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# Two-Color Photoelectric Photometry of the Earthshine

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This paper presents two-color observations of the earthshine made during 14 nights of July and August 1965 at the Boyden Observatory in South Africa. Although the information provided is limited because the observations cover a range in phase angle of only 45°, it is possible to derive earth albedos of 0.30 in $V$ and 0.36 in $B$, both accurate to about 10%.

The efforts of *Danjon* [1954] and colleagues have established the average visual Bond albedo of the earth to lie near 0.36. However, it is difficult to assess to what extent this value varies with changing meteorological conditions and differing observing locations. Danjon's observations were carried out only in France, and both he and *Fritz* [1949] have indicated the benefits of photometry from other stations. *Wildey* [1964], although beset by various uncertainties, has obtained from a photometer carried in Mariner 2 results that differ from those of Danjon by a factor of about 2. Danjon's measures, which result exclusively from visual observations, are obtained by a clever method that is very successful in dealing with light scattered from the sunlit portion of the moon and with atmospheric extinction. However, his method does require a determination of the brightness variation of the average lunar crescent and of the brightness of the sunlit moon in terms of a known source. Recent observations [*Gehrels et al.*, 1964] indicate that the sunlit portion of the moon undergoes substantial brightness fluctuations for which these authors consider luminescence a possible explanation.

The present study aims, first, to provide $V$ and $B$ photoelectric observations of the earthshine that are not measured in terms of the sunlit lunar crescent, and, second, to find the maximum lunar phase at which reliable measurements could be readily obtained. We present here photometry of two regions on the earthlit portion of the moon measured on 14 nights at the Boyden Observatory in South Africa during July and August 1965. The chief problem encountered, and one not completely solved, was the accurate evaluation of scattered light contributed by the sunlit lunar crescent. To determine the amount of scattered light, we first obtained isophotes of the sky surrounding the waxing and waning moon at crescent phases. For phases less than first quarter or greater than last and under different sky conditions, isophotes that passed through ±20° selenographic latitude at the moon's dark limb were parallel to the terminator. This fact suggested that we confine observations to homogeneous areas that fulfilled these two positional requirements. The chosen regions were Mare Crisium (18°N, 60°E) for morning, or waning moon, observations, and a region at (19°N, 60°W), near but not including Aristarchus, in Oceanus Procellarum for evening observations. After a measurement of one of these areas it was fairly simple to obtain a sky reading by setting the diaphragm of the photometer just off the lunar surface and parallel to the terminator. Figures 1*a* and *b* reveal that the sky background has probably been underestimated when $\tau \equiv |180° - \text{lunar phase angle}|$ was greater than $\sim 65°$. This is particularly true of the measurements of Mare Crisium, which, during the course of these observations, was farther from the lunar limb than the Oceanus Procellarum region. Mare Crisium and Aristarchus, which served to locate the second region, were sufficiently conspicuous to enable us to obtain reliable positional settings for $\tau \gtrsim 80°$.

All observations reported here were obtained at the Cassegrain focus of a 16-inch reflector. Two diaphragms with diameters of 50.5 and 78.4 seconds of arc were used throughout. The two regions measured were sufficiently homogeneous over such a scale that both diaphragms gave the same value of the earthlight when reduced to magnitudes per square second of arc. Although measurement of the earthlight near new moon required observations through several air masses, atmospheric extinction never proved a serious problem. It was always possible to find late *A*, *F*, *G*, and early *K* stars sufficiently near the moon so that the air-mass difference between the moon and usable comparison stars was less than 0.15. Extinction coefficients did, however, vary by substantial amounts from night to night. Hence the use of a seasonal mean extinction seemed unsound, and we have relied upon nightly values. The filters used were Corning 3384 for *V*, and Corning 5030 plus 2 mm of Schott GG13 for *B*. Observations of 13 standard stars on three nights of fine quality provided transformations to the *B-V* system.

