J. Earth Syst. Sci. (2020)129 212
https://doi.org/10.1007/s12040-020-01474-1

Bleaching of blue light stimulated luminescence of quartz by moonlight

H M Rajapara[1,2,*], Vinayak Kumar[1], Naveen Chauhan[1], P N Gajjar[2] and A K Singhvi[1]

[1]*AMO-PH Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India.*
[2]*Department of Physics, Electronics and Space Science, University School of Sciences, Gujarat University, Ahmedabad 380 009, India.*
**Corresponding author. e-mail: hmrajapara@gmail.com*

MS received 13 December 2019; revised 27 June 2020; accepted 9 July 2020

Moonlight is sunlight reflected from the moon's surface. It is additionally modulated by the Earth's atmosphere, dust and pollutants on its way to the surface of the Earth. This contribution reports the bleaching rates of blue light stimulated luminescence (BLSL) signal of Quartz under full moonlight exposure at the Earth's surface. Quartz BLSL reduced to 70% by an exposure of 5 hrs moonlight, is in contrast to ∼90% reduction in < 3 s with daylight. This was anticipated due to (a) reduced moonlight flux by about a factor of half a million (Agrawal in Lat. Am. J. Phys. Educ. 4(2):325–328, 2010; J. Phys. Astron. 5(1):1–15, 2017); (b) inverse power law dependence of bleaching efficiency on wavelength (Spooner in The validity of optical dating based on feldspar, Ph.D. Thesis, Oxford University, Oxford, 1993; Chen and McKeever in Theory of Thermoluminescence and related phenomena, World Scientific Publications, London, 1997, Chen and Pagonis in Thermally and optically stimulated luminescence: A simulation approach, Wiley and Sons, Chichester, 2011); and (c) moonlight and daylight have spectral peaks around 650 and 550 nm, respectively. Deconvolution of OSL components suggests that moonlight affects the fast component of OSL signal the most. This has ramification for the application in polar regions, where the availability of daylight is at a premium during the winter months. Within a given context, it is conjectured that this could be used to infer the seasonality of sediment transport.

Keywords. Blue light stimulated luminescence (BLSL); moonlight bleaching; daylight bleaching; luminescence dating.

1. Introduction

Optical bleaching of quartz and feldspar luminescence depends on the intensity and spectrum of light and the duration of exposure along with the luminescence behaviour of individual mineral grains of sand and their grain size (Godfrey-Smith *et al.* 1988; Jain *et al.* 2003). While considerable efforts have been expended in understanding the bleachability of luminescence signal under daylight exposures (Singhvi *et al.* 1982; Aitken 1985, 1998; Sohbati *et al.* 2017), only limited (possibly one) studies have been carried out on bleaching from the nightlight/moonlight. This study reported that 3 hrs of exposure to nightlight in Sweden comprising moonlight and city lights bleached the BLSL signal of Quartz by up to 40% (Lindvall *et al.* 2017).

Despite the obvious simplicity, experimental data on the rate and extent of bleaching of blue light stimulated luminescence due to moonlight is

Published online: 15 October 2020

not available. This manuscript provides data on moonlight bleaching from a tropical region, quantifies the effect of moonlight exposure on blue light stimulated luminescence (BLSL) signal of quartz, and its components. In the end, some future possibilities are discussed.

2. Samples and sample preparation

Quartz samples from Charlotte, northern territory in Australia (12.84°S, 130.49°E) were used. Standard procedures for the extraction of quartz were followed. Briefly, the samples were treated with 1N hydrochloric acid (HCl) for 8 hrs to remove carbonates followed by a 30% hydrogen peroxide (H_2O_2) solution for 12 hrs to remove organic fractions. Grains of size range 90–150 μm in diameter were dry sieved and quartz grains were separated using Frantz Magnetic separator at two different magnetic field strengths generated by passing 0.5 and 1.5 A current through the electromagnetic coils (Porat 2006). The grains were then etched with 40% hydrofluoric acid for 60 min (to remove the alpha skin of quartz and residual feldspars) followed by a treatment with 37% HCl to convert insoluble fluorides to soluble chlorides. The quartz grains thus obtained were re-sieved to collect grains in 90–150 μm size range and were tested for their purity using infrared stimulated luminescence (IRSL) response for three representative aliquots. For this a sequence of measurement of natural signal + preheat + IRSL + OSL + dose + preheat + IRSL + OSL and dose + preheat + OSL was adopted. Finally, Dose + TL was measured (see Appendix). Diagnostic TL peaks of feldspar were not seen and no response to IR stimulation beyond the instrumental background was observed.

