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Polarimetry of moonlight: A new method for determining the refractive index of the lunar regolith

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ABSTRACT

We present a new method for remotely measuring the refractive index of the lunar regolith, using polarised moonlight. Umov's Law correlates the polarisation (P_{max}) of scattered moonlight and the albedo (A) of the scattering lunar regolith. We discuss how deviations from this correlation have previously been linked to the so-called 'Polarimetric Anomaly Parameter', $(P_{max})^a A$, which was proposed by Shkuratov and others as being related to variations in regolith grain size. We propose a reinterpretation of that parameter. We develop models of light scattering by regolith grains which predict that variation in the refractive index of regolith grains causes deviations from Umov's Law. Variations in other grain parameters such as grain size and degree of space weathering do not produce this deviation. The models are supported by polarimetric measurements on powdered terrestrial materials of differing refractive index. We derive a simple formula to express the relationship between refractive index and the deviation from Umov's Law and apply it to telescopic measurements of regions of the lunar surface. We show that the Aristarchus Plateau and the Marius Hills regions both comprise materials of unusually low refractive index. These results are consistent with recent estimates of the mineralogy of those areas. Picard and Peirce craters, in Mare Crisium, are shown to contain material of low refractive index similar to highland regions, as has been suggested by earlier studies of these craters.

1. Background

Moonlight is linearly polarised at almost all lunar phase angles. The degree of linear polarisation is defined as $P = (I_\perp - I_{||})/(I_\perp + I_{||})$ where $I_\perp$ and $I_{||}$ are the intensities of the components of moonlight with electric field vectors resolved perpendicular ($\perp$) or parallel ($||$) to the scattering plane. This quantity varies with lunar phase angle and reaches a peak (P_{max}) at lunar phases typically lying between about 95° and about 110°. This peak value correlates strongly with the albedo (A) of the lunar surface region in question. The correlation, known as Umov's Law, is linear when displayed on logarithmic axes and may be described by an equation of the form: $log_{10}(A) + a_1 log_{10}(P_{max}) = a_2$. Dollfus and Bowell (1971) applied this regression relation to observations of over a hundred small regions across the lunar surface. In the visual spectral range of light, they found that $a_1 = 0.72$ and $a_2 = -1.81$. Deviations from Umov's Law caught the interest of Shkuratov, Dollfus and others (Shkuratov, 1981; Dollfus, 1998; Shkuratov and Opanasenko, 1992; Geake and Dollfus, 1986; Novikov et al., 1982) who studied this law in relation to granular terrestrial materials and lunar regolith samples alike. When applied to moonlight, it was found that departures from Umov's Law occurred as a 'polarisation excess' when associated with the ejecta of some bright young craters, and as a 'polarisation deficit' notable on the Aristarchus Plateau (so-called 'Wood's Spot') and the Marius Hills, for example. It was suggested that a 'polarisation excess' was caused by anomalously large median grain sizes within the granular material being observed. The 'Polarimetric Anomaly Parameter': $(P_{max})^{a_1} A$ was derived as a means of quantifying departures from Umov's Law and it was suggested that variations in this parameter quantified variations in the median grain size of the lunar regolith. Shkuratov proposed that 'polarisation deficit' might result from grains of anomalously low albedo causing a breakdown of Umov's Law, though later work suggested that lower median grain sizes might be the cause. The question of how to interpret 'polarisation excess' and 'polarisation deficit' has received very little attention since. Indeed, more recent work (Shkuratov et al., 2007; Hines et al., 2008; Jung et al., 2014) on lunar polarimetry has assumed the correctness of this interpretation of the 'Polarimetric Anomaly Parameter'.

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In this paper we address this question. We propose a new interpretation of 'polarisation deficit' and 'polarisation excess'. This new interpretation is that departures from Umov's Law are the result of variations in the refractive index of lunar regolith grains. This allows a new method for determining the refractive index of the lunar regolith remotely.

2. The plan of this paper

We begin in Section 3 by presenting a simple 2-dimensional (2D) model of light scattering from a lunar regolith grain. We show how this model may be used to interpret the structure of a correlation obeying Umov's Law, including a consistent interpretation of both a 'polarisation excess' and a 'polarisation deficit'. We then test this simplistic 2D model by considering a 3-dimensional (3D) multi-grain regolith model and show that it fully supports our interpretation of 'polarisation excess' and 'polarisation deficit'. Next, in Section 4, we describe polarimetric experiments conducted on terrestrial grain samples and lunar regolith simulants. We show that these experiments confirm our new interpretation of 'polarisation excess' and 'polarisation deficit'. Finally, in Section 5, we apply our interpretation to the polarimetry of moonlight. We show how polarisation measurements can be applied to determine the refractive index of the lunar regolith. The Aristarchus Plateau and the Marius Hills are considered in detail, in order to allow a comparison with the work of Shkuratov (1981) who considered these areas in particular. Mare Crisium is also discussed in terms of its stratigraphy as revealed by observational results presented here.

3. Theory

Our simple 2D model represents an idealised regolith grain in isolation. This model assumes that inter-grain scattering of light has a negligible influence upon the polarisation properties of moonlight. Our 3D model takes account of inter-grain scattering and we will show that these two models provide a mutually consistent interpretation of Umov's Law.

