PHOTOMETRY OF THE LUNAR SURFACE *

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Abstract. The photometry of the Moon gives us some information about the properties of the lunar surface. The photometric uniformity of the lunar surface as a scattering screen is determined by the shadow phenomena on small irregularities due to the dust layer covering the whole surface. A small component of light (< 10 %) exhibits the features of the luminescence excited by solar radiations.

1. Introduction

The photometry of the Moon has provided much information about the optical properties of the lunar surface which was subsequently confirmed in many cases by the lunar Apollo missions. Every student of the Moon should be therefore informed of the work carried out in this domain not only from the historical point of view but also from the perspective of future work. It is now evident that the number and the locations of lunar missions will necessarily remain limited and that continued use of distant photometric methods suitably calibrated by direct measurements will be still useful for the exploration of other spots on the Moon not visited by man.

Like no other celestial body the Moon offers us the opportunity for the photometric exploration of its surface. The absence of an atmosphere and the proximity of the Moon favour this kind of research. At first integral photometry gives us a rough insight into photometric properties which are further considerably deepened by detailed photometry. Our lecture also includes the photometry of lunar eclipses and of the Earth's light, both being more or less directly connected with the proper study of the Moon. The lecture is limited to the experimental part of lunar photometry without going into extended theoretical interpretations of the obtained results.

2. Photometric Parameters of the Moon

The light of the Moon is essentially derived from the solar light scattered on the lunar surface. Photometric measurements from the Earth give three categories of parameters:

(a) Brightness,
(b) Color,
(c) Polarisation.

For each of these parameters we can consider its value relative to the whole disk or

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to some detail of its surface. Further we must take into account the influence of the phase angle varying considerably during the lunation.

3. Photometric Definitions

Let us first recall some photometric definitions used in lunar photometry. What is named the stellar magnitude is a simple function of the illumination by the celestial body falling upon the aperture of the measuring instrument. The illumination is defined by the ratio of the luminous flux and the surface

$$e = \frac{F}{S}.$$

Between the illumination and the corresponding stellar magnitude Pogson's well-known relation gives

$$m_2 - m_1 = - 2.5 \log_{10} \frac{e_2}{e_1}.$$

In consequence, the star of zero magnitude $m=0$ gives the unit illumination $i=1$ (wega).

The stellar magnitude according to the effective wavelength of the photometer may be visual, photovisual, or photographic. The zero of these different systems is defined by suitable stellar sequences on the sky. The stellar magnitude can be used for every celestial body, stars, planets or even for the lunar crescent.

For the surfaces of celestial bodies we introduce the notion of the surface brightness or the luminance. By optical means we isolate a small part of the surface subtending the solid angle ω and the illumination given by it will be

$$e = b\omega,$$

where ω is expressed in steradians (srd) and b stands for the luminance.

For scattering surface it is useful to introduce the notion of an ideal white screen scattering in space all incident flux without loss and obeying the Lambert law, *i.e.*, having the same luminance in all observing directions. Such a screen receiving the illumination e will have the luminance

$$b = \frac{e}{\pi}.$$

For a white screen which is not ideal, but obeying the Lambert Law, we can write by analogy

$$b = A \frac{e}{\pi},$$

where A is the scattering power or albedo of the surface ($A<1$).

4. Principal Methods of Lunar Photometry

In lunar photometry we mostly use the comparison with a photometric standard which can be terrestrial or celestial (the Sun, or stars) and we measure in principle the following quantities:

A. THE ILLUMINATION PRODUCED BY THE MOON

This kind of measurement is relatively easy considering the intensity of the light. An example shows it clearly. Rougier (1933) used a simple photoelectric cell placed at the bottom of a tube directed toward the Moon and provided with several diaphragms limiting the field on the sky. After the amplification the photoelectric current was matched with a standard electric lamp, placed at variable distances. The inverse square law of distances gave the ratio of illumination Moon : lamp. In order to eliminate the variations of atmospheric extinction Rougier observed under different known zenithal distances and extrapolated the above ratio outside the terrestrial atmosphere by the classical method of Bouguer's straight lines.

B. THE LUMINANCE OF DETAILS ON THE MOON

The photographic method is here the most simple if not the most precise. The Moon's image on the plate enables us to study by the classical methods of photographic photometry every detail of the lunar surface.

The photographic effect on the plate giving the measured density of the image depends on the illumination

$$e = b\Omega pp' + v,$$

where b is the luminance of the detail, Ω the solid angle of the objective aperture viewed from the focus, p and p' the loss of light in the atmosphere and in the telescope and finally v the parasitic illumination of the veil due to the atmosphere and the optical surfaces. The measured densities are reported to the photometric scale impressed on the plate under similar conditions and connected by some appropriate way with some standard source such as the Sun or stars.

The more precise photoelectric photometry entails also a more elaborate optical device. The image of the Moon is formed on the diaphragm whose field delimits the measured spot on the Moon. Behind the diaphragm the Fabry lense collects the light and forms the image of the objective aperture on the photocathode of the multiplier. Its current depends on the luminous flux impinging on the photocathode

$$F = b\pi\varrho^2 Spp' + v,$$

where S is the surface of the objective aperture, ϱ the angular value of the diaphragm and other quantities have the same designation as above.

The visual methods used some decades ago are not now used except perhaps for eclipse photometry where Danjon's cat's eye photometer (1928) is still used for its potentiality of eliminating automatically the veil which is particularly harmful in the case of eclipses.

5. Integral Photometry of the Moon

The integral photometry of the Moon gives us information on two points, *i.e.*, the phase curve which can be expressed in relative units, and the stellar magnitude of the Moon, especially of the full Moon at the phase angle $\varphi = 0$.

(i) The phase curve of the Moon has been measured by different photometric methods. The latest determinations refer to the blue region (4450 Å) with the photoelectric photometer by Rougier (1933). According to his curve (Figure 1) a small and

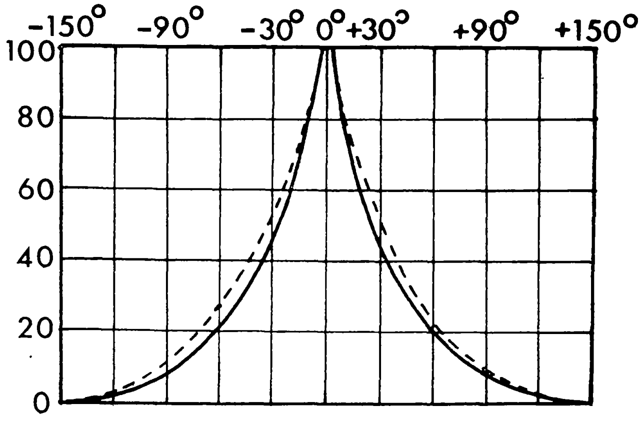

Fig. 1. Phase curve of the Moon: full line according to Rougier (1933), dotted line according to older measurements of Russell.

variable asymmetry in respect to the full Moon can be seen. Between the quarters and the full Moon ($110° > \varphi > 0°$) the waxing Moon is slightly brighter than the waning Moon and the inverse takes place between the quarters and the new Moon ($110° < \varphi < 180°$). In the first case the explanation could be found in the different distribution of bright continents and dark seas on the visible disk but this explanation fails in the second case. Eventually new determinations of this part of the phase curve are needed in order to confirm this anomalous behaviour.

