ences were detected in the interior and bottom samples.

Studies of the crystalline rocks (10003 and 10044) are still in progress, but it is evident that the TL carrier (plagioclase) in these rocks is different from the TL carrier in the breccias and the fines. There is more TL, by several orders of magnitude, than there is in the fines; there is a natural peak above 400°C, with no evidence of a peak at 350°C; and the artificial glow curves are unlike those of the fines. There also appear to be differences between the glow curves of the two crystalline rocks, although these differences are not as pronounced as those between the crystalline rocks and the fines and breccias. These differences in TL characteristics are probably caused by dissimilarities either in composition or in the degree of shock metamorphism.

Finally, it is of interest to consider the amount of energy represented by TL in the lunar material. This has been estimated for the fines and breccias by taking the entire area under the glow curves (in lumen-sec), converting it to units of energy through use of the conversion factor for monochromatic green light at 5550 Å, and assuming that the light is emitted from the sample equally in all directions. The values are 8×10^{-9} cal/g for the fines and 2×10^{-9} cal/g for the breccias. Although only rough estimates, these data indicate that TL energy stored in the Apollo 11 samples is exceedingly small.

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References and Notes

1. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969); "Apollo 11 Preliminary Science Report," *NASA Spec. Publ. No. 214* (1969).
2. J. T. Randall and M. H. F. Wilkins, *Proc. Roy. Soc. London Ser. A* **184**, 366 (1945); L. I. Grossweiner, *J. Appl. Phys.* **24**, 1306 (1953).
3. J. A. Ryan, in *The Lunar Surface Layer*, J W. Salisbury and P. E. Glaser, Eds. (Academic Press, New York, 1964), p. 265.
4. We thank B. Myers for assistance with the laboratory measurements. Publication authorized by the director, U.S. Geological Survey.

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Luminescence and Thermoluminescence Induced by Bombardment with Protons of 159 Million Electron Volts

Abstract. *We have observed a red luminescence, qualitatively similar to that of enstatite achondrites, in unsorted fines, their separated mineral phases, and rock chips. The energy efficiency of the plagioclase fraction is approximately 1 percent. At −196°C the effect is enhanced by a factor between 1 and 2. All fractions except ilmenite exhibit blue thermoluminescence with a glow peak near −135°C and an energy efficiency* $\approx 4 \times 10^{-6}$. *Unlike the thermoluminescence of terrestrial and meteoritic material, it is nonrepeatable even after annealing at 200°C. Similar thermoluminescence is seen in rock chips, but in unsorted fines it is masked by the opaque fractions.*

There are two reasons for studying the luminescence of lunar rocks. First, the results may be used, alone or in combination with results from terrestrial and meteoritic rocks, as indicators of specific crystalline defects, hence giving information on the thermal and chemical history of the lunar surface. Second, the existence of a class of transient lunar phenomena has often been ascribed to luminescent effects, and studies of the energy efficiency of such processes, in conditions approximating those found on the moon, are clearly relevant to this interpretation.

Using techniques similar to those we have employed previously (*1*), we have measured the luminescence of samples from Apollo 11 when irradiated in the extracted proton beam of the synchrocyclotron at the Atomic Energy Research Establishment, Harwell. Our beam flux of about 4×10^{8} protons cm^{-2} sec^{-1} gave rise to a local energy density of ionization of 2×10^{15} ev g^{-1} sec^{-1}, which is insufficient to cause radiation damage during the measurements. This energy density is comparable with that resulting from the solar wind on the lunar surface and is a factor of 10^{7} less than the value obtained with low-energy, electrostatically accelerated protons (*2*). Spectra were observed with a set of seven wide-band interference filters and an EMI 9558 photomultiplier tube. The specimens could be cooled to liquid nitrogen temperature and heated to 200°C. The phototube current and thermocouple voltage were recorded on a two-pen recorder.

The specimens studied were two unsorted aliquots of the < 1-mm fines, sample 84; four separated mineral phases from these fines; and two rock chips, a surface and an interior piece, from sample 17. The mineral separation was performed by washing and sieving, followed by magnetic separation of the fraction in the size range 40 to 150 μm. Modal analysis of the four phases yielded the following compositions: (i) plagioclase 88 percent (with 10 percent colorless glass and 2 percent pyroxene composites); (ii) pale pyroxene 68 percent (with 17 percent plagioclase, 13 percent glass, and 2 percent ilmenite); (iii) dark pyroxene 66 percent (with 26 percent ilmenite composites, 4 percent plagioclase and 4 percent glass); (iv) ilmenite 80 percent (with 16 percent pyroxene composites, 2 percent plagioclase, and 2 percent glass). Fractions B and C each contain about 3 percent of unidentified olivine. Note that this size range contains only about 5 percent of glassy fragments and spherules.