3.1. 2D model

3.1.1. Grain structure

A lunar regolith grain is represented as a core of uniform material of diameter *D* as shown schematically in Fig. 1. This core carries a uniform coating of space-weathered core material defining a shell of thickness *d*. The shell consists of a proportion (ϕ) of nano-phase metallic iron beads (npFe) embedded in the same material as the core. The effective refractive index of the space-weathered layer is represented by $m_1 = n_1 + ik_1$ and is calculated using the refractive index ($m_2 = n_2 + ik_2$) of the core material and the refractive index ($m_{Fe} = n_{Fe} + ik_{Fe}$) of the npFe beads. The refractive index of the grain core was based on values for pyroxene and olivine stated by Hiroi and Pieters (1994), which include the necessary wavelength dependency. For npFe, the optical properties of iron were taken from Johnson and Christy (1974). By applying Maxwell–Garnett effective medium theory, we define:

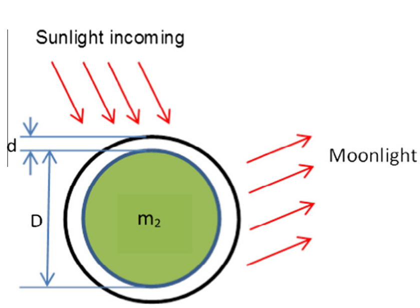

Fig. 1. The 2D model regolith grain.

$$K_1 = \left(1 + \frac{3\phi(K_{Fe} - K_2)/(K_{Fe} + 2K_2)}{1 - \phi(K_{Fe} - K_2)/(K_{Fe} + 2K_2)}\right) \quad (1)$$

Here, $K_{Fe} = (n_{Fe} + ik_{Fe})^2$, $K_2 = (n_2 + ik_2)^2$ and $K_1 = (n_1 + ik_1)^2$ from which m_1 is obtained. The absorption coefficients of the grain core and space-weathered layer, for light of wavelength λ, are defined as $\alpha_2 = 4\pi k_2/\lambda$ and $\alpha_1 = 4\pi k_1/\lambda$ respectively. The absorption coefficient (α_2) for the grain core was derived from graphs presented by Nimura et al. (2008) concerning Apollo 16 soil samples. This type of model has also been used by Nimura to represent the upper layer of the lunar regolith (Nimura et al., 2008).

We calculate the Fresnel amplitudes $\hat{r}_{ab}^{\|,\perp}(\theta)$ for reflected light polarised perpendicular ($\perp$) or parallel ($\|$) to the scattering plane at each internal and external grain boundary, where θ is the angle of incidence of a ray traversing between medium "*a*" and medium "*b*". Transmission and reflection coefficients were then calculated, and applied in a manner suggested by Hapke (2005) to derive an expression for the proportion of light scattered by the grain at a given phase angle (*g*), and the degree of linear polarisation (*P*(*g*)) of that scattered light. To do this, we calculated the single scattering albedo (*w*) of the grain in terms of the total scattering (s_{ab}) and transmission (t_{ab}) activities using angle-averaged values ($r_{ab}^{\|,\perp} = 2\int|\hat{r}_{ab}^{\|,\perp}(\theta)|^2 \cos\theta \sin\theta d\theta$) of the Fresnel amplitudes. These are identified in Table 1 in terms of boundaries between different media at or within the grain. The reader is referred to schematic Figs. 2 and 3 presented by Nimura et al. (2008) which succinctly show the light scattering processes being modelled here.

The total single scattering albedo is given by $w = (w_\perp + w_\|)/2$. We calculated the degree of linear polarisation according to the definition provided by Hapke (Chapter 14, Eq. (14.3) (Hapke, 2005)) in terms of bidirectional reflectance as:

$$P(g) = \frac{[X_\perp(g/2) - X_\|(g/2)]}{[X_\perp(g/2) + X_\|(g/2)] + 2[wH^2 - Y]} \quad (2)$$

where *g*/2 is the angle of incidence and reflection. Here, the term *Y* is the angle-averaged value of $(X_\perp(\theta) + X_\|(\theta))$. The terms $X_\perp(\theta)$ and $X_\|(\theta)$ are the back-scattering activity expressed using angle-dependent (i.e. not angle-averaged) reflectances ($R_{ab}^x(\theta) = |\hat{r}_{ab}^x(\theta)|^2$). These are defined in Table 1 in terms of reflectances at boundaries between different media at and within the grain, and they account for back-scattered light from the space-weathered layer both externally at the grain surface and also internally, having performed one round-trip through the grain core and back. The angle $\theta_T = arcsin(\sin(g/2)/m_2)$ is the internal angle at which an incident light ray enters the grain core from within the space-weathered layer. It is also the angle at which it subsequently strikes the space-weathered layer from within the core before leaving the grain at an exit angle of *g*/2. The *H*-function, defined by the well-known radiative transfer theory of Chandrasekhar, is defined as:

$$H(\mu, w) = \left[1 - \left(1 - \sqrt{1-w}\right) \times \mu \times \left\{r_0 + \left(1 - \frac{1}{2}r_0 - r_0\mu\right)\ln\left(1 + \frac{1}{\mu}\right)\right\}\right]^{-1};$$
$$\mu = \cos(g/2); r_0 = \left(2/(1 + \sqrt{1-w}) - 1\right) \quad (3)$$

Thus, the regolith grain is defined in terms of five parameters. We restricted the value of grain parameters to lie within ranges comparable to values identified for the fine fraction of regolith samples returned to Earth by the Apollo and Luna missions. The parameter ranges are shown in Table 2.