The most interesting feature of the phase curve $f(\varphi)$ is the very steep rise of brightness as we approach the full Moon. This phenomenon, called the 'opposition effect', will be mentioned later, together with the detailed photometry of the Moon.

(ii) The phase curve $f(\varphi)$ can be expressed also in stellar magnitudes and we consider generally the stellar magnitude of the full Moon. Its true value is impossible to determine as the phase angle $\varphi = 0$ is attained only during the total eclipse. We adopt generally $m_☾ = -12.7$ but the extrapolated value at $\varphi \to 0°$ can amount to -13.5^{m}.

The stellar magnitude of the Sun being $m_\odot$ we can compute the *spherical albedo* of the Moon according to the definition by Bond, *i.e.*, the fraction of incident parallel solar beam scattered by the Moon in all directions.

If $E_\odot$ is the solar illumination on the Moon, the incident flux will be

$$F_1 = \pi a^2 E_\odot$$

where a stands for lunar radius. For the scattered flux let us consider a sphere having its center in the Moon and passing through the Earth. Knowing the phase curve of the Moon $E_☾ f(\varphi)$ we can compute the illumination at each point of the illuminated hemisphere and obtain by integration the total flux falling upon it

$$F_2 = 2\pi E_☾ r^2 \int_0^\pi f(\varphi) \sin\varphi \, d\varphi .$$

The Bond albedo will, therefore, be

$$A = \frac{F_1}{F_2} = \frac{2E_☾ r^2}{E_\odot a^2} \int_0^\pi f(\varphi) \sin\varphi \, d\varphi .$$

Putting there the measured photometric values

$$m_☾ = -12.75^{\mathrm{m}}, \qquad m_\odot = -26.78^{\mathrm{m}},$$

the geometrical values

$$r = 3.844 \times 10^5 \text{ km} \qquad a = 1.738 \times 10^3 \text{ km}$$

and according to Rougier's curve

$$2 \int_0^\pi f(\varphi) \sin\varphi \, d\varphi = 0.585$$

we obtain for the albedo

$$A = 0.072,$$

which is a relatively low value in comparison with terrestrial substances (No. 6). The dependence on color will be shown later (No. 7).

6. Detailed Lunar Photometry

The luminance of a small area of lunar surface is a complex function of three angles: i the angle of incidence, ε the angle of scattering and φ the angle of phase. In addition the luminance b depends on the nature of the spot examined on the Moon.

Generally we compare the measured luminance b with the luminance of an ideal white screen b_n placed at the same point but normal to the incident solar rays ($i_n = 0°$), writing

$$\frac{b}{b_n} = A_0 f(i, \varepsilon, \varphi)$$

where A_0 is called the *normal albedo* and $f(i, \varepsilon, \varphi)$ is the *photometric function* normalised to $f(0, 0, 0,) = 1$ for the center of the full Moon.

Let us summarise the main results relative to the detailed photometry of the Moon:

(i) All lunar formations reach their maximum luminance at the full Moon ($\varphi = 0°$) at every point of the disk when also $i = \varepsilon$ (Figure 2). The only exceptions are some lunar craters with bright rays whose maximum of luminance is displaced by 10–15° in phase angle toward the culmination of the Sun above the crater.

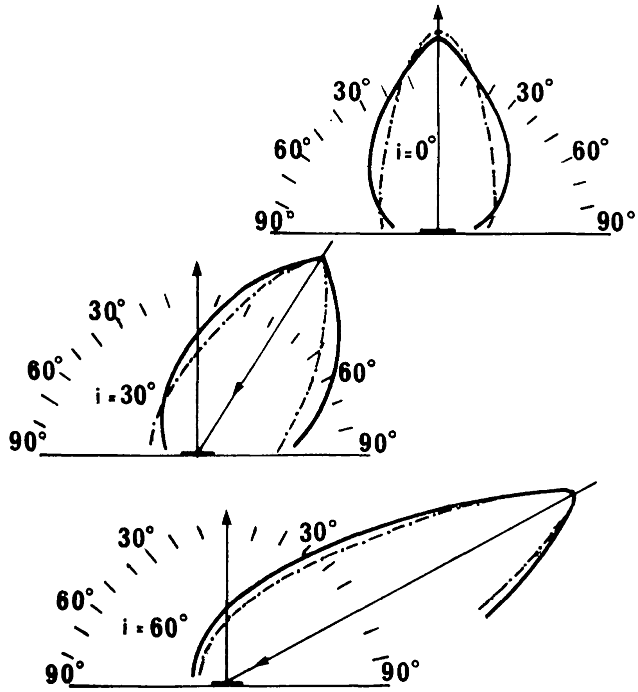

Fig. 2. Scattering indicatrices of lunar surface for different angles i, full lines continents, dotted lines maria, according to Orlova (1956).

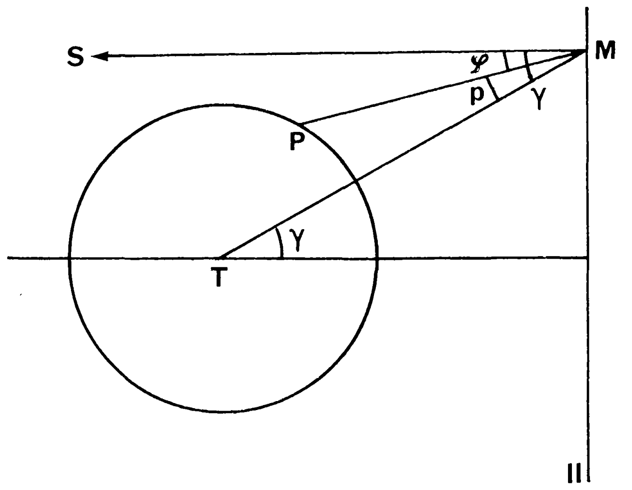

Fig. 3. Topocentric phase angle φ for the observer at P, is smaller than the geocentric angle γ for the observer at T.

(ii) The photometric function $f(\mathrm{i}, \varepsilon, \varphi)$ is approximately identical for all lunar formations. The exceptions are again the craters with bright rays near the full Moon showing somewhat steeper rise.