3. Instrumentation

For BLSL measurements, a Risoe TL/OSL reader (DA-20) system was used (Bøtter-Jensen and Murray 1999; Bøtter-Jensen *et al.* 2003). Blue light stimulation (BLSL/OSL) comprised blue light LEDs emitting at 470 ± 30 nm, and IRSL was measured by stimulating with IR LEDs emitting at 870 ± 40 nm (Bøtter-Jensen *et al.* 2000). Typically, 70% of the full power of LED (delivering an estimated 50 mW/cm^2 blue light at the sample) was used for stimulation. The detection optics comprised a 7 mm Hoya U-340 filter allowing a transmission band 290–370 nm with a peak at ∼340 nm (Aitken 1998). Beta irradiations used a 40 mCi ^{90}Sr/^{90}Y source delivering a dose of 0.051 Gy/s or 3.08 Gy/min to the aliquot.

4. Measurements and analysis

BLSL measurements were carried out on ∼3 mm diameter monolayer quartz grains mounted on stainless steel disc using silicon oil (Silkospray^{TM}). Table 1 gives the measurement procedure. Typically, 24 aliquots with quartz grains were annealed for 2 hrs at 450°C to maximize their OSL sensitivity and to ensure that no sensitivity change occurs during measurements (Singhvi *et al.* 2011). Thereafter, a beta dose of 12.8 Gy was given to each aliquot. The aliquots were then sub-divided in eight groups. For each exposure data point, a group was exposed to moonlight on a full moon night for time durations of 15 min to 6 hrs. This moonlight exposure experiment was carried out in the duration of 11:00 PM of 2nd March to 06:00 AM of 3rd March, 2018. The samples were exposed to moonlight on the terrace of an isolated high-rise (∼30 m) building. The location of the building was chosen such that it had minimal effect of surrounding city lights. Further, as an extra precaution, an opaque cardboard box of approximately 30 × 20 × 20 cm size was used to ensure a normal incidence of moonlight and to minimize exposure from scattered city lights. Daylight exposure was carried out on the next day in a similar manner.

The residual equivalent dose (D_e) after moonlight exposure was estimated using the single aliquot regeneration (SAR) protocol (Murray and Wintle 2000; Wintle and Murray 2006). Details are given in table 1. A preheat of 240°C for 30 sec was used prior to BLSL measurement at 125°C for 40 sec. Luminescence signal in the first 0.16 sec, which may contain ultrafast components, was ignored as a matter of abundant caution and photon counts in the interval 0.16–1.6 sec (channel 2–10) was used as a signal and the normalized photon counts averaged over last 8 sec of decay curve were used as the background (Jain *et al.* 2008). A test dose of 2.56 Gy was used to normalize the signal intensity. Acceptance criterion for D_es was < 5% recuperation, < 5% recycling ratio, < 5% test dose error. Laboratory generated dose response curves were fitted to a single saturating exponential. Further, as the samples were sensitized in the laboratory, Natural Correction Factor (NCF) (Singhvi *et al.* 2011), correction was taken as 1. This is reasonable

Table 1. *Measurement protocol showing step-by-step measurements.*

Steps	Treatment	Observed
1	Anneal at 450°C for 2 hrs	
2	Dose 12.8 Gy	
3	Moonlight exposure (15 min–6 hr)	
4	TL or preheat 240°C for 30 sec, background subtracted	
5	OSL blue led for 40 sec after holding for 10 sec at 125°C	Lx
6	Test dose for 2.56 Gy	
7	TL or preheat 240°C for 30 sec, background subtracted	
8	OSL blue LED for 40 sec after holding for 10 sec at 125°C	Tx
9	Illumination by Blue LED for 200 sec after holding for 30 sec at 250°C	
10	Regenerative dose D_i	
11	Repeat step 4	

