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Interpreting lunar polarimetric anomalies at large phase angles

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ABSTRACT

This work was inspired by the paper "Polarimetry of moonlight: A new method for determining the refractive index of the lunar regolith", by Fearnside et al. [Icarus 2016, 268, 156–171], in which the authors show that the parameter of polarimetric anomaly describing the deviation from the Umov law solely is a function of the real part of the refractive index. Within their model, this parameter does not depend on the average particle size. We consider that the geometrical optics (GO) model by Fearnside et al. (2016) is oversimplified and, therefore, it is not applicable for the lunar regolith. In particular, this model is similar to other GO models that do not produce the negative polarization branch of the Moon. Most critically, experimental measurements of the lunar regolith and lunar simulants demonstrate that the parameter of polarimetric anomaly does depend on particle size. We show that the applications of the Fearnside et al. (2016) model in lunar optics (e.g., their lunar maps of the real part of the refractive index) must be considered with caution.

1. Introduction

Although lunar polarimetry has a long history (e.g., Lyot, 1929; Dollfus and Bowell, 1971; Dollfus and Titulaer, 1971; Dollfus and Geake, 1977; Shkuratov, 1981; Shkuratov and Basilevsky, 1981; Kornienko et al., 1982; Novikov et al., 1982; Akimov and Shkuratov, 1983; Shkuratov et al., 1980; 1984; Kvaratskhelia, 1988; Shkuratov et al., 1992a; Shkuratov and Opanasenko, 1992; Opanasenko and Shkuratov, 1994; Dollfus, 1998; Shkuratov et al., 1994, 2007a, 2011), it has not been a popular topic for two reasons: first, no lunar probes have incorporated polarimetric capabilities in their instrument suites; and second, until recently the interpretation basis of polarimetric measurements has been rather poor. On the other hand, the polarimetric technique continues to attract the attention of authors in the context of planetary investigations (e.g., Kaydash et al., 2015; Shkuratov et al., 2015; Jeong et al., 2015; Fearnside et al., 2016), including laboratory measurements of planetary regolith analogs (e.g., Geake and Dollfus, 1986; Shkuratov and Opanasenko, 1992; Shkuratov, 1987; Shkuratov et al., 2002, 2006, 2007b, 2008; Levasseur-Regourd et al., 2015) and theoretical modeling that includes the Discrete Dipole Approximation calculations (DDA) (e.g., Draine and Flatau, 1994; Zubko et al., 2008, 2011, 2013, 2015a,b; Videen et al., 2015), Finite-Difference Time Domain (FDTD) or Discontinuous Galerkin Time Domain (DGTD) method (Grynko et al., 2013, 2016), the T-matrix approach (e.g., Petrov et al., 2008; 2010, 2011; Mishchenko et al., 2009), and the computer ray-tracing technique based on the geometrical optics (GO) approximation (e.g., Shkuratov et al., 1992b; Grundy et al., 2000; Grynko and Shkuratov, 2003, 2007, 2008; Grynko et al., 2006, 2013, 2016; Shkuratov and Grynko, 2005; Stankevich et al., 2007). Thus, polarimetry potentially is an important tool to study the Moon (Shkuratov et al., 2011).

A typical lunar curve of the linear polarization degree as a function of the phase angle α is shown in Fig. 1 for the wavelength $\lambda = 430$ nm. We construct this curve using the observations of Kvaratskhelia (1988) of the Luna-16 landing site. The dependence has a negative polarization branch at small phase angles $\alpha < 25°$ and a positive branch with a maximum (P_{max}, α_{max}) occurring at $\alpha_{max} = 100$–$105°$. Distributions of the parameter P_{max} on the lunar surface at different wavelengths show a close correlation with the surface's radiance factor (the apparent albedo) A determined at arbitrary phase angle, if the influence of the lunar topography and global brightness trend from the limb to terminator are excluded (Hapke, 2012; Shkuratov et al., 2011, 2015). This correlation, which is known as the Umov law, can be expressed as

$$P = \left(I_{\perp} - I_{\parallel}\right)/\left(I_{\perp} + I_{\parallel}\right) \propto 1/A, \quad (1)$$

where $I_{\perp}$ and $I_{\parallel}$ are the intensities of light passing through a polarizer oriented perpendicular and parallel to the scattering plane. Thus, according to formula (1), albedo increases as polarization decreases. The correlation was experimentally found to be linear on

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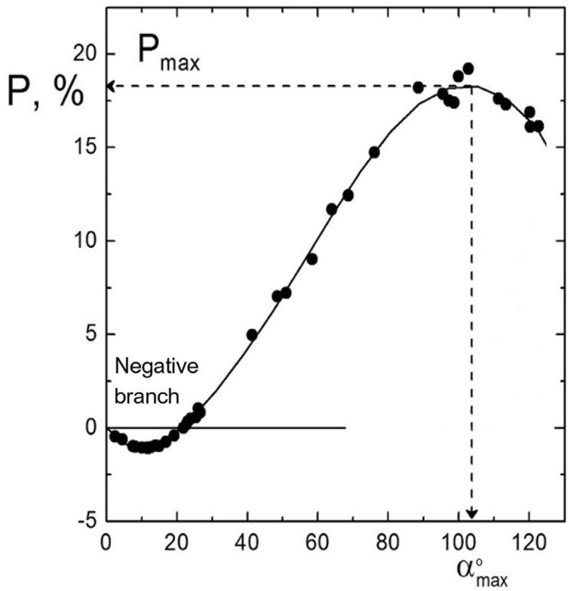

Fig. 1. Polarimetric phase function of the Luna-16 landing site measured by Kvaratskheliya (1988) at the wavelength $\lambda = 430$ nm.

a log-log scale:

$$\log A + a \log P_{\max} = b, \tag{2}$$

where a and b are constants in a first approximation.