(iii) The rise of luminance toward the full Moon ($\varphi \to 0°$) is very rapid when $\varphi < 10°$. It is impossible to descend below 1.2° for a geocentric observer because of the penumbra, but van Diggelen (1965) arrived nevertheless at the phase angle of 0.7° taking advantage of the topocentric parallax (Figure 3).

These unusual properties can be explained by the shadow phenomena on the surface covered with dust whose existence was confirmed by lunar missions.

(iv) The normal albedos A_0 are very low in comparison with terrestrial materials:

Moon	Oceanus Procellarum	Maria	Continents	Aristarchus	Amplitude
	0.05	0.06	0.10	0.18	1:3
Earth	Volcanic lava	Basalt	Granit	Limestone	
	0.06	0.14	0.24	0.56	1:9

For the difference of amplitudes from 1:3 to 1:9 we have two possible explanations. The first is that the lunar values are the average values over several square kilometers of the lunar surface and therefore these values should naturally display smaller variations than the individual components of it corresponding to terrestrial conditions. Secondly the terrestrial materials if pulverised give much smaller variations than in the compact state and the lunar surface approaches the former state.

7. Colorimetry of the Moon

The light of the Moon is slightly redder than the solar light. In more quantitative manner the B − V color index of the Sun is 0.62^{m} while that of the Moon is +0.94 (Gallouet, 1963). This reddish color of the Moon is also reflected in the variation of the albedo along the spectrum:

2000–3000 Å	4300 Å	5400 Å	25.000 Å
0.01–0.02	0.055	0.073	0.25
(Lebedinsky *et al.*, 1967)	(Gallouet, 1963)		(Wattson and Danielson, 1965)

The UV albedo has been measured from space by Zond (No. 13). In the IR there exists some danger of contamination by thermal radiation but at any rate the albedo does really increase from UV to IR.

According to Gehrels *et al.* (1964) a small variation of the color with the phase angle can be detected, the Moon being a little redder at the quarters than at the full phase

$$B - V = 0.838^m + 0.0017^m (|\varphi|) .$$
$$\pm 0.0002$$

More recently, Mikhail (1970) measured with a photoelectric photometer the colors and their variations in 4 spectral regions between 0.4 μ and 0.8 μ of 15 lunar objects. In the B–V region the mean phase reddening factor is 0.0015^m/ degree in good agreement with Gehrels' value given above. Near the full Moon an appreciable increase of the reddening factor has been found corresponding to the opposition effect (No. 6/(iii)).

As far as the lunar details are concerned their color varies only to a very small extent, by 0.09 in the color index. Generally bright objects (continents) are redder than thed ark ones (maria). The conspicuous exception is Aristarchus which is bluer than it should be according to its high intensity.

8. Polarimetry

The natural light, *i.e.*, solar light scattered from the rough surface of the Moon, becomes partially polarised. The degree of polarisation P is given by the formula

$$P = \frac{I_1 - I_2}{I_1 + I_2},$$

where I_1 is the intensity of vibration perpendicular, and I_2 the intensity of vibration parallel to the plane of vision containing the Sun, the observer and the Moon. The value of P can be positive or negative according to the relative values of both components I_1 and I_2.

In general P depends in the first place on the phase angle φ. The general feature of the curve $P(\varphi)$ for two different regions such as the Oceanus Procellarum (albedo = = 0.05) and the crater Krüger (albedo = 0.12) in orange light according to Dollfus and Bowell (1971) is given on the Figure 4. We remark on their following particulars:

(i) The degree of polarisation is $P = 0$ at the full Moon ($\varphi = 0$).

(ii) Between $0 < \varphi < 23°$ approximatively, P is negative, *i.e.* $I_2 > I_1$.

(iii) From about $\varphi > 23°$ onward P becomes positive and attains the maximum at about $\varphi = 105$–$110°$.

(iv) On the positive branch, *i.e.*, for $\varphi > 20°$ the polarisation of dark areas is higher than the polarisation of bright continents.

(v) On the negative branch for $\varphi < 20°$ the value of $P(\varphi)$ is identical for all points the disk and the separation according to the albedo begins at about $\varphi = 20°$.

(vi) There is an independence of P in the inclination of the surface at the observed point.

There exist some relations with color (Gehrels *et al.*, 1964):

(vii) The inversion angle (about 23°) depends slightly on the color. From 0.3 μ to 1.1 μ its value rises from 21° to 26°.

(viii) The maximum polarisation is greater in the blue than in the red.

(ix) The phase angle of the maximum polarisation for a given place is independent of the color.

From the polarisation of lunar light and the comparison with terrestrial samples we must conclude that the lunar surface is covered with a dark powder spread out in a layer which covers all the surface. This deduction was confirmed by landings on the Moon, especially by those of Apollo missions bringing to the Earth many samples of lunar dust.

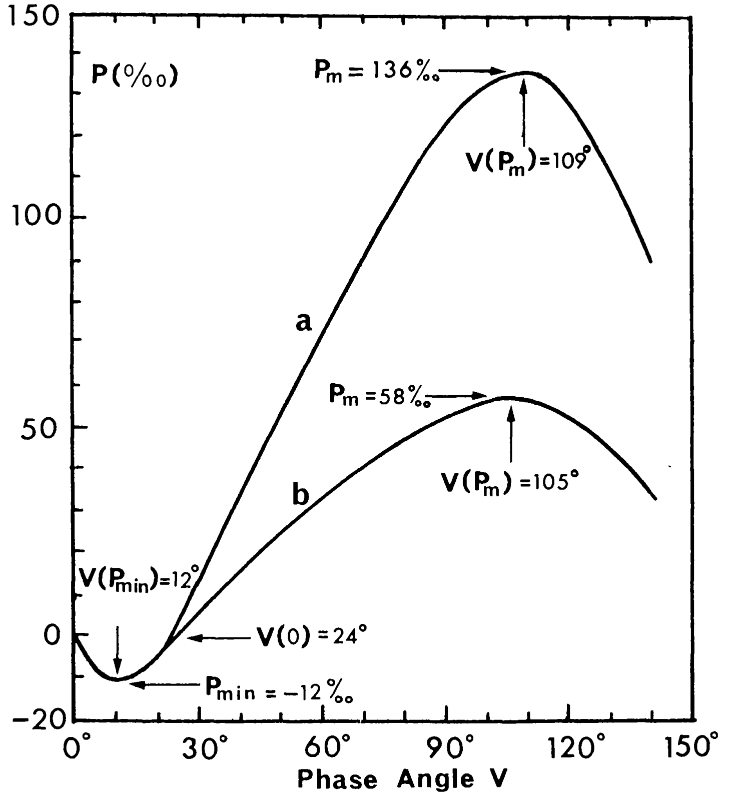

Fig. 4. Curves of polarisation (*P* versus the phase angle *V*) for Oceanus Procellarum (a) and for the crater Krüger (b) according to Dollfus and Bowel (1971) $V=\varphi$.