The six powder specimens were mounted on aluminum disks using nonluminescent silicone grease. The amount of plagioclase and pale pyroxene was insufficient to completely cover the

Table 1. Luminescent and thermoluminescent parameters of lunar rocks.

Material	Energy efficiency of direct luminescence		Thermoluminescence	
	−196°C	+100°C	Glow peak (°C)	Efficiency
Unsorted fines	1.97×10^{-3}	1.13×10^{-3}		
Plagioclase	1.07×10^{-2}	6.66×10^{-3}	−134	4.32×10^{-6}
Pale pyroxene	7.16×10^{-3}	4.12×10^{-3}	−135	0.72×10^{-6}
Dark pyroxene	3.97×10^{-3}	2.80×10^{-3}	−135	4.09×10^{-6}
Ilmenite	2.54×10^{-3}	1.83×10^{-3}		
Surface chip	Optical depth not known		−132	Optical depth not known
Interior chip			−145	

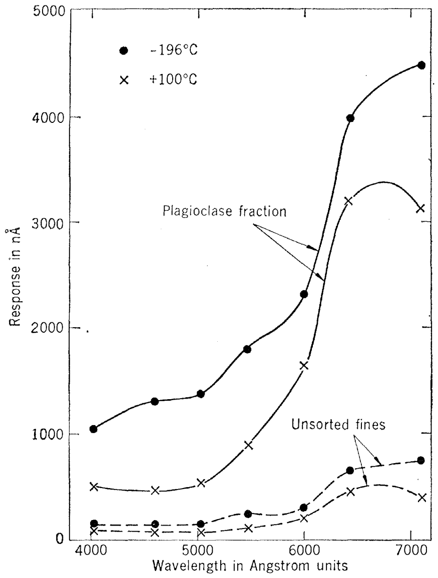

Fig. 1. Luminescent spectra of the unsorted fines and the plagioclase fraction, at −196° and +100°C.

beam target area and allowance was made for this in calculating absolute efficiencies. Spectra for the powder specimens were taken at −196°, 20°, and 100°C, the first and last corresponding roughly to lunar night and day temperatures. Thermoluminescence was looked for after irradiation at −196°C, using a heating rate of approximately 0.5°C sec^{-1}. We also searched for natural thermoluminescence in the unirradiated unsorted fines. No effect was seen on heating from room temperature to 200°C.

The rock chips were mounted similarly. Spectra were taken at 20°C and −196°C; thermoluminescence spectra were also recorded, though the temperature scale of these spectra is unreliable owing to the thickness (≈4 mm) of the chips and the consequent temperature difference between irradiated face and thermocouple junction.

All constant temperature spectra were recorded twice, with an average reproducibility of ±3 percent. Using our knowledge of the gain of the phototube, its spectral response, the transmission of the filters and other optical elements, and the geometry of the system, we were able to deduce from the phototube output current the total number of photons emitted per second per unit wavelength interval, $N(\lambda)$. From this result and the bandwidth of the filters, the total energy emitted as visible light, E, was calculated. We estimate the systematic standard error of $N(\lambda)$ to be ±14 percent and of E to be ±17 percent.

In a subsidiary experiment we measured the optical depth of our powder samples and found it to be 0.0099 ± 0.0003 g cm^{-2} for the unsorted fines and 0.0078 ± 0.0006 g cm^{-2} for the ilmenite. The other specimens were transparent and thinner than their optical depth.

We then calculated E_0, the energy deposited within the optical depth by the proton beam. The energy efficiency ε of the direct luminescence is given by E/E_0 and of the thermoluminescence by

$$\left(\int_0^{t=t_1} E\,dt\right)\Big/\left(\int_0^{t=t_0} E_0\,dt\right)$$

where t_0, t_1, are the times of irradiation and heating, respectively. Estimating the systematic error of E_0 to be ±12 percent, we find the systematic error in ε to be ±20 percent.

The spectra for direct luminescence exhibit the following features. There is a pronounced red enhancement at all three temperatures, the ratio red/blue being about seven at 20° and 100°C, and varying from 2½ (pale pyroxene) to 4½ (unsorted fines and ilmenite) at −196°C. The spectra of all specimens have the same general shape and vary significantly in their absolute brightness. In Fig. 1 we show the responses of plagioclase (the brightest fraction) and the unsorted fines, at −196° and 100°C. As is generally the case with terrestrial and meteoritic specimens, the responses at 20° and 100°C are very similar. The unsorted fines and the ilmenite fraction have almost identical spectra, presumably because the opaque ilmenite grains mask the brighter response of the transparent minerals. In Table 1 we show the energy efficiency ε summed over the visible spectrum using the expressions above. We give ε for each specimen at 100° and −196°C. The ratio is seen to vary from 1.39 to 1.75.

