MODEL OF LIGHT SCATTERING BY LUNAR REGOLITH AT MODERATE PHASE ANGLES: NEW RESULTS.
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Introduction: We have presented in [1] a model for the polarimetric and photometric characteristics of the lunar regolith at moderate phase angles based on realistic assumptions on regolith microstructure (see description below).

Now we have new important observational data, which allow to improve a determination of model parameters and to make some conclusions about physical characteristics of the lunar surface:

1. We have performed in 2004 photopolarimetric CCD-observations of the Moon at very large phase angles 145 and 153° (earlier we had data only for phase angles <123°). So we can now study both sides of maximum of positive polarization.

2. We have used data of absolute photometry of Lane and Irvine at phase angles 40–120° in two spectral bands. This has allowed us to find the model parameters for different wavelengths, and, besides, our model has had a good agreement with both brightness and polarization phase dependences at phase angles, at least, 40–120°.

Before discussion of these results let us briefly describe our model [1]. Full description is available at our site http://www.univer.kharkov.ua/astron/dslpp/moon/polar/.

Description of the model: We consider following processes occurring at light scattering by regolith surface:

- single scattering on particles of wavelength-comparable sizes;
- Fresnel's reflection on large (in comparison with a wavelength) microsurfaces;
- multiple scattering (and reflection, refraction) in a medium of such microparticles;
- shadow-hiding effect on all scales of relief;
- multiple scattering on elements of relief.

Intensity of scattered light can be written like this:

$$\mathbf{I}(\alpha)=\begin{pmatrix} I_{\parallel} \\ I_{\perp} \end{pmatrix}=\left(F(x,\pi-\alpha)\begin{pmatrix}\cos^2\alpha \\ 1\end{pmatrix}+b\begin{pmatrix}1\\1\end{pmatrix}+k\begin{pmatrix}R_{\parallel}\\R_{\perp}\end{pmatrix}\right)e^{-h\alpha}+c\begin{pmatrix}1\\1\end{pmatrix}, \quad (1)$$

where $\mathbf{I}(\alpha)$ – intensity at mirror point ($i=\varepsilon=\alpha/2$) in relative units ($I_{\parallel}$ and $I_{\perp}$ – intensity components, parallel and perpendicular to scattering plane correspondingly), i – incidence angle, ε – emergence angle, $\alpha=\pi-\theta$ – phase angle, θ – scattering angle, k – weighting coefficient, $R_{\parallel}$ and $R_{\perp}$ – Fresnel's reflectances (parallel and perpendicular to scattering plane correspondingly) as functions of refractive index m and scattering angle, h – roughness factor [2], *b* – intensity of multiple scattering in micromedium, *c* – intensity of multiple scattering on relief, function F – indicatrix of Rayleigh-Gans (for spherical particles):

$$F(x,\theta)=C(x)\, j_1^{\,2}\left(2x\sin(\theta/2)\right)/\sin^2(\theta/2),$$

$$j_1(z)=-\cos(z)/z+\sin(z)/z^2,$$

where $x=2\pi R/\lambda$ – size parameter, R – size (radius) of particle, λ – wavelength, and C(x) – normalizing factor for indicatrix:

$$C(x)\approx\begin{cases}27/\left(16x^2\left(1-2x^2/5\right)\right), & x\le 1,\\ 180x^4/\left(109x^4+45x^2-180x^2\ln x-90\right), & x>1.\end{cases}$$

Linear polarization degree can be written like this:

$$P(\alpha)=\frac{F(x,\pi-\alpha)\sin^2\alpha+k(R_{\perp}-R_{\parallel})}{F(x,\pi-\alpha)(1+\cos^2\alpha)+k(R_{\perp}+R_{\parallel})+2(b+ce^{h\alpha})}. \quad (2)$$

The model contains six parameters: x, k, m, h, *b*, *c*. We have fixed refractive index: m=1.55 (as typical for quartz), and other 5 parameters were fitted using observational phase dependences of lunar brightness and linear polarization degree.

Some preliminary results were presented in [1]. Now we have essentially expanded the set of observational data.

New observational data: We have performed in 2004 polarimetric observations of the Moon at very large phase angles 145 and 153°. Observations were carried out using our CCD-photopolarimeter [3] in two spectral bands ("R" – 0.67 μm, "B" – 0.46 μm). And now for studying the positive polarization maximum we can use a set of images of the Moon in sufficiently wide range of phase angles (45–153°).

Also, for describing the phase dependence of lunar brightness we have used data of absolute integral photometry of Lane and Irvine [4]. These data have been corrected in [5] for systematical errors caused by influence of libration variations and changing of contribution of mares and highlands in integral brightness with phase changes. Earlier we had reliable data of absolute photometry only for $\alpha<60°$ and only for band "R" (Akimov [6]). Now we can use the phase dependences of brightness at $\alpha<120°$ in both spectral bands.