9. Luminescent Phenomena

In addition to the scattered solar light there seems to exist another component in the light of the Moon, namely the *luminescence of the lunar surface*. Qualitatively all necessary conditions for the existence of the luminescence are fulfilled, *i.e.*, the exciting solar radiation – UV, *X* or corpuscular – which in the absence of a lunar atmosphere can reach the surface.

The existence of a small luminescent component in the global light may be detected in all cases where (i) the visible solar light undergoes an attenuation which is more important that the attenuation of exciting radiations or (ii) when the exciting radiations are fluctuating as a consequence of solar activity or for other reasons. The combination of both situations favours naturally the detection of the luminescence as well as the low albedo of the lunar surface.

From an experimental point of view the luminescent component, having the character of additional light, may be simulated by other sources of this light such as the parasitic light due to the instruments or to the observing method.

10. Eclipse Photometry

The principal aim of the eclipse photometry is to obtain the optical density of the shadow cast by the Earth on the Moon which plays here the role of a scattering screen. The density of the shadow depends on the structure of the terrestrial atmosphere and eclipse photometry represented before the introduction of space techniques a powerful tool for the exploration of the upper atmosphere.

At first the properties of the lunar surface were considered of small interest as long as its constancy was guaranteed. As a consequence of detailed and extended research it seems now that these properties are not constant and so trivial as it was assumed. During the eclipses we meet the both above mentioned situations (i), (ii) favourable to the luminescence.

11. Photometry of the Penumbra

The situation in the penumbra is very clear. The observer placed there sees the partial eclipse of the Sun by the Earth and it is easy to compute for every point of the penumbra the solar illumination, taking into account the darkening of the limb and in the inner part of the penumbra the influence of the terrestrial atmosphere.

In a great majority of cases (3/4) an excess of light was found in the inner penumbra (Figure 5) amounting to 100% near the edge of the umbra. Three explanations of it have been proposed:

(i) The illumination by the terrestrial atmosphere which was not included in the theory. Assuming very drastic conditions for the luminous fringe of the scattering atmosphere of 120 km height, surrounding completely the terrestrial disk and having the luminance of the daylight sky, we obtain for the illumination produced at the Moon

$$e = \text{luminance} \times \text{solid angle} = 10^4 \times 3 \times 10^{-5} = 0.3 \text{ lux}$$

instead of 100 lux observed at the edge of the umbra.

(ii) The opposition effect too is inadequate to explain the excess of light, as can be seen on Figure 5. The rise of observed brightness in the penumbra is much steeper than the curve of observed opposition effect.

(iii) The last known explanation is that of lunar luminescence (Link, 1946), if we consider the excitation by short wave radiation (UV, EUV, X) whose source is mainly concentrated on the limb of the solar disk or possibly in both zones of sunspots. The intensity of the luminescent component should be proportional to the unocculted

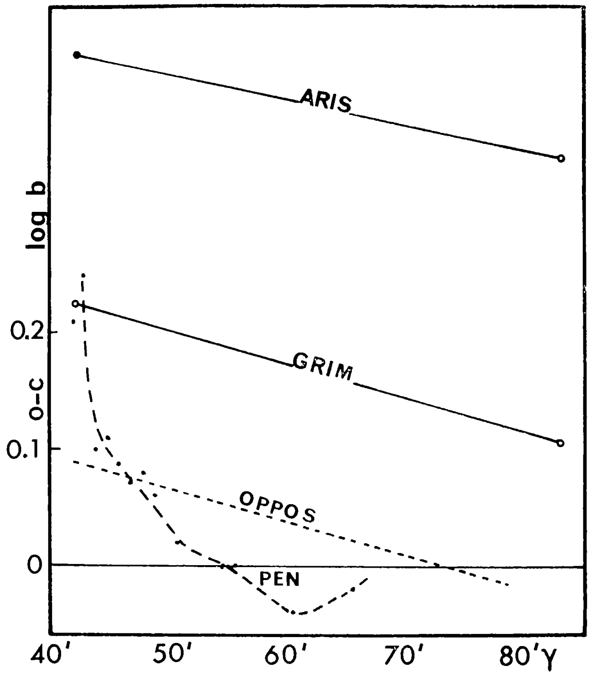

Fig. 5. Opposition effect as observed for two craters Aristarchus and Grimaldi (van Diggelen, 1965) compared with supposed opposition effect in the penumbra (Oppos) and with the observed excess of light (Pen).

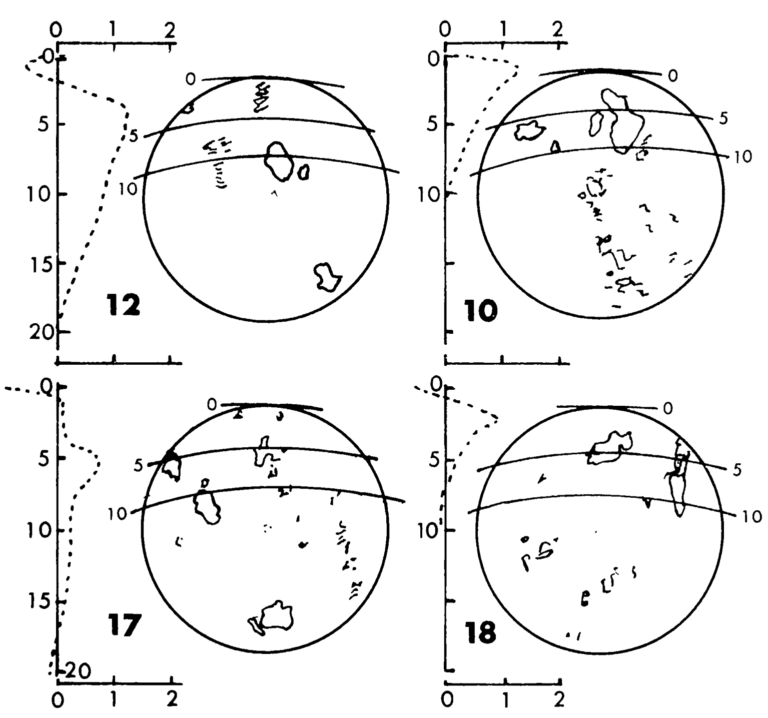

Fig. 6. Excess of light in the penumbra for 4 eclipses in comparison with the simultaneous position of the Earth's limb over the solar disk with K-3 plages. On the left the distances in minutes from the edge of the umbra given also (0–5–10) on the terrestrial limb. On the horizontal scale (0–1–2) excess of light in stellar magnitudes.

portion of these sources. The intensity of the scattered component computed by the theory is proportional to the unocculted part of the disk. For geometrical reasons the limb or zone fraction is superior to the disk fraction in the inner part of the penumbra and inferior in the outer part while the equality takes place at the midpoint of the penumbra. In consequence we may expect an excess of light in the inner part, a defect in the outer part and the equality at the midpoint, and this was actually observed (Figure 5).

