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Mechanism of Lunar Polarization

Abstract. *A theoretical model to explain the negative polarization of moonlight at small lunar phase angles is developed. The model is based on the polarization of light in the diffraction region bordering the geometric shadow of an opaque dielectric obstacle.*

The polarization of moonlight as a function of lunar phase angle θ (earth-moon-observer angle) has been studied by many workers (*1, 2*). Surfaces have been made of various powdery substances which simulate the polarization behavior of the lunar surface (*1–3*). A typical polarization curve for the lunar disk is shown in Fig. 1. The sign convention for polarization by reflection assigns a positive polarization to light whose stronger component is polarized with its *E*-vector perpendicular to the plane of incidence. While the positive polarization at large phase angles is characteristic of reflection from any dielectric (as in Rayleigh scattering, for example), the mechanism which generates the negative polarization has not been understood. I now suggest a mechanism which explains the origin and magnitude of this negative polarization.

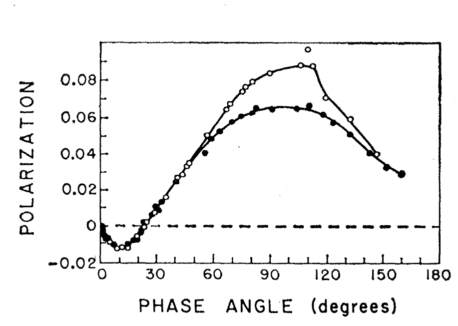

Fig. 1. The polarization $P \equiv (I_\perp - I_\parallel)/(I_\perp + I_\parallel)$ of moonlight as a function of lunar phase angle. The solid circles are results for positive phase angles, and the open circles for negative phase angles (after Lyot, *9*). $I_\perp$ and $I_\parallel$ are the intensities of light polarized with their *E*-vectors respectively perpendicular and parallel to the plane of incidence.

The strong increase in the brightness of the lunar surface for small phase angles is believed due to the effect of shadow (*4*). When a distant object illuminated by a point source is viewed from the direction of the source, all visible regions of the object are also visible to the point source, hence are illuminated. No shadow is visible. Viewed from some other direction, some observable regions are in shadow, and the mean brightness of the surface will be correspondingly reduced. Recent measurements by van Diggelen (*5*) have shown that the lunar surface brightness increases very rapidly with decreasing phase angles even for phase angles as small as 1° to 2°. It seems natural to search for an explanation of the negative polarization, which also increases rapidly at very small phase angles, by the same shadow mechanism.

Let us examine the shadow problem in more detail. Consider the problem of a square opaque object mounted above a diffusing screen, illuminated at normal incidence from above by an unpolarized source (Fig. 2). Observer N, observing the screen at normal incidence, sees no shadow. Observer O, observing at oblique incidence, sees into the shadow region and sees part of the brightly illuminated region obscured. Well outside the geometric shadow region, the illumination falling on the screen is unpolarized. Well inside the region of geometric shadow, the light intensity on the screen is negligible. In the diffraction region, however, the light can be polarized by diffraction. If so, the integrated light from the screen arriving at O might be partially polarized. Observer N, from the symmetry of his location, must observe no net polarization.

The light seen by O may have been polarized by diffraction either in traveling to the diffusing screen or in returning to O. Polarization by diffraction simultaneously in both paths is a higher order effect. Thus, the polarization seen by O is the same as the polarization of the light falling on the screen in the area of the screen directly observable by geometric optics to the observer at O, multiplied by a factor of 2 to account for the light polarized by diffraction in returning to O. It is necessary then only to calculate the polarization of the flux arriving at the diffusing screen.

To calculate approximately the polarization pattern in the vicinity of the shadow line, the opaque obstacle will be replaced by a perfectly conducting halfplane. The solution to this problem, first given by Sommerfeld, can be readily calculated in terms of equations given in Born and Wolf (*6*) and Fresnel integral tables. Let I_0 be original unpolarized incident flux, and $I_\parallel$ and $I_\perp$ be the intensity of the light incident on the diffraction, screened polarized parallel and perpendicular respectively, to the plane of incidence (but respectively perpendicular and parallel to the edge of the half-plane). The polarization $P(x)$ at the screen is given by

$$P(x) \equiv \frac{I_\perp - I_\parallel}{I_0} = \left(\frac{\lambda}{8\pi^2 r}\right)^{\frac{1}{2}} A(x) \quad \ldots . (1)$$

where x is the distance from the geometric shadow line, r is the obstacle-screen distance, and λ is the wavelength of the light.

$A(x)$ is plotted in Fig. 3, with x

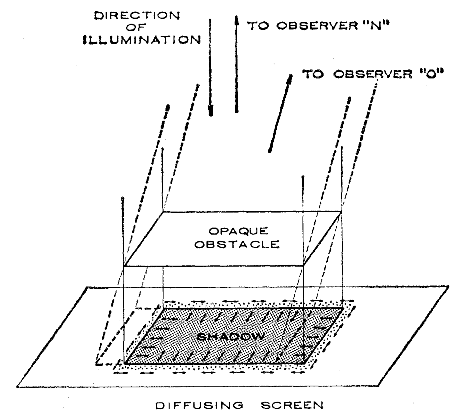

Fig. 2. The geometry of the problem of ideal shadow polarization. The shadow region and the geometric field of view of the two observers are shown, and the dominant polarizations in the diffraction regions indicated by small arrows.