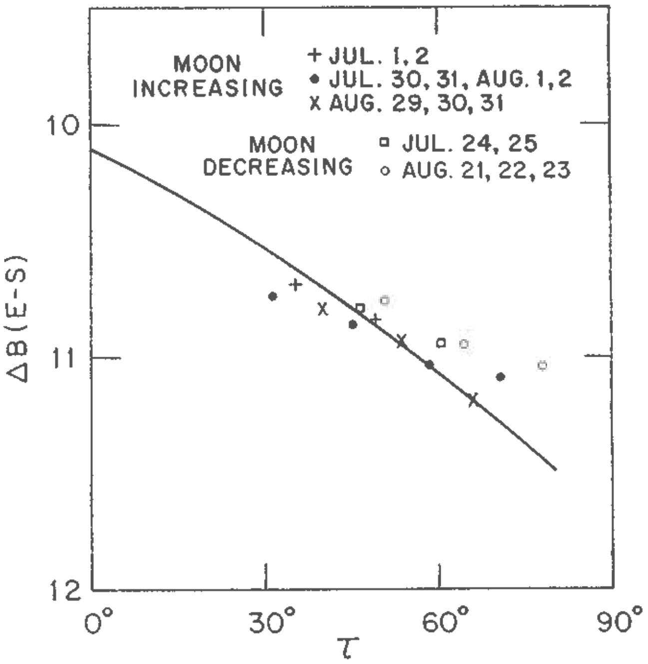

Fig. 1*a*. Difference in magnitude in blue light (*B*) between the earth and sun as a function of the phase angle *τ*.

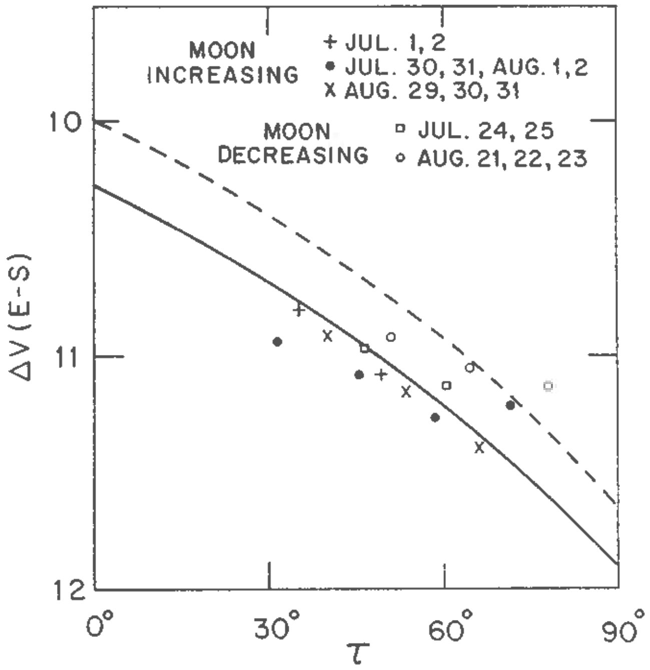

Fig. 1*b*. Difference in magnitude in yellow light (*V*) between the earth and sun as a function of the phase angle *τ*. The dashed curve is from *Danjon* [1954].

Table 1 and Figure 1 present the photometric results. The phase angle *τ* tabulated in column 3 and used as the abscissa in Figures 1*a* and *b* is the angular separation of the moon and sun as viewed from the earth. Columns 4 and 5 give *V* and *B* magnitudes per square arc second of the moon as illuminated by the earth at the mean earth-moon distance of $3.844 \times 10^5$ km. Thus these values contain the combined effects of the earth's brightness and the local lunar reflectivity. We can remove the latter effect thanks to the work of *Wildey and Pohn* [1964]. They have observed a large number of lunar features near full moon, at lunar phase angles as low as 1.1°. Their observations include photometry of Mare Crisium and a region in Oceanus Procellarum that closely resembles the area that we have measured in earthlight. The difference between their magnitudes and those in columns 4 and 5 at the same phase angle gives the brightness difference between the earth and sun. It is, however, impossible to make both sets of observations at the same phase angle. The relevant phase angle in the case of earthshine measurements is the angular separation between the center of light of the earth and the observer as viewed from the moon. For our observations this angle varies between 0.7 and 0.9°, while the minimum angle at which *Wildey and Pohn* [1964] could observe was somewhat greater than 1°. Although the difference between these two phase angles is small, this is just the region where theory predicts [*Hapke*, 1963] and observation confirms [*Gehrels et al.*, 1964] that the lunar phase curve becomes steep and nonlinear. Thus an extrapolation of Wildey and Pohn's results even from a phase angle of 1.2° to the mean value of 0.8°, which we adopt