Table 2. *Fast, medium and slow components strength after each step of bleaching. Here decay constants λ_1, λ_2 and λ_3 are kept fixed, as shown, to obtain the value of the amplitude of fast component A1, medium component A2 and slow component A3, respectively. Here, these decay constants λ_1, λ_2 and λ_3 are obtained from unbleached shine down curve.*

λ_1 (sec^{-1})	1.57 ± 0.29
λ_2 (sec^{-1})	0.26 ± 0.02
λ_3 (sec^{-1})	0.01 ± 0.00

Moonlight bleaching duration (hrs)	Fast component amplitude A1 (10^6)	Medium component amplitude A2 (10^4)	Slow component amplitude A3 (10^3)
0	4.6 ± 0.2	2.4 ± 0.1	2.6 ± 0.1
0.25	3.8 ± 0.3	1.6 ± 0.1	2.9 ± 0.1
0.5	2.7 ± 0.1	0.9 ± 0.1	2.8 ± 0.1
1	2.9 ± 0.2	1.3 ± 0.1	3.7 ± 0.1
5	1.5 ± 0.2	1.4 ± 0.3	4.6 ± 0.1

assumption given that all the samples were treated identically in respect of sunlamp exposure and thermal sensitization. While we could have compared light intensities of weight normalized samples, the use of equivalent dose was preferred, both to offset the variabilities and the assumptions associated with weight normalization as well as to gain the magnitude of the effect in terms of radiation dose, the quantity used for age computation.

The component analysis of OSL decay curves of samples bleached by moonlight is shown in figure 2. A MATLAB based computer program developed by Murari (2006) for the deconvolution of the OSL decay curves using Levenberg–Marquardt algorithm was used. Murari (2006) demonstrated that the decay constants were dose independent and therefore, for comparison of the amplitudes of decay curves within a set of identical samples was a valid option. In the present case, the decay constant was determined using the decay of unbleached samples (Bailey *et al.* 1997; Bailey 2000, 2001). The decay constant so derived were used as constants to compute the amplitudes of components from decay curves after bleaching. Table 2 provides the decay constant and the amplitudes for various components with moonlight exposure.

5. Results and discussion

Figure 1 shows the dose recovered after the bleaching with moonlight for variable durations. The dose recovered after 15 min and 4 hours duration of moonlight exposure were respectively, 93% and 68% of the given dose. The recovered dose decreased with the duration of moonlight exposure. Lindvall *et al.* (2017) reported ∼40% loss of signal for 3-hr night light exposure in Sweden (55.71°N, 13.20°E). The difference between the present study and their estimates is possibly due to extended duration, addition of city-light, the difference in