In addition we have been able to detect in several cases the direct influence of K-3 plages as sources of exciting radiation. If during the penumbral phase these plages disappear or appear on the terrestrial limb we observe the corresponding perturbations on the density curve of the penumbra (Figure 6) (Dubois-Link, 1969).

12. Umbral Photometry

In the umbra too we observe an excess of light with regard to the theory. Only the corpuscular radiation can penetrate into the umbra to excite the luminescence there but we must at first consider the possible influence of atmospheric illumination.

At 10′ from the edge of the umbra the observed density 3.3 is by 0.5 smaller than its theoretical value computed in the ideal atmosphere. In other words the observed luminance is at least 3 × greater there than expected from the theory. This excess of light cannot be explained by the atmospheric illumination, as we shall demonstrate on the television image of the solar eclipse on the Moon taken by the Surveyor III on 24 April 1967. On this picture we can estimate the relative importance of the refraction image of the Sun, which produces the computed luminance, to the importance of the atmospheric fringe needed for the explanation of the light excess. The ratio of both images is about 10:1 while the necessary value should be of 1:3. The discrepancy of 1:30 makes the atmospheric interpretation quite unrealistic.

The brightness of lunar eclipses shows a very pronounced correlation with solar activity. We have several arguments to support this assertion:

(i) Danjon (1920) studied the variations of the luminosity of eclipses far in the past by discussing their verbal description. He established a convenient luminosity scale from 0 to 4 which is very useful at times when no photometric measurements are available. In this manner he disclosed an 11-year variation of the luminosity (Figure 7). The Danjon relation can be explained in terms of lunar luminescence excited by corpuscular radiation (Link, 1947a). If we assume, for example, that only 1% of the luminescent component is contained in the light of the full Moon and that the corpuscular radiations can reach the inner parts of the umbra without a great attenuation, this component becomes very important in the umbra where the direct solar illumination is reduced at least to 10^{-3} of its normal value.

Now the intensity of corpuscular radiation in the space Earth-Moon varies not only with the sunspots curve but also with the position of active centers on the solar disk. At the beginning of a solar cycle (minimum) these centers according to Spörer's law are located at high heliographical latitudes and progressing within the cycle, their zone

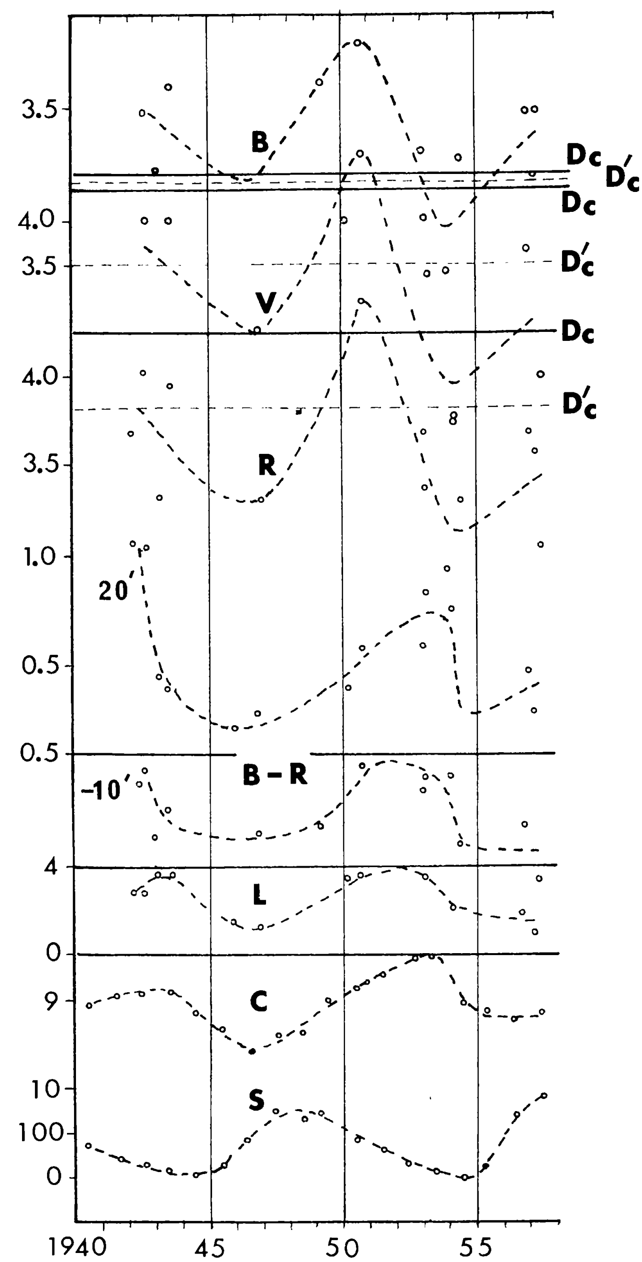

Fig. 7. Lunar eclipses and the solar activity 1940–1958 (Link, 1960): Densities of the umbra at 10′ from its edge in blue (*B*), green (*V*) and red (*R*) light. Lines (*D*) are the theoretical values *Dc* without and D′*c* with ozone, *B-R* the color of the inner umbra (20′) and of the external umbra (— 10′), *L* the luminosity curve according to estimates in Danjon's scale, *C* the curve of ashen light and *S* the sunspot curve.

approaches to the equator and extinguishes near it at the beginning of the new cycle. As the emission of the corpuscules is mainly radial and the Moon is near the plane of the solar equator the curve of corpuscular radiation should display the same saw-toothed form as the curve of eclipses, with a sudden drop at each solar minimum. In other words the variation of corpuscular bombardment during the solar cycle is the logical explanation of Danjon's relation.

(ii) The annual variation of the luminosity of lunar eclipses according to the measurements from 1921 displays the same form as the curve of geomagnetic activity or the curve of auroral frequency with two maxima near equinoxes and two minima near solstices (Figure 8). For geomagnetic activity and auroral frequency this behaviour is generally explained by the variable orientation of the solar equator in respect to the Earth which influences the intensity of corpuscular radiations on the Earth. In consequence we may assume the same explanation for lunar eclipses, adopting the lunar luminescence as origin of these variations (Dubois-Link, 1970).