TABLE 1. Photometric Results

| Date and UT | Region | Phase Angle $\tau$, deg | $V$ | $B$ | $(V_E - V_S)$ | $(B_E - B_S)$ | $(B_E - V_E) - (B_S - V_S)$ |
|---|---|---|---|---|---|---|---|
| 7/1.7/65 | O.P. | 35.4 | 14.37 | 15.05 | 10.81 | 10.69 | −0.12 |
| 7/2.7 | O.P. | 49.4 | 14.64 | 15.20 | 11.08 | 10.84 | −0.24 |
| 7/24.1 | M.C. | 60.2 | 14.71 | 15.37 | 11.13 | 10.95 | −0.18 |
| 7/25.2 | M.C. | 46.7 | 14.55 | 15.22 | 10.97 | 10.80 | −0.17 |
| 7/30.7 | O.P. | 31.6 | 14.50 | 15.10 | 10.94 | 10.74 | −0.20 |
| 7/31.7 | O.P. | 45.4 | 14.65 | 15.23 | 11.09 | 10.87 | −0.22 |
| 8/1.7 | O.P. | 58.6 | 14.84 | 15.40 | 11.28 | 11.04 | −0.24 |
| 8/2.7 | O.P. | 71.4 | 14.78 | 15.45 | 11.22 | 11.09 | −0.13 |
| 8/21.1 | M.C. | 78.1 | 14.71 | 15.47 | 11.13 | 11.04 | −0.09 |
| 8/22.1 | M.C. | 64.8 | 14.64 | 15.37 | 11.06 | 10.95 | −0.11 |
| 8/23.2 | M.C. | 51.1 | 14.48 | 15.18 | 10.90 | 10.76 | −0.14 |
| 8/29.7 | O.P. | 40.1 | 14.48 | 15.16 | 10.92 | 10.80 | −0.12 |
| 8/30.8 | O.P. | 53.8 | 14.72 | 15.29 | 11.16 | 10.93 | −0.23 |
| 8/31.8/65 | O.P. | 66.0 | 14.96 | 15.56 | 11.40 | 11.20 | −0.20 |
|  |  |  |  |  |  | Mean | −0.17 |

as applying to all earthshine measures, can introduce an uncertainty of perhaps a tenth of a magnitude. The phase curve of Mare Crisium obtained by *Gehrels et al.* [1964] agrees quite well with that of Wildey and Pohn, so that for this region we have adopted from these two sources $V = 3.58$ and $B = 4.42$ mag per square arc second at 0.8°. For the Oceanus Procellarum region the observations of Wildey and Pohn give $V = 3.56$ and $B = 4.36$ at the same phase angle. (Dr. Wildey has kindly pointed out that the magnitudes given in their paper refer to the sun-moon distance at the time of observation. The magnitudes quoted here apply at 1 AU.) Subtracting these magnitudes from the appropriate ones of columns 4 and 5 gives the earth-minus-sun magnitudes of columns 6 and 7. Column 8 tabulates the color of the earth with respect to the sun. The scatter around the mean value of 0.17 mag conceals any possible dependence of color on phase angle. *Danjon* [1954] finds the color of the earth to have a pronounced seasonal dependence but with a mean value also somewhat bluer than the sun. This color probably results from haze and Rayleigh scattering in the earth's atmosphere.

Figures 1*a* and *b* plot the entries of columns 6 and 7 against the phase angle $\tau$. Also included is Danjon's mean curve. It is at once clear, first, that our photometry yields a fainter value for the brightness of the earth than did Danjon's measurements, and, second, that the contribution of light scattered from the sunlit moon to observations for $\tau \lesssim 65°$ has probably been underestimated. Our results and those of Danjon are not necessarily in conflict. We have already noted the evidence for luminescence presented by *Gehrels et al.* [1964]. Such an effect could influence all the photometry referred to in this paper. One would also expect the brightness of the earth to be a function both of the observer's location and of terrestrial meteorology. Both before and after new moon, oceans, which have lower reflectivities than land areas, constitute a slightly larger portion of the illuminated earth for a station in South Africa than for one in France. Before new moon, Australia, Southeast and Central Asia, and the Indian Ocean region are the areas that illuminate the moon as viewed from South Africa, while after new moon, the American continent, the Atlantic Ocean, and Northwest Africa are responsible. The land-to-ocean ratios are roughly equal for these two general areas.