To retrieve additional information from polarimetric measurements at large phase angles, it is necessary to study deviations from the Umov law. Over 35 years ago, Shkuratov et al. (1980) introduced the parameter $b = \log(P_{\max})^a A$ for lunar imaging. It was shown that this parameter is independent of the albedo and polarization degree (Shkuratov et al., 1980; Shkuratov, 1981; Kornienko et al., 1982; Novikov et al., 1982; Shkuratov and Opanasenko, 1992). This parameter has been related to the average size of lunar regolith particles (Shkuratov et al., 1980; Shkuratov, 1981; Kornienko et al., 1982; Shkuratov and Opanasenko, 1992) and, perhaps, to the porosity of the lunar surface (Shkuratov et al., 1980; Shkuratov and Basilevsky, 1981; Novikov et al., 1982). One needs to emphasize these conclusions were drawn based on laboratory polarimetric measurements of different powders that were considered as feasible structure analogs of the lunar surface (see below).

Recently Fearnside et al. (2016) suggested a new interpretation of the parameter b, which is based on their calculations with a ray-tracing (GO) model, using in particular the well-known Hapke (2012) photometric model that, however, is very approximate (e.g., Shkuratov et al., 2012a). They also used their own laboratory polarimetric measurements of powders with different mean grain sizes and refractive indexes. The gist of the Fearnside et al. (2016) reinterpretation of the parameter b is that it varies over the lunar surface not due to the average particle size, but because of differences of the real part n of the refractive index m, i.e. $n = \mathrm{Re}(m)$. Shkuratov (1981) considered this to be theoretically feasible, showing that the product $P \times A$ at phase angles close to the Brewster angle of silicates can be roughly estimated as follows:

$$PA \approx \frac{n^2 - 1}{n^2 + 1}. \tag{3}$$

However, later, using laboratory polarimetric measurements of structure analogs of planetary regoliths, Shkuratov and Opanasenko (1992) could not confirm this relationship experimentally, showing that the product $P \times A$ is rather a function of particle sizes.

Fearnside et al. (2016) suggest a simple formula to express the relationship between the refractive index and the deviation from Umov's law and apply it in the interpretation of telescopic measurements of regions of the lunar surface deducing mineral composition for such well-known areas as the Aristarchus Plateau, the Marius Hills, and other polarimetric anomalies.

We should note that there is the difference in definition of polarimetric anomaly characterization suggested in our works and used by Fearnside et al. (2016). We exploit a vertical offset from the regression line in Umov plots, whereas Fearnside et al. introduce a lateral offset that is perpendicular of the regression line, like it was done, e.g., in Shkuratov et al. (2012b) for correlations between reflectance and phase ratio. This difference, however, does not influence conclusions of our paper.

2. Comments on the Fearnside et al. (2016) approach

The Fearnside et al. (2016) ray-tracing model is poorly described. It also lacks a comparison between theoretical and lunar (or laboratory) phase curves of polarization degree. Unfortunately, Fearnside et al. (2016) have been unable even to provide information either objectively disproving or corroborating existing models, e.g., by Grynko and Shkuratov (2008). In such a situation it is not easy to criticize any model. However, there are a number of common features of ray-tracing models based on their underlying assumptions that are widely known. We here use our experience and known features of ray-tracing models to exhibit the principal shortcomings of the Fearnside et al. (2016) approach (e.g., Shkuratov and Grynko, 2005; Shkuratov et al., 1992b; Grynko and Shkuratov, 2007, 2008; Grynko et al., 2006).

2.1. Particle size

We experimentally show once again that independently of the Fearnside et al., (2016) calculations and measurements, the parameter b does depend on average particle size. Over the past four decades, numerous powdered samples have been measured. These samples have different chemical and mineral composition, including colored and colorless glasses, terrestrial minerals and rocks, meteorites, and lunar samples. All these samples consist of particles of different sizes and different albedo. The principal results of these photopolarimetric measurements have been published in multiple papers during several decades (e.g., Akimov and Shkuratov, 1983; Geake and Dollfus, 1986; Shkuratov and Opanasenko, 1992; Shkuratov et al., 1992a, 1994, 2006, 2007b, 2008).

While the albedo of the lunar samples and basalt powders depends on the average particle size, all the samples of colorless glass reveal almost constant radiance factor close to $A = 95\%$, independent of the average particle size, but different values of the parameter b. It should be emphasized that all samples of the colorless glass have the same refractive index. Thus, the average particle size is experimentally shown to be an important factor affecting the parameter of polarimetric anomaly b. Thus, the laboratory measurements and modeling results presented in Fearnside et al. (2016) are inconsistent with the experimental results shown in Fig. 2 (see dark points). The explanation of this appears to be straightforward from the experimental results shown in Fig. 2: The samples consist of (or include) small particles, when the GO approximation is not valid.

Geake and Dollfus (1986) found a correlation between the parameter b and average particle size of powders of terrestrial basalt. In Fig. 2 we summarize several series of measurements that unambiguously demonstrate a dependence of average particle size on the parameter of polarimetric anomaly b for terrestrial basalt (Geake and Dollfus, 1986), colorless glass, and lunar samples Luna-16 (fine), 2002–1.6; Luna-24 (fine); Luna-16, L-16-19-1); Luna-24