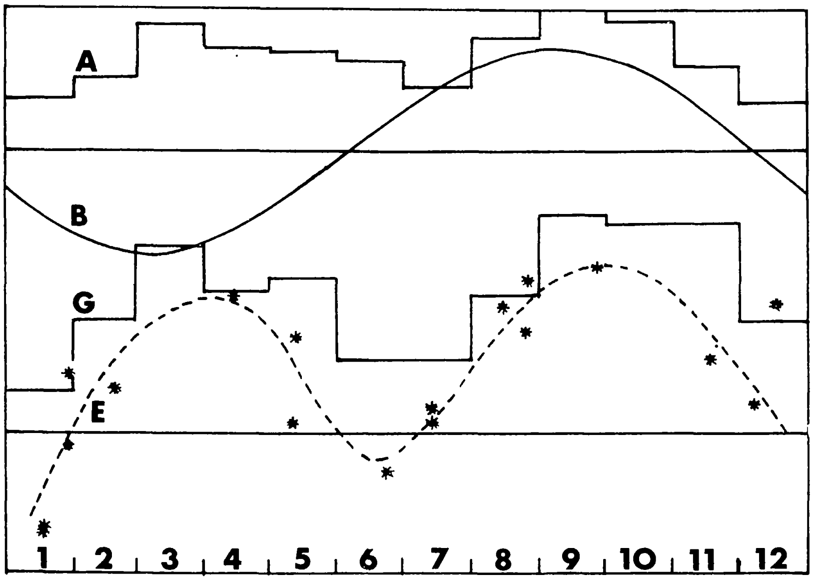

Fig. 8. Annual variations of: *A* frequency of aurorae, *b* heliographic latitude of the apparent center of solar disk, *G* geomagnetic activity, *E* luminosity of eclipses.

(iii) In the series of 20 measured eclipses between 1921–1968 we meet 4 well defined cases of sudden light surges lasting 10–30 min and having an amplitude of 100% or more. It is quite difficult to explain these phenomena by instrumental or observation errors as well as by short-lived 'atmospheric windows' in the Earth's atmosphere to the extent of some 10,000–20,000 km round the terminator. The natural explanation can be found (Dubois-Link, 1971) in the lunar luminescence excited by a transient beam of solar corpuscules. Deep in the umbra where we meet these surges the direct solar illumination is very low (10^{-5}) and even a small transient luminescent component can give rise to the observed surges. Outside the umbra the same phenomenon would be completely obliterated in the high solar illumination.

To the same category of phenomena belong fluctuations of light observed visually during several eclipses and explained sometimes as optical illusions, but which can have a real base in the lunar luminescence.

(iv) If we select in the above series of measured eclipses the five darkest and five brightest ones and confront them with simultaneous spectroheliograms in K-3 light (Figure 9) no further comment is needed relative to the reality of solar influence on lunar eclipses (Dubois-Link, 1970).

(v) There seems to exist a correlation between the geomagnetic planetary index

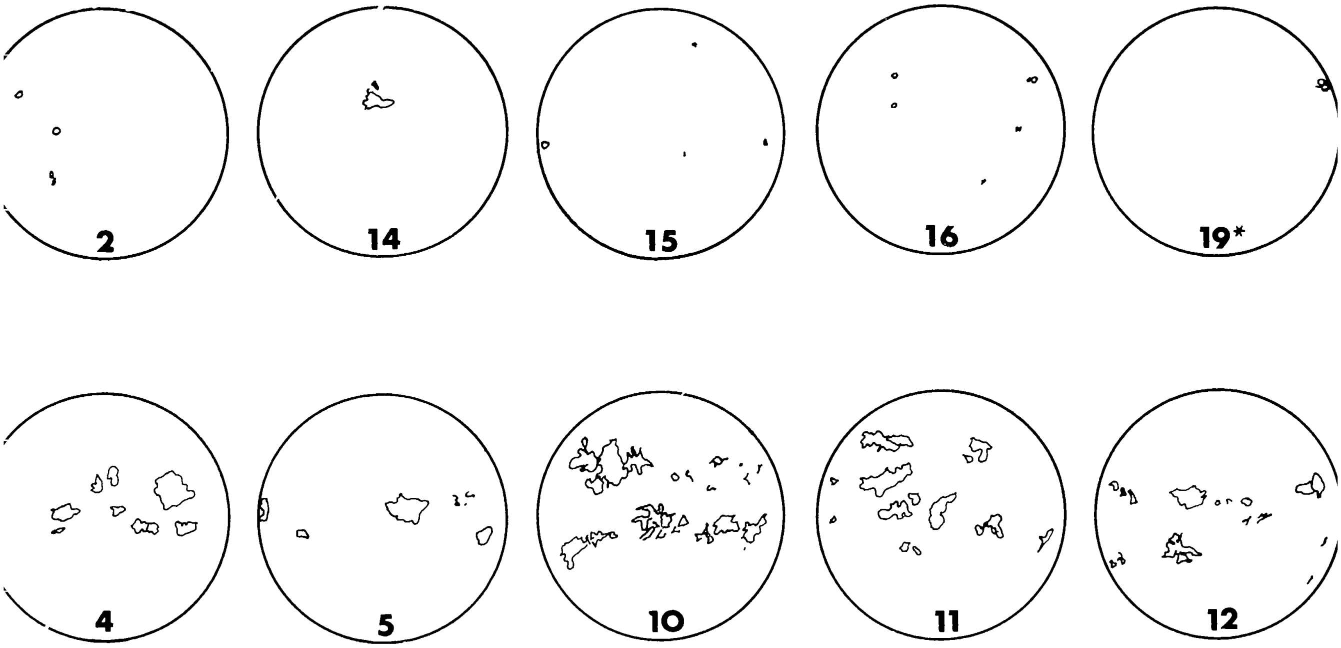

Fig. 9. Spectroheliogrammes in K-3 line for 5 darkest (top) and 5 brightest (bottom lunar eclipse measured between 1921–1967.

signaling the arrival of solar corpuscules into terrestrial space with the shadow density in the outer parts of the umbra as found by Matsushima (1966). This fact may be considered as another manifestation of lunar luminescence excited by solar corpuscules.

In general these above mentioned excesses of light in the umbra depend on the color being greatest and most frequent in the blue and smallest and less frequent in the red. The reason for it is mainly in the rise of solar illumination from the blue toward the red. In other words in the blue light of small intensity the same luminescent component predominates easily and the inverse occurs in the red.