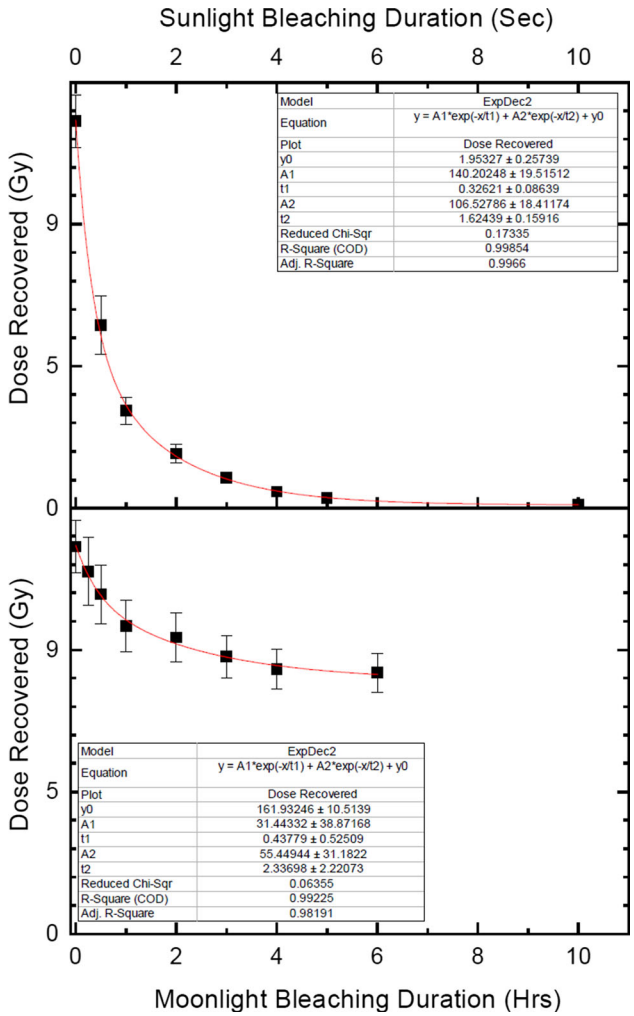

Figure 1. Dose recovered using SAR after each bleaching time and given dose of 12.8 Gy. Each data point is the mean of three aliquots with standard error. Luminescence signal was taken as sum of initial 1.6 sec leaving first 0.16 sec of ultra-fast component contribution after subtracting late background signal from last 8 sec. Upper part of the figure shown here is for the same experiment for daylight exposure up to 10 sec for reference purpose. Kindly note the difference in scale value.

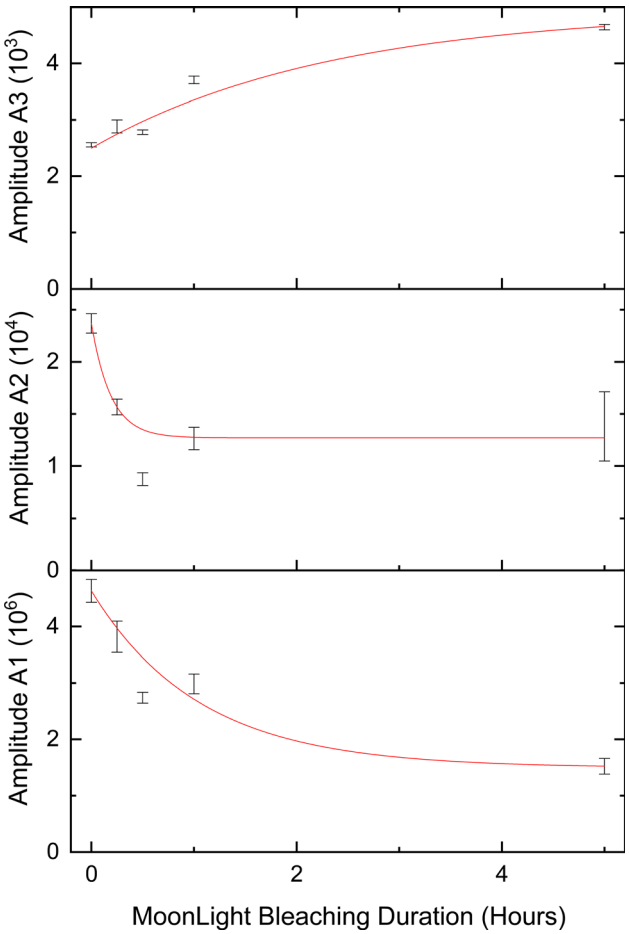

Figure 2. The graphs above show the portion of slow components (amplitude A3, top), medium components (amplitude A2, middle) and fast components (amplitude A1, bottom) remaining after moonlight bleaching. Each point on the graph correspond to intensity of component at T=0 for fast ($A1_0$), medium ($A2_0$) and slow ($A3_0$) components after variable duration of moonlight exposure.

the intensity of moonlight received at earth surface at two different locations and local atmospheric conditions. It is nonetheless clear that moonlight can remove up to 40% of the dose with a few hours of moonlight exposure.

Similar to moonlight bleaching experiment, a daylight bleaching experiment was also carried out for variable exposure times (0.5–10 sec) and dose was estimated following the protocol described in table 1. The effect of daylight on quartz luminescence dose is given in figure 1. The result suggests that 3 sec of daylight exposure bleached nearly 90% of luminescence dose and 5 sec exposure bleached over 95%.

