NATURAL THERMOLUMESCENCE OF LUNAR SAMPLES: REVIEW AND UPDATE. A. Sehlke[1], D. W. G. Sears[1] and the ANGSA Science Team. [1]NASA Ames Research Center/ Bay Area Environmental Research Institute, Moffett Field, CA 94035, USA, alexander.sehlke@nasa.gov.

Introduction: Thermoluminescence (TL), literally light emission caused by heating, is a widely used and widely studied process in dosimetry, dating and various industries. Ionizing radiations passing through crystalline materials cause electrons to be energized and "trapped" where they can be stable for minutes to billions of years [1]. Heat provides the energy for the electrons to fall back to their low energy ground states, releasing the excess energy as light. The number and energy level of trapped electrons is a balance between the radiation environment (i.e., the dose of ionizing radiation absorbed) vs. the thermal environment (i.e., storage temperature of the sample), as well as the petrology of the sample (i.e., type of crystal lattice and defects).

Measuring the natural TL, the TL of an "as-received" sample, informs on the extent of stored charges in the traps and thereby the absorbed dose and ambient temperature. The intensity (photon counts per second, cps) of the TL signal also depends on the availability of traps and luminescence centers, their saturation limit, and mineral.

Anomalous Fading is a type of process in which the TL intensity decays over time when held at constant temperature. It has been described for most Apollo sites [1-6]. To date, there is no consensus whether or not anomalous fading affects all types of materials equally. Thus, whenever samples are removed from their natural radiation and thermal environment, their TL information may have been altered.

Measurement Methods: For a TL measurement, usually ~4 mg of a sample is needed, but measurements can be also performed on single grains. A glow oven heats the sample from ambient to ~773 K at a linear heating rate, which is typically between 3-7 K s^{-1}. A Photomultiplier tube measures the intensity of the light emitted from the sample, whereby the temperature (T) and light intensity (I) is recorded. In the sample's natural state (i.e., space weathering and irradiation), the shape of the T-I data pair, or 'natural glow curve', is diagnostic of the radiation and thermal history of the sample.

Sample Requirements: Any crystalline sample is useful for natural TL measurements, such as regolith fines, clasts and fragments, as well as meteorites. Plagioclase is the main mineral responsible for luminescence in lunar samples; glass and minerals containing more than 2 mol% iron are non-luminescent. Removal of opaque grains, such as magnetite via a magnet, are recommend. Most importantly for natural TL measurements, the sample may not be exposed to any ionizing radiation or other light sources (such as fluorescent light bulbs) after it has been removed from its sampling location, because this artificial radiation exposure can provide enough energy to reconfigure trapped electrons (excitation and drainage).

Applications for Natural TL Measurements:

Transient Lunar Phenomenon. Interest in TL measurements on lunar surface materials was prompted in some part by the observations of light being emitted by the lunar surface, the so-called "transient lunar phenomenon" (TLP) [8]. It was quickly realized that sample luminescence was not efficient enough to explain the TLP and interest turned to using TL to estimate radiation and temperature related processes.

Regolith Radiation and Temperature Profiles. Studies and Apollo 11 [4,9] and Apollo 12 [10] core samples demonstrated that radiation levels within lunar cores vary with depth. Within the first ~17 cm, natural TL levels shifted in intensity towards lower glow curve temperatures with depth, which is attributed to the rapid decrease in mean temperature below the lunar surface. The daytime temperatures to which the material is subjected decreased rapidly with depth, resulting in slower TL decay rates with depth and hence the preservation of more, and lower temperature, TL levels. However, an intensity decrease of the natural TL glow curve was observed beyond the first 17 cm [4]. For example, the low temperature (150-170 ºC) glow curve TL levels at a regolith depth of 60 cm was only 36±6% compared to the TL levels from samples collected at a depth of 17 cm.

Such intensity decrease is due to attenuation of cosmic radiation with dept, as well as temperature increase towards the lunar interior, which would drain the TL levels at the low temperature end of the glow curve. Natural TL levels were used to derive a thermal gradient of 2 K m^{-1}.