13. Light Fluctuations Outside the Eclipses

The large excess of light found during the eclipses leaves room for several percent for the luminescence component in the integrated light outside the eclipses. To detect this component we use the fluctuations of solar activity and the subsequent variations of exciting radiation:

(i) In the integrated light on the phase curve of the Moon obtained by Rougier (1933) we noted (Link, 1957b) that the individual deviations Δm from the mean curve can be correlated with simultaneous variations Δc of the solar constant obtained by Abbot. We got a significant correlation (Figure 10)

$$r = -0.44 \pm 0.08 \text{ p.e.} \qquad n = 94 .$$

According to the slope of the regression curve a 1% variation of solar constant is accompanied by a 26% variation of visible light. In other words, there is no direct

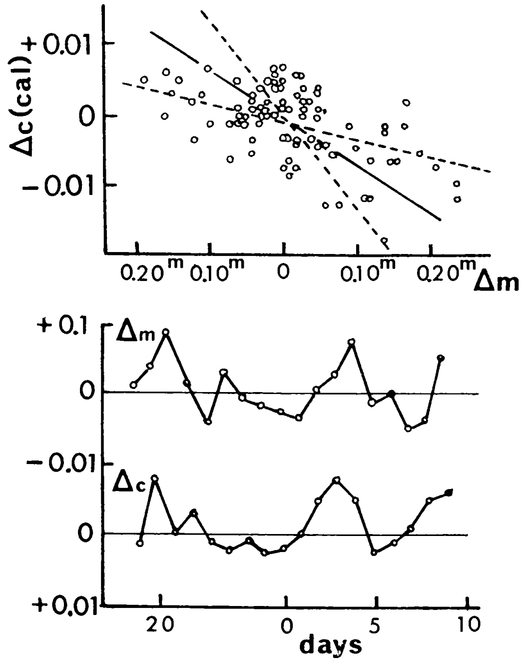

Fig. 10. Correlation between Δc and Δm (top) and 27 days recurrence of Δc and Δm (bottom).

relation of both values but an indirect one by lunar luminescence. The exciting radiation varies in much larger limits with the solar activity as the visible light directly connected with the solar constant. We meet a similar situation in the ionospheric domain controlled, too, by short waves or corpuscular radiation.

Using the same material we traced the 27 days recurrence of Δm and Δc. We find there (Figure 10) a lag of 1–2 days between the peaks on both curves. This seems to indicate the corpuscular origin of Δm fluctuations.

Gehrels *et al.* (1964) performed an extensive photometric and polarimetric survey of the lunar surface using photoelectric techniques. From photometric measurements they conclude that during the period 1958/59 (maximum of solar activity) the average lunar surface was by a factor of 1.14 ± 0.014 brighter than that in 1963/64 (minimum of solar activity). Also some individual measurements show an increase of 36% (1956, XI, 17) or 27% (1956, XI, 18) above the average level 1963/64.

An independent confirmation of the above findings is given by polarimetry. The ratio

$$P = \frac{I_1 - I_2}{I_1 + I_2}$$

is affected by the luminescence only in the denominator provided that the luminescent component is not polarised. In fact the degree of polarisation was larger in 1963 than in 1959 which leads to the photometric ratio 1.12 ± 0.02, in fair agreement with the above given value. In a similar way Lyot's polarimetric measurements gave in reference to 1924, II, 29 the surface brightness on 1924, IV, 27 by 10% lower and on 1923, XI, 4 by 16% higher. Finally Mare Crisium in Gehrels' series displays unusual irregularities in the polarisation which can be due to the high luminescence of this region found also by Cimino and Fresa (1958) in the penumbra.

Moreover the analysis by Hopmann (1965) of photometrical series by Wildey and Pohn (1964) revealed several increases of brightness which exceed largely the limits of observational errors.

(ii) The *line-depth method* (Link, 1950) is based on the superposition of the luminescent band over a Fraunhofer line in the lunar spectrum. The core of the absorption line is partially filled-up or the central intensity is increased in respect to the solar spectrum. (Figure 11). If $R_☾$ and $R_\odot$ are the central intensities expressed in terms of the adjacent continuum then the ratio

$$\varrho = \frac{R_☾ - R_\odot}{1 - R_☾}$$

gives the fraction of the luminescent component in the same units.

Several series of measurements by Dubois (1959), Kozyrev (1956), Grainger and Ring (1962), Spinrad (1964), Scarfe (1965), and McCord (1967) observed an effect ranging from 1–30% while Wildey (1964) and Ney *et al.* (1966) failed to detect any measurable value at the time of their observations.

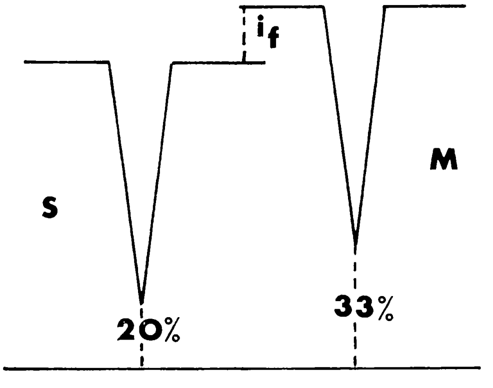

Fig. 11. Line depth in solar (left) and lunar spectrum (right) with luminescence component i_f.

The classical spectral resolution was substituted by Blamont and Chanin (1968) with magnetic sweeping by optical resonance. The results obtained on Mare Tranquillitatis and Tycho in red (7699 Å) show a variation of ϱ during the lunar day probably connected with the temperature.

The line-depth method enables us to explore different lunar places as Dubois (1959) did by examining 90 points on the Moon from which about a half displayed a measurable luminescence.

(iii) The color determination leads to similar results. Kopal and Rackham (1964) working photographically with green and red interference filters observed a spectacular enhancement in the red in the Kepler region, covering 60,000 km^2, twice in the night 1–2 November, 1963. The photoelectric reduction of the plate gave $\varrho = 0.86$, the greatest value ever found. This lunar flare followed by 3 days a great solar flare of class 3 on 28, X, at 2^h UT. But curiously enough the same solar flare was followed 48 hours later by the observation of three spots flaring in red light near the crater Aristarchus and lasting about half an hour. This visual observation, made by very cautious professional observers Greenacre and Barr (1963), merits full confidence even more because, at the time, it was fully independent of Kopal's findings given above.

Roberts (1968) used a very elaborate three-color photoelectric photometer at the Pic-du-Midi Observatory in order to detect small and rapid variations of the color by scanning the regions near Aristarchus and Ptolemaeus on 21,600 distinct points close to the full Moon. Variations in the range from 5 to 15% have been disclosed with a period of the order of 1^s, though longer fluctuations of the order of hours were also observed.

More recently, Sekiguchi (1971) observed photoelectrically an anomalous enhancement near Aristarchus on March 26,1970 about 29 hours after a solar flare of class 2B in the central part of the solar disk. The brightening was of about 0.3 magnitude, and is consistent with the lowering of the polarisation from 5 to 4% measured simultaneously in the same region.

Lebedinsky *et al.* (1968) obtained the curve of the albedo in the 1900–2750 Å range using the Zond-3 space probe. Several peaks have been found producing an excess of 10–50% over the mean curve. As a possible explanation the luminescence is proposed by the authors.

(iv) About 600 examples of transient and localised glows on the Moon which occurred from 1540 to the present time (1967) are reported in the Catalogue of Middlehurst *et al.* (1968). Aristarchus appears at the first place followed by Plato, Schroters Valley, Alphonsus, Tycho and Mare Crisium. The famous observation of Aristarchus by W. Herschel in the night of 18–19 April, 1787 is frequently quoted, not only because of the skill of the observer, but also that it occurred during a very important aurora observed in low latitudes showing the anomalous presence of solar particles in the circumterrestrial space. The modern observations using the Moon-Blink method (Cameron, 1967) seem to confirm the reality of lunar transient phenomena and their explanation by lunar luminescence in some cases is obvious.