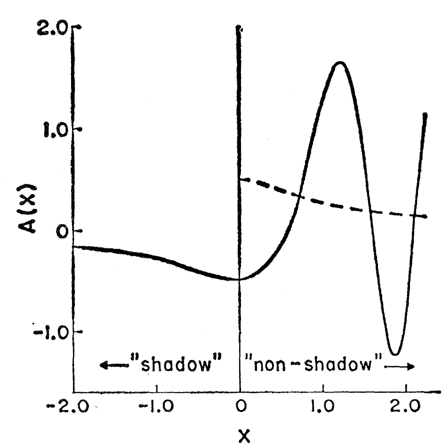

Fig. 3. The function $A(x)$ in the vicinity of the geometric shadow edge. The dotted line shows the monatonic part of $A(x)$ in the region of full illumination.

measured in units of the diffraction length $(\lambda r/2)^{\frac{1}{2}}$. Inside the shadow region the polarization contribution is negative. Outside the shadow region, there are two terms to the polarization, one of which oscillates with zero integral, and the other of which is positive and shown by the dashed line of Fig. 3.

The arrows drawn in Fig. 2 show the direction of the electric vector present in excess in the diffraction region. The observer at O will see a net negative polarization, for, compared to the observer N, he sees an additional shadow area polarized parallel to the plane of incidence and has his view of an area of positive polarization obscured by the object.

A piece of opaque lunar dust does not precisely duplicate the diffraction conditions represented by an infinitely conductive, infinitesimally thick, half plane. It does, however, preserve the physical characteristics which cause the polarization; namely, a diffracting edge which screens the electric field by induced currents. There is a difference between driving screening currents parallel and perpendicular to the diffracting edge, because of the surface charge generated by a normal component of the current. It is this difference which distinguishes the two polarizations. The polarization of light in the shadow region for diffraction of visible light by a steel knife edge was measured by Jentzsch (*7*). Under these less ideal circumstances of both the dielectric properties and geometry, the measured polarization in the shadow region was about twice as large as that of the idealized theory, and of the same sign. As expected, the basic electromagnetic effect of polarization by diffraction around an opaque dielectric obstacle seems a qualitative effect, existing under circumstances far from those ideal cases readily calculated.

Consider a model of a lunar surface consisting of opaque "particles" of low albedo (so that multiple reflections can be ignored—a good approximation for an albedo of the order of 0.1, like that of the moon). Each particle, if particles are loosely packed, produces a "shadow" on the other particles which can collectively be regarded as a diffusing screen. With such a model, a lunar polarization of

$$P = \frac{I_{\perp} - I_{\parallel}}{I_{\perp} + I_{\parallel}} \approx -\frac{\lambda}{d}\,\frac{f}{\pi}\left[\ln\left(1 + \frac{\pi}{2}\,\frac{d^2}{\lambda r}\right)\right] \qquad \text{................(2)}$$

is obtained as the saturation polarization to be expected for angles larger than the diffraction angle $(\lambda/2r)^{\frac{1}{2}}$. The dependence d^{-1} on the length d of the side of the square originates in the ratio of edge length (which produces polarized return) to the total return (proportional to the area of the square). The factor f is a depolarization factor which represents the fact that half the source of the lunar polarization is light diffracted before striking the diffusing screen. This light will be partially depolarized on reflection. Dollfus (*1*) has measured this depolarization factor to be 1/3, so a value of 2/3 for f is appropriate. The maximum negative lunar polarization of -0.012 can be produced by Eq. 2 for a wavelength of 5000 Å, a particle size of 5 microns, and a particle separation of the order of magnitude of the particle size.

While there are no direct experiments which show this polarization mechanism to be that responsible for the negative lunar polarization, two qualitative results from laboratory experiments on simulated lunar surfaces are in striking agreement with the theory. First, the negative polarization at small angles seems to be a general characteristic of reflection from powders having irregular opaque grains of sufficiently small size, relatively independent of the details of particle shape and composition (*1–3*). Second, Dollfus (*8*) has found that dark powders which produce a negative polarization at small angles do not produce this negative polarization when well-separated free-falling grains are examined. In this experiment the effect of shadow would be absent.

It is tempting to infer, from laboratory simulation, a particle size from polarization measurements. Particle size cannot be precisely defined for an unknown structural form. If the present mechanism is correct, however, there must be of the order of 10^6 cm of *shadow-producing* edges per square centimeter to explain the lunar polarization. Such a surface has at least one typical dimension of its subunits of the order of 10 microns.

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Low-Energy Protons: Average Flux in Interplanetary Space during the Last 100,000 Years

Abstract. *The radioactivity of aluminum-26 in two cores of Pacific sediments is an order of magnitude higher than was expected, as a result of its production by cosmic-ray interactions in the terrestrial environment. The higher activity can be explained only by postulating influx with extraterrestrial cosmic dust that had been exposed to significant flux of energetic particles capable of producing nuclear interactions. These particles may well be the "solar" cosmic rays that are sporadically accelerated by Sun during certain solar flares, since the steady galactic cosmic-ray flux is inadequate. The long-term average flux of low-energy protons in interplanetary space, required to yield the observed rate of influx of aluminum-26, is deduced on the basis of certain assumptions.*

Recent detection in our laboratory of Al^{26} in marine sediments (*1*) has implications regarding the long-term intensity of low-energy protons in interplanetary space. In this investigation several sections of two Pacific cores, up to 1 m in depth, were analyzed for activities of Al^{26} and Be^{10}. The radioactivity of Al^{26}, a positron emitter, was measured specifically by means of a sensitive gamma-gamma coincidence spectrometer; the observed signal in the 0.51-Mev photopeak was shown not to be due to the presence of contaminating activity. The summed coincidence spectra for all aluminum sam-