The albedo of the surface of the Moon is 0.136, i.e., the full moon reflects about ∼14% of incident solar flux out of which ∼70% reaches the Earth surface (Matthews 2008). The moonlight spectrum on the Earth's surface has a peak in the region 550–650 nm (Agrawal 2017). The solar spectrum peaks at 520 nm extending from 400 to 700 nm (Cramer *et al.* 2013). This gives daylight two orders of magnitude higher bleaching ability due to higher energies (322–500 nm) compared to the reflected lunar spectrum received on earth surface. This is based on the work of Spooner (1987) who showed that light in the region of 322–500 nm has significantly higher efficiency for emptying out the traps compared to higher wavelengths.

Referring figure 1, to achieve 10% reduction in BLSL signal, the daylight to moonlight exposure

time ratio is estimated to be ∼1:3000. Thus, despite of reduced flux and longer wavelength, moonlight does bleach OSL signals and the maximum bleaching for its spectrum at the surface of the earth is ∼40% of dose. Despite substantive literature search, we could not get any report on the latitudinal changes in moonlight flux on Earth. However, similarity of present results with those of Lindvall *et al.* (2017), suggest that the latitudinal variation of moonlight spectrum and flux may not be significant.

The results show the change in the amplitude of various components with moonlight exposure, and it is clear that the major change occurs in the fast component which decreased by 70%. The medium and slow component contribute little to the total light sum, but an evidence of photo-transfer into the medium component is observed, analogous to that reported by David and Sunta (1985).

Despite the fact that the peak of the lunar spectrum is on the higher wavelength (lower energy) side and spectrum has lower UV component compared to solar spectrum (Carver *et al.* 1974), results from the present study suggest that moonlight at ground level can still bleach the luminescence signal but at a slower rate compared to daylight. This may have an interesting implication on the estimation of seasonality of sediment deposition. We conjecture that in a sediment core, certain sediment fractions have a higher OSL compared to other due to higher prepositional residual signal for samples transported under moonlight as compared to those transported under daylight. A proper protocol with sufficient precision in measurement may enable this. The results also suggest that fast component is affected most by moonlight, due to which estimations based only on fast component can give ∼70% lower dose for moonlight bleached samples (figure 2).

6. Conclusions

This study suggests that the moonlight on earth's surface can bleach luminescence signals to up to 40%. Additionally, if we consider component-specific effects, the moonlight exposure can bleach up to 70% of fast component which is the most important signal in luminescence dating. Though slower, the bleaching does occur and this fact offers prospects of improving the dating of sediments in polar region as also in determining the seasonality of sediment deposition. The limit of bleaching also puts some bound on the accuracy of ages of sediment transported only under moonlight conditions. Detailed study of latitudinal variability in moonlight intensity and its effect on luminescence signal will be of much importance. However, we could not get data of variability in moonlight flux at high latitude regions. The results can then be scaled to suit any latitude, scaling the fluxes with respect to Ahmedabad.

Acknowledgements

AKS thanks the Department of Science and Technology, India for JC Bose National Fellowship and Year of Science Chair Professorship (YOSCP); the Department of Atomic Energy, India for a Raja Ramanna Fellowship. HMR thanks the DST – JC Bose/YOSCP fellowship to AKS for the research fellowship. We thank Prof. R J Wasson and Prof. Stephen Garnett for the sample.

Appendix

Results of IRSL test conducted for feldspar contamination:

We have conducted an IRSL test on three representative quartz aliquots prepared from an extracted bulk quartz sample. The step of measurement protocol involves: Natural dose + preheat + IRSL + OSL + test dose + preheat + IRSL + OSL + test dose + preheat + OSL + test dose + TL.

