References and Notes

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Luminescence of Apollo 11 Lunar Samples

Abstract. *Luminescence measurements were made of four lunar rocks, two terrestrial rocks (granite and gabbro), and one terrestrial mineral (willemite) by comparing the spectral curves with the curve of a barium sulfate standard. Efficiencies with 3000 angstrom excitation were* $\leqslant 6 \times 10^{-5}$ *for the lunar samples,* $\leqslant 8 \times 10^{-5}$ *for gabbro of very similar composition to the lunar samples, approximately* 10^{-4} *for granite, and approximately* 2×10^{-2} *for willemite. If these are typical values for other ultraviolet excitation wavelengths, the Apollo 11 site appears to contribute little to the observed lunar luminescence.*

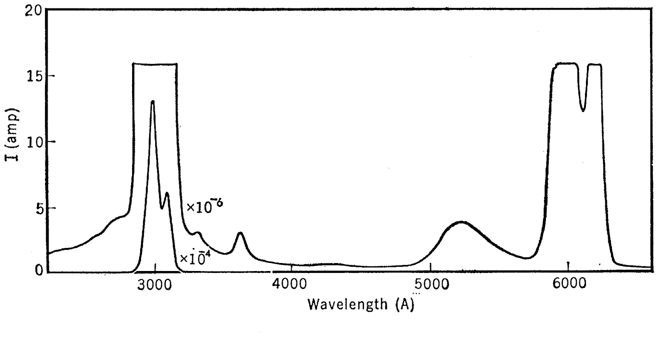
On the basis of lunar eclipse observations, Link *(1)* proposed that the light of the moon contained a luminescence component in addition to the reflected solar component. Later observations, especially by means of the Fraunhofer line-depth technique, seemed to confirm this idea *(2–5)*. Our objective is to evaluate these observations and understand the luminescence behavior of lunar lithologic materials by measuring the luminescence spectra and efficiencies of the lunar samples with the chief excitation sources in the space environment and by comparing the results with those of similar measurements of terrestrial rocks and minerals. The excitation sources of interest are ultraviolet, x-rays, protons, and electrons.

We give here some results of our measurements of the Apollo 11 samples with ultraviolet excitation. A Hanovia 2500-watt high pressure xenon-mercury lamp was the source of ultraviolet. The light, before striking the samples, passed through a Gaertner quartz prism monochromator with a Corning 7-54 filter at the exit slit to cut out wavelengths longer than 4000 Å. The light from the sample passed through a Jarrell-Ash 0.25-m grating spectrometer, either with or without a Corning 3-74 filter at the entrance slit to cut out wavelengths shorter than 4000 Å, and finally to an EMI 9558Q photomultiplier tube. The photomultiplier output was recorded by a Moseley 2D-2 X-Y recorder.

Initially, some runs were made on terrestrial comparison samples with a Hunter hydrogen capillary glow discharge lamp as a source. This lamp, which concentrates the glow discharge within a small capillary, is used as our source of hydrogen Lyman-alpha (1216 Å). The light in this case irradiated the sample directly with only a magnesium fluoride window intervening. Preliminary results appeared to show no significant luminescence. The luminescence excited by Lyman-alpha appears to be less than that excited by the middle and near ultraviolet and will require a different experimental set-up to be detected and measured. For this reason, subsequent runs on the lunar and terrestrial samples were made with maximized irradiation intensity with the Hanovia lamp. A wavelength band of about 200 Å width at half maximum, centered at about 3000 Å, was used.

The samples were mounted on a 12-position turntable inside a vacuum chamber. Six samples from four lunar rocks were included: 10044,38 (exterior) and 10044,53 (interior) from a coarse-grained igneous rock, 10048,36 (interior) and 10048,37 (bottom) from a breccia, and 10057,45 (interior) and 10022,55 (surface) from two fine-grained igneous rocks. The exposed surface area ranged from a little less than 1 to a little less than 2 cm^2. Terrestrial comparison samples consisted of granite (El Capitan formation, Mariposa County, California), gabbro (near San Marcos, San Diego County, California), and willemite (Franklin Furnace, New Jersey), the latter a highly luminescent mineral. The remaining three turntable positions were occupied by a barium sulfate surface to serve as a reflectance standard, a thermopile for absolute energy calibration of the excitation beam and the system, and an aluminized mirror for alignment of the system.

The luminescence efficiencies at 3000 Å excitation for all samples except the willemite proved to be too low to give a distinct, unambiguous luminescence spectrum. The curve for willemite (Fig. 1) shows the spectrum obtainable from a material of high efficiency, in this case about 2×10^{-2}. The other eight samples gave curves of the type shown in Fig. 2 recorded for lunar sample 10057,45. In these cases, at the maximized intensity of irradiation and the high sensitivities required to sense any luminescence, the effects of scattered light and of the small, nonzero transmission of the filter made



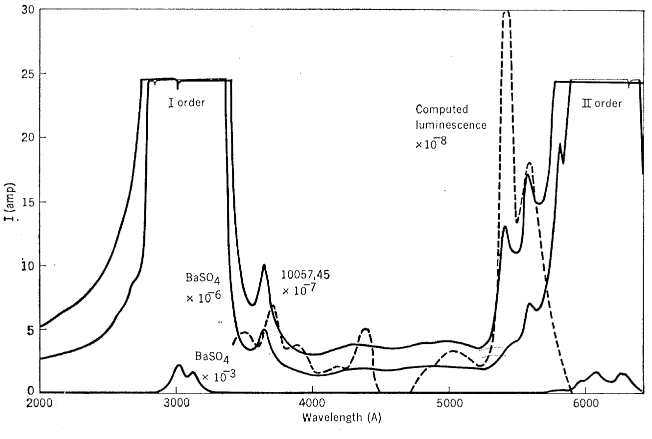


Fig. 1 (above). Luminescence of willemite with 3000-Å excitation. Fig. 2 (right). Luminescence of lunar sample 10057,45 compared with barium sulfate standard (3000-Å excitation).

the signal background limited. To extract the luminescence signal, shown as the computed curve of Fig. 2, therefore, it was necessary to use the technique of comparing the sample curve with that of the barium sulfate reflectance standard.