14. The Ashen Light

The photometry of the Moon has been also extended to the very small ashen light which is properly speaking the Earth's light on the Moon. This was known in the 15th century by Leonardo da Vinci and Maestlin, even if sometimes Kepler is also quoted as the author of this explanation. The layman can observe the ashen light easily between the new Moon and the quarters, but the astronomers aided by the coronograph (Dollfus, 1955) can photograph it till the phase angle of 20°, *i.e.*, 1 1/2 days before the full Moon.

The ashen light comes from the solar light scattered by the Earth toward the Moon and rescattered again by the Moon toward the terrestrial observer. The study of the ashen light enables us to obtain the albedo of the Earth which is largely influenced by the meteorological conditions, which is outside the scope of our lecture. Nevertheless, there are some special aspects connected directly with the Moon which merit our attention.

Danjon (1936) performed a large series of measurements with his cat's eye photometer in order to obtain the difference $m_{♁} - m_{\odot}$ observed from the Moon as a function of the phase angle. In the intervals between $-160° < \varphi < -60°$ and $+160° > \varphi > +60°$ his results can be represented by the formula

$$m_{♁} - m_{\odot} = 9.90^{m} + 0.0156^{m}(180° - \varphi) + 5.1^{m} \times 10^{-7}(180° - \varphi)^{3};$$

and the observed deviations from it are represented on Figure 12. They have no systematic character in the above-given intervals, but nearer the full Moon the differences become suddenly larger and negative, *i.e.*, the ashen light becomes systematically brighter.

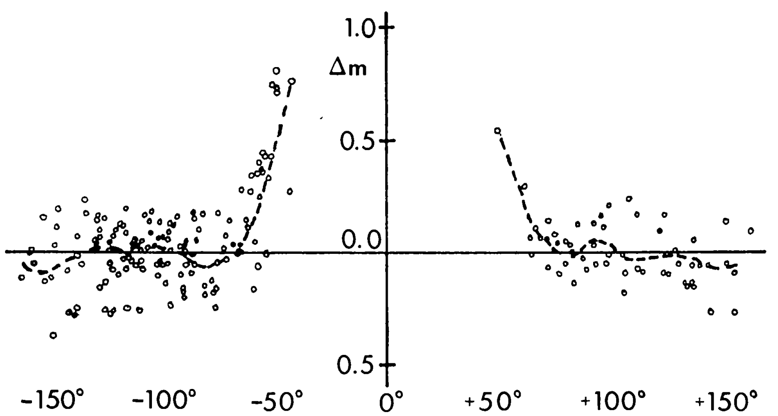

Fig. 12. Deviations from $m_{♁} - m_{\odot}$ during the lunation.

Danjon explained this behaviour by a systematic increase of the Earth's albedo just before or just after the full Moon. In the first case the thin Earth crescent is situated over the Atlantic Ocean and in the second case on the east continent. According to the satellite determinations of the Earth's albedo (Arking, 1963) the continents are, on average, more cloudy and brighter than the seas, contrary to Danjon's statement. Otherwise we must assume that every night when the weather was clear in France and when Danjon observed, the weather over the Earth's crescent some thousand kilometers to the East and West was cloudy.

Another feature of ashen light is that during the 11-year solar cycle its intensity fluctuates in similar manner to the luminosity of eclipses (Figure 7) (Dubois, 1944).

We can in both cases propose luminescence as the origin of the observed phenomena. During each lunation the Moon enters the vicinity of its full phase in the space of the magnetic tail of the Earth where an anomalous concentration of solar particles seems to be plausible. As for the 11-year curve is concerned its interpretation is similar to the Danjon relation given above (Link, 1963).

Vassy (1956) proposed to explain the 11-year variations of ashen light and of the luminosity of eclipses by the scattering of light on aerosols formed in the upper atmosphere by the impact of solar particles. This explanation is not satisfactory in quantitative respect for two reasons. The amplitude of variation of ashen light is much smaller (1 : 2,6) than the amplitude of eclipses (1 : 10–15). Moreover the aspect of the Earth during the lunar eclipse (No. 12) gives a small importance to the atmospheric light in comparison with the direct solar flux refracted by the atmosphere as explained before.

15. Some Comments on the Preceding Phenomena

Since a quarter of century ago, beginning with the discovery of light excess in the penumbra (Link, 1946), about 6–7 kinds of different phenomena observed on the Moon during and outside the eclipses seemed to point to the existence of lunar luminescence. But confronting the intensity of observed phenomena with available excitation energy of solar radiation, together with the quantum efficiency of most terrestrial and lastly of the genuine lunar materials, a serious conflict arose (cf. *Science*, 1970, No. 3918) : the assumed luminescence on the Moon is be several orders of magnitude too high as compared with laboratory tests. We have perhaps a double choice to explain this discrepancy:

(i) All the above observed or measured phenomena are due to different causes, such as parasitic light, atmospheric perturbations, instrumental errors or even optical illusions. In some cases, the lack of theoretical interpretation may be also invoked. In other words the authors have succumbed to the apparent facility of explanation of different phenomena by one common cause which is the luminescence. I don't know if these authors will accept this eventuality, as in the majority of cases they have performed a serious discussion of all possible perturbing effects. At any rate it would be perhaps useful to re-examine separately each category of the above phenomena, bearing in mind the negative results obtained in the laboratory.

(ii) On the contrary if we accept after this new discussion the reality of the observed phenomena from the Earth some doubts must be cast on the reproductibility of lunar conditions in our terrestrial laboratories both on excitation conditions and on the state of lunar material transported on the Earth.

Without going far in these considerations we may imagine that the excitation of lunar luminescence is more complicated and not so direct a phenomenon as we assume. The storage of energy can be present with a sudden liberation of light after a certain limit has been attained by the triggering action of solar wind or short wave radiation. An amplification of solar wind in the geomagnetic tail of the Earth is also to be considered.

In the presence of these multiple and complex phenomena our feeling is that we should not abandon this kind of research even if the laboratory tests of lunar material failed to show the luminescence in the expected range and as long as we are not sure of having perfectly reproduced the lunar environment in terrestrial laboratories.

Note added in proof. Recent work by Cameron (1972) shows a rapid rise of the number of transient lunar phenomena between the same phase angles as the rise of the above curve (Figure 12). Something therefore happens on the Moon – probably the arrival of solar particles condensed or accelerated within the bow-shock front of the magnetosphere – which enhances the ashen light and originates the lunar transient phenomena on several sensitive lunar spots (Link, 1972).

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