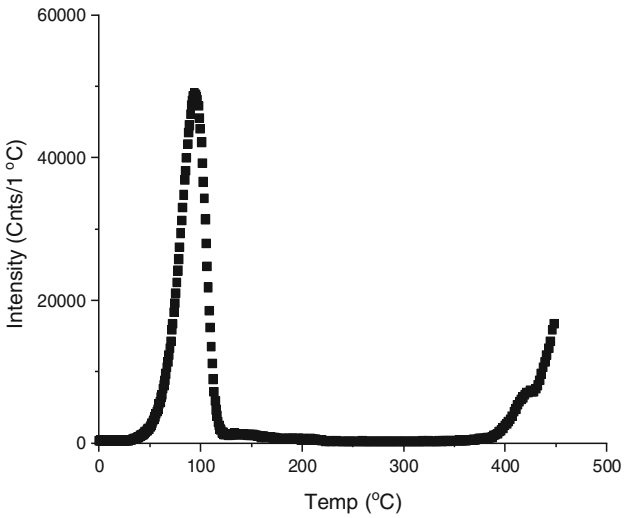

Figure A1. TL glow curve measured after 5 Gy irradiation dose to the bleached quartz aliquot. This clearly suggests that there is no feldspar contamination in measured quartz.

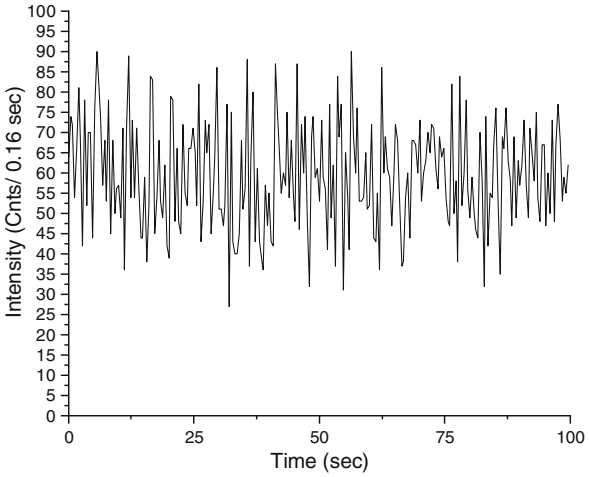

Figure A2. IRSL shine down curve for IRSL after 5 Gy test dose irradiation and prior preheat of 240°C for 10 sec.

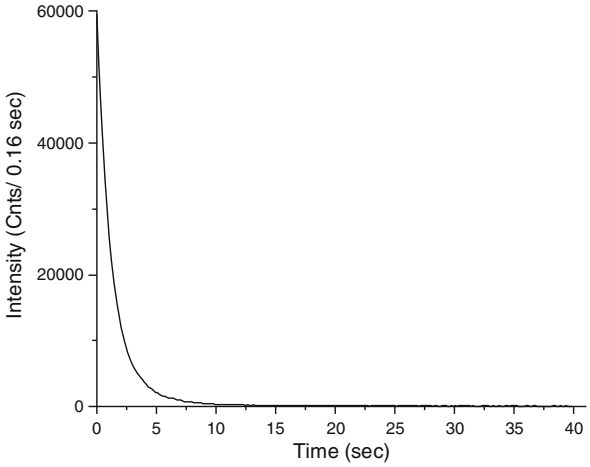

Figure A3. OSL shine down curve for OSL after 5 Gy test dose irradiation and prior preheat of 240°C for 10 sec.

Referring figures A1–A3, it is concluded that there is no feldspar contamination to the quartz.

Author statement

HMR, PNG and AKS developed the hypothesis; HMR and NC designed experiments, selected quartz sediments and analysed the results; HMR and VK performed luminescence measurements and components specific analysis. All authors contributed to the writing of the manuscript.

References

Agrawal D C 2010 Solar luminous constant versus lunar luminous constant; *Lat. Am. J. Phys. Educ.* **4(2)** 325–328.

Agrawal D C 2017 Moon, super-moon, planets of the solar system and star vega: Brightness and size; *J. Phys. Astron.* **5(1)** 1–15.

Aitken M J 1985 *An Introduction to Optical Dating*; Academic Press, Cambridge.

Aitken M J 1998 *Thermoluminescenec Dating*; Oxford University Press, ISBN 0-19-854092-2.

Bailey R M 2000 Slow component of quartz optically stimulated luminescence; *Radiat. Meas.* **32(3)** 233–246.

Bailey R M 2001 Towards a general kinetic model for optically and thermally stimulated luminescence of quartz; *Radiat. Meas.* **33(1)** 17–45.

Bailey R M, Smith B W and Rhodes E J 1997 Partial bleaching and the decay form characteristics of quartz OSL; *Radiat. Meas.* **27(2)** 123–136.