As a check on our calculations we also measured the luminescence of a granite specimen that had previously been compared with a commercial phosphor of known efficiency. The results were in agreement with the previous measurements and confirm that the efficiencies approach 1 percent for the plagioclase fraction.

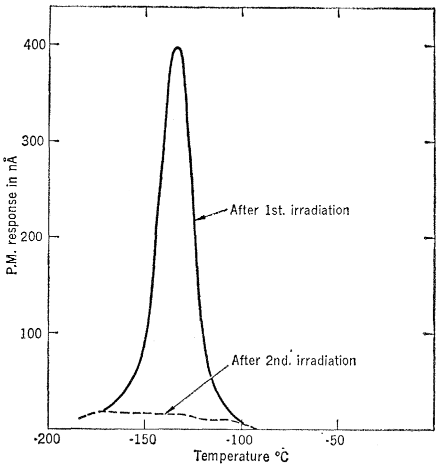

Fig. 2. Thermoluminescence of the plagioclase fraction, measured in the wavelength band 4350 to 4850 Å.

All specimens except the ilmenite and the unsorted fines showed pronounced blue thermoluminescence, peaked sharply in the region 4350 to 4850 Å, at temperatures below −120°C. The glow peak for the plagioclase fraction is shown in Fig. 2. There was no significant thermoluminescence in any other wavelength band nor at higher temperatures. Specimens were heated to 200°C and held at this temperature for several minutes. A very interesting effect was then noted: it was not possible to reproduce the blue glow peaks after a second irradiation at low temperature. This effect is shown in Fig. 2, where in place of the sharp peak we see only a small effect not very different from the background.

This phenomenon renders precise calculation of the energy efficiency rather difficult, as this quantity will be determined eventually by the number of luminescent centers available rather than by the period of irradiation. The values of ε given in Table 1 are therefore lower limits (since the same glow curve could perhaps have been produced by a shorter irradiation).

The rock chips exhibited similar thermoluminescence, and it is interesting to note that, though our knowledge of heating rates is poor, the glow peaks for the interior and the surface chip have very different efficiencies. We do not yet know whether this phenomenon reflects a real difference in radiation history or is due, for instance, to different minerals' being fortuitously exposed.

As with many other properties of the lunar rocks, these spectra are not precisely matched by any terrestrial counterpart. It is nevertheless interesting to note that the red luminescence seen in enstatite achondrite meteorites [Khor Temiki (*1*), Bustoe (*3*), Bishopville (*3*)] is qualitatively very similar and is roughly of the same magnitude. The similarity in the blue is strikingly improved if one assumes an equal admixture of terrestrial vesicular basalt, spectra of which show, at −196°C, the plateau near 5000 Å characteristic of all our lunar specimens. The enstatite achondrites do not show such bright blue thermoluminescence as do the lunar rocks. They have been studied by ourselves [Khor Temiki (*1*)], and by Sun and Gonzales [Cumberland Falls (*4*)], and we both find a red glow peak near 0°C. Sun and Gonzales saw a blue glow peak near −120°C, but we found this peak to be much less intense than the red one, which does not appear at all in the lunar rocks.

Presumably the red luminescence shown by all our specimens is due either to a mineral phase common to all fractions or to the ubiquitous presence of an activator that is increasingly quenched by the larger concentrations of iron in the more magnetic fractions. In view of the modal analysis above, showing a moderately clean separation, we incline to the second suggestion.

The blue thermoluminescence might be ascribed to the same activator were it not for its complete absence from the ilmenite fraction. As regards its nonrepeatability, such an effect is observed in some crystalline phosphors, particularly alkali halides, in which thermoluminescent recombination occurs at *F* centers that are thermally stable up to the annealing temperature. However, we had not previously seen this effect in any of our terrestrial or meteoritic specimens. The phenomenon is obviously highly relevant to the problem of transient lunar phenomena, many of which have recurred in the same areas of the moon's surface.

Two lines of thought have been suggested. Either the surface is irradiated at night and glows on heating during the day, or subsurface layers at temperatures near − 50°C (*5*) are sporadically exposed and heated and give off as light the energy accumulated during many years of irradiation (by high-energy particles). We can now state, at least for the Sea of Tranquillity, that the energy efficiency of thermoluminescence is too low for the first effect to be seen and that the glow appears at a temperature too low for the second hypothesis to hold. Moreover, repeated thermoluminescence of the same material is unlikely as local temperatures never exceed 200°C.