The barium sulfate has a reflectance of very nearly 100 percent over the entire wavelength band investigated and is not known to have any significant luminescence in this band. Its curve, therefore, represents the spectrum of the light exciting the sample, and the ratio of the sample curve to that of barium sulfate is the sample reflectance. Any increase of apparent reflectance of the sample can be the result of either reflectance changes or luminescence or both. Comparison of such curves from all samples showed increases, and therefore possible luminescence, in the neighborhood of 5300, 5500, 3500 to 4100, 4300 and 4970 Å, in order of decreasing intensity. The 3500- to 4100-Å band, especially, is a region in which we have found granite and gabbro reflectance values to remain constant or to decrease, so that in this region, at least, the case for luminescence is strengthened. However, the effects are small and could arise from other than luminescence. In this event, the calculated efficiences represent an upper limit for the samples for the conditions of this particular set of measurements.

The efficiencies are as follows: all lunar samples, $\leqslant 6 \times 10^{-5}$; granite, $\sim 10^{-4}$; gabbro, $\leqslant 8 \times 10^{-5}$; and willemite, $\sim 2 \times 10^{-2}$. The values represent total efficiencies; that is, the ratio of energy in the luminescent band to energy in the band incident upon the sample. Despite the uncertainty, the values shown are consistent in that the lunar samples, which are very similar to gabbro in composition, are also similar in apparent luminescence efficiency.

The outstanding feature of these results is the low values of the efficiencies for the lunar samples and the two terrestrial rocks. They are comparable to the terrestrial rock efficiencies that we and Nash measured with protons and that we measured with electrons and x-rays; they are also much lower than those we estimated for terrestrial rocks with the 1800- to 2200-Å band by a less refined filter method (*6*, *7*). In our earlier study, with a 1 percent efficiency for the 1800 to 2200 Å band, we calculated a level of luminescence, 5 percent of the reflected background in the 2200 to 2500 Å band, that was the average observed around 3950 Å by Grainger (*4*), who made the most accurate line-depth measurements of the moon. The efficiencies we measured in this study of the Apollo 11 lunar samples are more than two orders of magnitude lower; in a similar calculation they would yield a level of luminescence that would be undetectable by the line-depth technique. If our further studies with excitation at other ultraviolet wavelengths and with proton, electron, and x-ray excitation show no greater efficiencies than these, the Apollo 11 landing area can be considered to contribute little or nothing to the luminescence determined by the line-depth technique. Grainger's observations did not include the Apollo 11 landing area; if correct, they imply higher luminescence efficiencies on other areas of the moon. Terrestrial gabbros, which are similar in composition to the Apollo 11 rocks, are found in both this and previous studies to possess low luminescence efficiency as compared to granites. Therefore, other lunar areas, especially in the highlands, could contain rocks of higher efficiency than those from Apollo 11. In this connection, note that the Surveyor 7 alpha-scattering analysis measured less than half as much iron, a luminescence-quenching element, at the Tycho site than was measured at the Surveyor 5 and 6 mare sites (*8*). Finally, it is possible that certain excitation mechanisms that exist in the space environment, such as simultaneous irradiation with ultraviolet and charged particles, may result in higher efficiencies and await laboratory testing. For these reasons, samples from many areas of the moon need to be studied in order to characterize the luminescence of the lunar rocks and to understand its significance.

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Luminescence and Reflectance of Tranquillity Samples: Effects of Irradiation and Vitrification

Abstract. *Luminescence measurements of Tranquillity samples indicate that energy efficiencies for excitation by protons and ultraviolet are in the range 10^{-6} or below; natural and induced thermoluminescence is even weaker. If these samples are typical, lunar surface luminescence cannot occur at reported levels. Comparison of proton luminescence spectra from the exterior and interior of rocks and fine fragments provides evidence of solar wind impingement on the moon's surface. Spectral reflectance and albedo measurements of fresh rock powders before and after both laboratory proton irradiation and fusion indicate that vitrification may be an important mechanism of lunar darkening.*

Experiments simulating solar wind proton irradiation and solar ultraviolet irradiation on the moon's surface were performed to determine the emission properties and energy efficiencies of luminescence and thermoluminescence as well as the effects of irradiation and vitrification on spectral reflectance (0.23 to 2.5 μm) and albedo. Samples examined (*1*) represent each of the three rock types and fine soil collected (*2*).

Samples were handled and prepared in dry N_2. This was later omitted when experiments showed no detectable effects on any of our measurements from exposure to air. Proton and ultraviolet irradiations were conducted in vacuum at 10^{-6} torr. Thermoluminescence and spectral reflectance measurements were made with instruments flushed with dry N_2.

Irradiations were carried out with 1-, 2-, and 4-kev protons (to simulate solar wind) at fluxes in the range 3 to 10×10^{13} protons cm^{-2} sec^{-1} (~ 5 to 15 μa cm^{-2}) for doses of up to 4×10^{19} protons cm^{-2} (equivalent to 2×10^{4} years of solar wind) per sample, and simultaneously and independently with