Although clearly of limited accuracy and covering an incomplete range in phase, our measurements allow an approximate determination of the earth's phase integral. This quantity is defined [*Russell*, 1916] as

$$q \equiv 2 \int_0^{\pi} \phi(\tau) \sin \tau \, d\tau \qquad (1)$$

where $\phi(\tau)$ is the ratio of the brightness of an object at phase angle $\tau$ to its brightness at full

TABLE 2. Photometric Parameters of the Earth in $V$ and $B$

| $(V_B - V_S)_{\tau=0°}$ | $10.28 \pm 0.10$ | $(B_B - B_S)_{\tau=0°}$ | $10.11 \pm 0.10$ |
|---|---|---|---|
| $q$ | 1.079 | $q$ | 1.079 |
| $p$ | $0.281 \pm 0.027$ | $p$ | $0.329 \pm 0.032$ |
| $A$ | $0.30 \pm 0.03$ | $A$ | $0.36 \pm 0.04$ |

phase. Fortunately, our observations cover the phase range in which the integrand of equation 1 assumes its maximum value. The resulting value of $q$, which to the accuracy of these observations is independent of color, is 1.079. Application of *Russell*'s [1916] rule,

$$q = 2.2\phi(50°)$$

gives $q = 1.074$. *Danjon* [1954] finds $q$ to be 1.095. Since Danjon's mean curve served as a basis for the extrapolation to $\tau = 0°$ and beyond quarter phase, the determination here cannot be regarded as independent.

To obtain the albedo of the earth, we must extrapolate the observed phase curves to 'full earth' or, in other words, to $\tau = 0°$. Again we have relied on the shape of Danjon's mean visual curve for this extrapolation in both $B$ and $V$. This in effect places low weight on the observations for which $\tau > 60°$, which is the region where the earthshine measurements have apparently been contaminated by scattered light. We thus find that at full earth $(V_B - V_s)_{\tau=0°} = 10.28$ and $(B_B - B_s)_{\tau=0°} = 10.11$ mag. Note that we have assumed the average color difference of 0.17 mag found for larger phase angles applies at $\tau = 0°$. It is, however, conceivable that the intercept at $\tau = 0°$ for the blue curve lies nearer $\Delta B = 10.4$ than 10.1 mag.

It is difficult to evaluate the error range associated with the points of Figures 1*a* and *b*. The standard deviation of the mean of all observations on any single night, based upon an average of eight separate settings on the moon, is $\pm 0.03$ mag. That the scatter from night to night is greater than this could be due to fluctuations in the brightness of the earth and moon or the presence of scattered light from the bright moon. On the basis of Figure 1 we suggest an error range of $\pm 0.10$ mag for both $(V_B - V_s)_{\tau=0°}$ and $(B_B - B_s)_{\tau=0°}$, though it may be greater. These two differential magnitudes and accompanying error ranges lead to the values of and limits on the geometric albedo $P$ and Bond albedo $A$ given in Table 2.

*Danjon* [1954] has derived an average visual albedo of 0.40 from an observing site in France, but he has suggested 0.36 as a better figure for a worldwide average value. Despite the apparent difference between his value and the one derived here, a closer examination reveals that they are in close agreement. Although Danjon's value for the brightness difference between the full earth and the sun averaged over the year is 9.99 mag, his average value for July and August alone is 10.24, which is only 0.04 mag different from our result. He has also found for this period that the magnitude difference between the earth and sun is less for the decreasing moon than it is for the increasing moon by about 0.1 mag. Figure 1 shows the same effect.

That the brightness of the full earth is essentially the same at two stations in different hemispheres separated by 80° in latitude, but only by 20° in longitude, is perhaps a likely result. One might have expected the earthshine to be brightest in the southern hemisphere when faintest in the northern. It seems significant that Danjon's work shows the earthlight to be most faint when the snow cover is at a minimum. However, snow cover on those parts of the earth's surface responsible for the earthlight as observed from South Africa shows a small seasonal variation. In particular, the snow cover on land areas in the southern hemisphere is especially constant. Thus the seasonal albedo dependence probably varies in phase but with a smaller amplitude than the corresponding measurements made in France. The scatter of the points in Figure 1 for small $\tau$ suggests that brightness fluctuations shorter in duration than any seasonal ones may be at least as high as 0.1 mag.

The results of the photometry presented here are therefore entirely in accord with the visual measures of Danjon. We conclude with *Danjon*

[1954] and *Fritz* [1949] that the average Bond albedo of the earth is close to, or possibly less than, 0.36 in $V$, and we now suggest that it is about 20% higher in $B$.

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