Bøtter-Jensen L and Murray A S 1999 Developments in optically stimulated luminescence techniques for dating and retrospective dosimetry; *Radiat. Protect. Dosimetry* **84(1–4)** 307–315.

Bøtter-Jensen L, Solongo S, Murray A S, Banerjee D and Jungner H 2000 Using the OSL single-aliquot regenerative-dose protocol with quartz extracted from building materials in retrospective dosimetry; *Proceedings of the 9th Int. Conf. Luminescence and Electron-Spin Resonance Dating (LED99)*, **32(5)** 841–845.

Bøtter-Jensen L, Andersen C E, Duller G A T and Murray A S 2003 Developments in radiation, stimulation and observation facilities in luminescence measurements; *Radiat. Meas.* **37** 535–541.

Carver J H, Horton B H, O'Brien R S and O'Connor G G 1974 The ultraviolet reflectivity of the Moon; *The Moon* **9(3–4)** 295–303.

Chen R and McKeever S W S 1997 *Theory of Thermoluminescence and Related Phenomena*; World Scientific Publications, London, NJ, Singapore.

Chen R and Pagonis V 2011 *Thermally and Optically Stimulated Luminescence: A Simulation Approach*; Wiley and Sons, Chichester.

Cramer C E, Lykke K R, Woodward J T and Smith A W 2013 Precise measurement of Lunar spectral irrediance at visible wavelengths; *J. Res. Nat. Inst. Stand. Technol.* **118** 396–402.

David M and Sunta C M 1985 Quartz dosimeter for archaeological dating; *Nucl. Tracks Radiat. Meas.* **10** 625–629.

Godfrey-Smith D I, Huntley D J and Chen W-H 1988 Optical dating studies of quartz and feldspar sediment extracts; *Quat. Sci. Rev.* **7** 373–380.

Jain M, Murray A S and Botter-Jensen L 2003 Characterisation of blue-light stimulated luminescence components in different quartz samples: Implications for dose measurement; *Radiat. Meas.* **37(4–5)** 441–449.

Jain M, Choi J H and Thomas P J 2008 The ultrafast OSL component in quartz: Origins and implications; *Radiat. Meas.* **43(2–6)** 709–714.

Lindvall A, Stjern R and Alexanderson H 2017 Bleaching of quartz OSL signals under natural and laboratory light conditions; *Ancient TL* **35(2)** 12–20.

Murari M K 2006 *Component Specific Luyminescence of Natural Minerals and their Application to the Dosimetry of Natural Radiation Environment*; Ph.D. Thesis, Mohanlal Sukhadiya University, Udaipur, India.

Matthews G 2008 Celestial body irradiance determination from an under filled satellite radiometer: Application to

albedo and thermal emission measurements of the Moon using CERES; *Appl. Opt.* **47** 4981–4993.

Murray A S and Wintle A G 2000 Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol; *Radiat. Meas.* **32(1)** 57–73.

Porat N 2006 Use of magnetic separation for purifying quartz for luminescence dating; *Ancient TL* **24(2)** 33–36.

Sohbati R, Murray A S, Lindvold L, Buylaert J-P and Jain M 2017 Optimization of laboratory illumination in optical dating; *Quat. Geochronol.* **39** 105–111.

Spooner N A 1987 *The Effect of Light on the Thermoluminescence of Quartz*; Unpublished MSc thesis, University of Adelaide, Australia.

Spooner N A 1993 *The Validity of Optical Dating Based on Feldspar*; Ph.D. Thesis, Oxford University, Oxford.

Singhvi A K, Sharma Y P and Agrawal D P 1982 Thermoluminescence dating of sand dunes in Rajasthan, India; *Nature* **295(5847)**.

Singhvi A K, Stokes S, Chauhan N, Nagar Y and Jaiswal M K 2011 Changes in natural OSL sensitivity during single aliquot regeneration procedure and their implications for equivalent dose determination; *Geochronometria* **38** 231–241.

Wintle A G and Murray A S 2006 A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols; *Radiat. Meas.* **41(4)** 369–391.

Corresponding editor: Arkoprovo Biswas