples. This cannot be interpreted in terms of core history, since it appears that the stratigraphy has not been radically changed for at least 10^7 years [5,7], far greater than the ~10^5 years needed for TL to achieve equilibrium at 1 AU [8]. It is more likely that this sharp drop reflects changes in the energy spectrum, such that particles of sufficient energy are not present in great enough quantity to produce "normal" TL levels at these depths.

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Implications for meteorites: In light of these data and calculations, it should be possible to calculate TL profiles for meteroid bodies as well, making appropriate corrections for 4π irradiation. Our calculations are similar in nature to those of Honda [9] for cosmogenic nuclides. The results for meteoroid bodies of various radii (R) are shown in Fig. 3. In order to obtain absolute TL calibration, it is necessary to use TL values for meteoritic samples from known pre-atmospheric locations. In the present case, we use values for samples near the center of Knyahinya (as determined by cosmogenic nuclide profiles [10]; preatmospheric radii ~65 cm). We are presently seeking other additional calibration samples. Lunar core data could also be used for this purpose, but "anomalous fading" [11] must also be accounted for in these samples in order to compare their natural TL levels directly to meteorites. It is apparent from these calculations that the TL profile for an individual meteorite is fairly flat, with the smallest meteroids showing the smallest range. The range is greatest in the largest meteroid bodies, but exceeds 10 krad only in those with preatmospheric radii of >120 cm. Considering bodies between ~60 cm and ~4 cm in radius, encompassing all meteroid bodies currently studied in detail [10], the range in TL is only about a little more than a factor of three (i.e., 20 - 65 krad). This compares favorably with the range in natural TL observed in modern ordinary chondritic falls, most of which have TL between 20 - 70 krad [12] (however, see [8] for some exceptions) and with the TL profiles of individual meteroids such as St. Severin.

Conclusions: (1) The expected shape for TL profiles under 2π geometry irradiation can be calculated from estimated proton fluxes. The calculated profile has a fairly shallow slope as a function of depth, ranging over less than a factor of 10 over a thickness of 400 g/cm^2. TL profiles of three lunar cores, especially 70001-70009 seems to fit the shape of this calculated profile. (2) After corrections for 4π geometry irradiations, TL profiles in ordinary chondrites also have fairly shallow slopes as a function of depth, ranging over less than a factor of 2 for the largest meteroid bodies. The expected range of TL in a full range of meteroid sizes is only a factor of 3, which is similar to the range observed in samples from various modern falls. (3) While natural TL values of meteorites partly reflect their size during irradiation ("shielding"), they also reflect the recent thermal history of meteoroid bodies, including orbital effects [8,12] and terrestrial age [13].

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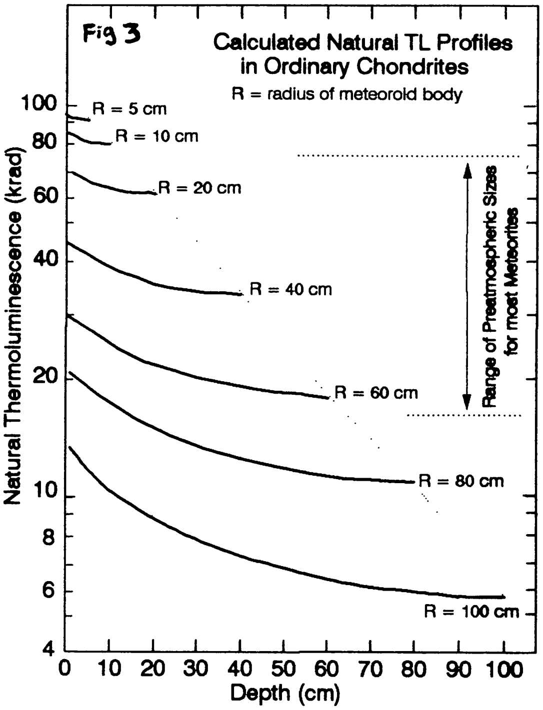
Fig 3

Calculated Natural TL Profiles in Ordinary Chondrites