Storage Durations and Temperature Estimates. Natural TL retained by soil samples from the shadow of Apollo 17 Station 6 boulders and from an adjacent sunlit area was used to derive the temperature in the shade and the length of time for which the shadow has been cast [10]. It was estimated that the shadow had been cast ~40,000-60,000 years and the mean temperature in the shaded area was estimated to be ~251 K. For boulders, such measurements allow inferences about boulder emplacement and timing.

Transit Times of Lunar Meteorites. Impacts on the lunar surface ejected crustal material into space, where these fragments are exposed to the cosmic radiation. The fragments equilibrate to the radiation levels within 10^8 years, after which they are saturated. Since the radiation level depends on how long the fragments have been in the space environment, a survey of lunar meteorites allows determining whether these objects resulted from either the same or different impact events.

Current Measurements on Lunar Samples: We study pristine Apollo 17 samples to refine the physical parameters that govern the TL process, because subtle changes in these parameters translate in uncertainties for the applications mentioned earlier. We also investigate the kinetics of anomalous fading through a series of experiments, where we compare the TL levels of pristine Apollo 17 samples in cold storage and their counterparts stored at nominal conditions, as well as to natural glow curves done in the 1970's. This unique 50-year experiment helps us to determine the presence and magnitude of anomalous fading in lunar samples, for which the natural TL levels need to be corrected for.

Curve fitting. Durrani et al. [6,7] used the natural thermoluminescence of these samples to calculate surface temperatures for the regolith in the vicinity. In order to do so they were required to estimate the kinetic parameters that govern the thermoluminescence build-up and decay, namely the trap depth and the rate constant, known as s, or the pre-exponential factor, or the Arrhenius factor. The present paper reports our efforts to date to determine these parameters using a new procedure which several authors suggest is superior.

Recent efforts to determine E and s by fitting theoretical curves to literature data are shown in Fig. 1.

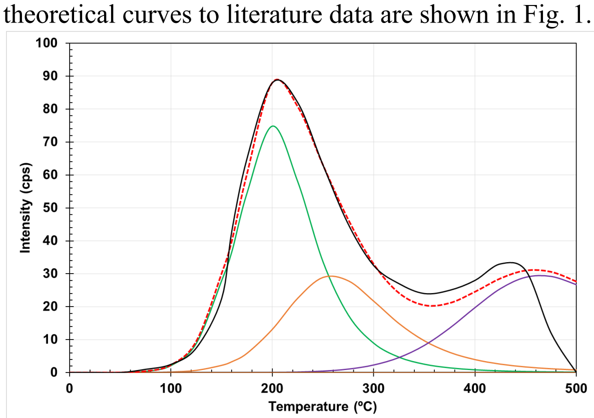

Fig. 1. Determining trap depth by curve fitting for sample 76241,23 collected from a boulder shadow. The glow curve, black line, was taken from the literature [6,7].

TL Measurements During Artemis: Our ongoing work is designed to further strengthen the TL method for the sort of applications outlined earlier. Future returned lunar samples through the Artemis mission can be surveyed in terms of their natural TL levels to determine thermal and radiation profiles at polar region [11], which can be expected to be much different to the ones for equatorial regions Apollo because of the differences in solar irradiation and temperature environment. Natural TL measurements are sensitive to any changes in radiation exposure, such as re-deposition of regolith through landslides or similar mass wasting events, as well as dust migration. TL measurements could be considered to evaluate permanently shadowed regions (PSRs) on the Moon, and whether or not any material from sunlit crater rims was deposited on top of regolith located inside permanently shadowed craters. Additionally, TL would also be useful for sample curation purposes, such as routine examination regarding artificial radiation exposure and temperature changes during the return of samples to Earth.

Ultimately, in-situ natural TL measurements on the lunar surface would enable evaluations of the thermal and radiation environment of the Moon while simultaneously providing geologic measurements in real time. TL data regarding the nature of rocks and boulders is key to planning human surface operations and assessing the potential for radiation shielding from regolith. TL measurements also contribute towards understanding lunar surface materials in terms of construction requirements and thermal history relevant to volatile (e.g., ^{3}He and water) retention. We have ideas to develop a TL instrument, which would be low mass, low volume, and low power [12].

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