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References and Notes

1. I. M. Blair and J. A. Edgington, *Nature* **217**, 157 (1968).
2. D. B. Nash, *J. Geophys. Res.* **71**, 2517 (1966).
3. C. J. Derham, J. E. Geake, G. Walker, *Nature* **203**, 134 (1964).
4. K. H. Sun and J. L. Gonzales, *ibid.* **212**, 23 (1966).
5. We thank Dr. W. J. French and Dr. A. B. Poole of the Geology Department, Queen Mary College, University of London, for assistance in separating and identifying the various mineral phases. We also thank Dr. J. A. Bastin for discussions particularly on lunar temperatures.

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Luminescence, Electron Paramagnetic Resonance, and Optical Properties of Lunar Material

Abstract. *Dust samples have been found to luminesce weakly under proton excitation, but not under ultraviolet. Damage, recovery, and heating effects have been investigated. Chips of breccia show luminescence, from white inclusions only, under ultraviolet and protons. Some rock chips show general luminescence, mainly from plagioclase. No natural or excited thermoluminescence has been found for dust or chips. The electron paramagnetic resonance spectrum shows the same broad* Fe^{3+} *dipole resonance for dust and for some chips; other chips show no response. The polarization characteristics of dust are found to be identical to those of the Sea of Tranquillity, independently of proton damage. Chips show characteristics unlike any part of the lunar surface.*

Dust sample 10084.6 showed no visible luminescence under ultraviolet excitation at room temperature, or when cooled in liquid nitrogen; two lamps emitting radiation at mainly 3650 and 2537 Å, respectively, were used. No infrared emission (beyond 7300 Å) was detected by a Ag-AgO-Cs photomultiplier or by a PbS cell when dust at either temperature was irradiated by intense visible light (cutoff at 6000 Å) from a quartz/iodine lamp.

Under excitation by 60-kev protons, weak luminescence with no afterglow was observed; the spectrum of this luminescence was scanned by a grating spectrophotometer with successive trialkali and Ag-AgO-Cs photomultipliers (Fig. 1). The emission is nearly white, with a low green peak at about 5600 Å and a lower blue one at about 4500 Å. The efficiency is very low; for fresh dust it is about an order of magnitude less than for Gnadenfrei meteorite (*1*) or standard basalt BCR-1 (*2*) and is estimated at about 10^{-5}. Basalt gave a peak of emission at about 7300 Å, and this was not found for the lunar dust.

The albedo, with a fresh MgO screen taken as unity, was about 7 percent when a tungsten lamp at 2850°K and a trialkali photomultiplier were used; for basalt it was about 40 percent. Heating the dust to about 760°C in argon (as described later) doubled both the luminescence efficiency under proton excitation and the albedo. The emission spectrum changed (Fig. 1) and so did the diffuse-reflection spectrum (Fig. 2), the dust now appearing brown in color. There is some x-ray evidence that heating produces some structural annealing, and this may be the cause of the increased efficiency. Dust heated to 960°C in argon appeared slightly darker than the 760°C sample, and its luminescence emission spectrum (Fig. 1) was slightly more like that for the fresh dust.

Damage by proton irradiation caused

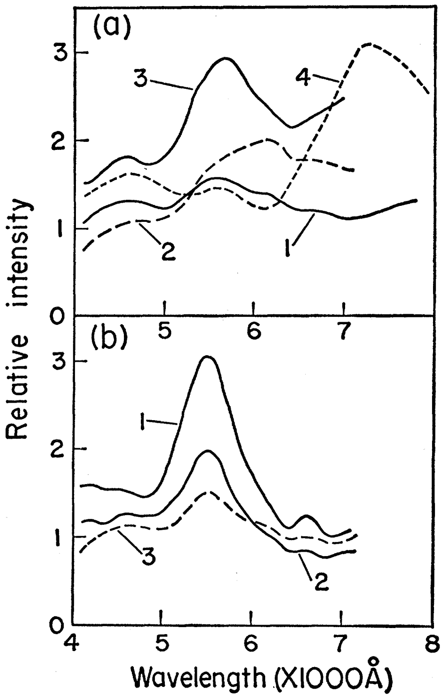

Fig. 1. Luminescence emission spectra with 60-kev proton excitation. (a) 1. Lunar dust 10084.6, fresh; 2. after heating to 760°C in argon; 3. after heating to 960°C in argon; 4. basalt BCR-1. (b) 1. Light fraction from rock 10044.43—mainly plagioclase. 2. Rock chip 10058.37. 3. Rock chip 10057.54. The intensity scales of the separate spectra are unrelated.