Approximation: Since phase dependence of brightness is mainly controlled by "macro"-parameters (h and *c*), we use Lane's and Irvine's data only for large phase angles (40–120°), where the phase dependence is controlled mainly by mesorelief [5] (i.e. macrorelief within the limits of resolution). For this phase range authors of [5] have found that phase dependence of brightness can be described by empirical function [2]

$$I(\alpha)=I_0 e^{-\mu\alpha}, \qquad (3)$$

where μ – effective roughness factor depending on wavelength: $\mu=0.77–0.06\lambda$ (λ in µm). So, we have $\mu=0.74$ for "B" and $\mu=0.73$ for "R". Analyzing dependence μ on albedo, we have obtained value of parameter h (0.78), which we suppose to be equal μ for zero albedo.

So, we have parameter h; parameters x, k, b were fitted with polarization phase dependence (2), and, simultaneously, parameter *c* was fitted with brightness phase dependence (1), which should be close to the "observed" function (3).

Results of approximation: On Fig.1,2 you can see results for two lunar areas in two spectral bands. In Table 1 you can see a comparison with the same results, but obtained with Akimov's absolute photometry at phase angles 30–50°. The agreement is good, but parameter *c* that was found using range of phase angles 30–50° is essentially higher than for range 40–120°.

Analysis of the results: There is expected correlation between characteristics of multiple scattering (*b* and *c*) and albedo A (see Fig.1).

Obtained values of size parameter x for highlands are smaller than for mares. It is due to smaller values of phase angle of polarization maximum α_{max} for highlands (Table 2). Difference of α_{max} for two spectral bands for any area is present, but noticeably smaller. So, the position of maximum of polarization depends mainly on type of surface and a lesser degree on albedo.

Shift of maximum position for highlands can be also explained by higher roughness (higher value of h) rather than by smaller particle sizes. But we have not data about difference of h for mares and highlands. To choose from these two variants one need to obtain new data of observation and laboratory simulation.

Ratio between modules of terms, proportional F and k in (1), one can consider as ratio between deposits of scattering and Fresnel's reflection into surface brightness correspondingly. According to our results, an estimation of part of Fresnel's reflection is about 20%.

Conclusions: 1. Our model can describe simultaneously observational phase dependences of both brightness and polarization degree of the lunar surface at phase angles, at least, 40–120°.

2. Since the parameter *c* is higher for smaller phase angle range, we suppose that multiple scattering on relief influences on brightness phase curve mainly at small (<50-60°) phase angles. Therefore, the microrelief, in which this multiple scattering is mainly formed, influences mainly on small-phase part of phase curve of brightness. The same conclusion was made in [5] on the base of analysis albedo dependence of phase slope.

3. Probably for such a dark surface as lunar one, albedo influences on polarization maximum position sufficiently weakly. Its smaller values for highlands may be explained by smaller particle sizes or higher roughness.

4. An estimation of deposits of scattering by microparticles and Fresnel's reflection into the lunar brightness is about 80% and 20% correspondingly.

References: [1] Velikodsky Yu. I. et al. (2004) *LPS XXXV*, Abstract #1311. [2] Akimov L. A. (1988) *Kinem. i Fiz. Neb. Tel v.4, No 2*, 10-16 [in Russian]. [3] Korokhin V. V. et al. (2000) *Kinematics and Physics of Celestial Bodies, 16, iss.1*, 63-67. [4] Lane A. P., and Irvine W. M. (1973) *Astron. J., 78, No 3*, 267-277. [5] Korokhin V. V. et al. (2005) *LPS XXXVI*, Abstract #1437. [6] Akimov L. A. et al.(1986) *UkrNIINTI, Kiev*.

Table 1. Model parameters for different phase ranges.

α range	x	k	h	b	c
30–50°	0.87	1.86	0.70	3.70	0.34
40–120°	0.77	1.53	0.78	4.15	0.10

Table 2. Phase angle of maximum polarization.

	mare, R	mare, B	highl., R	highl., B
α_{max}	102°	103°	97°	98°

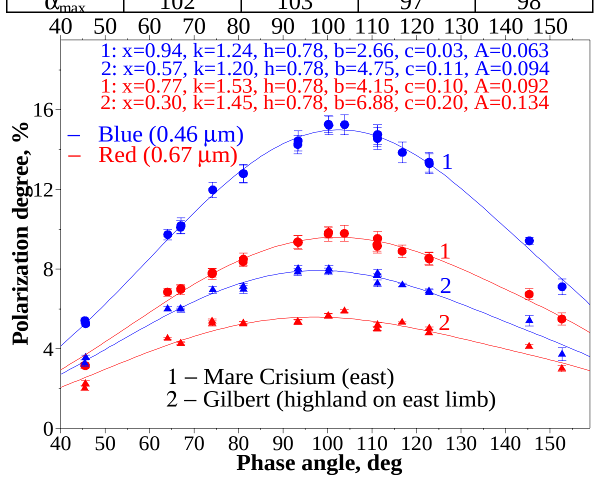

Fig. 1. Approximation of linear polarization degree

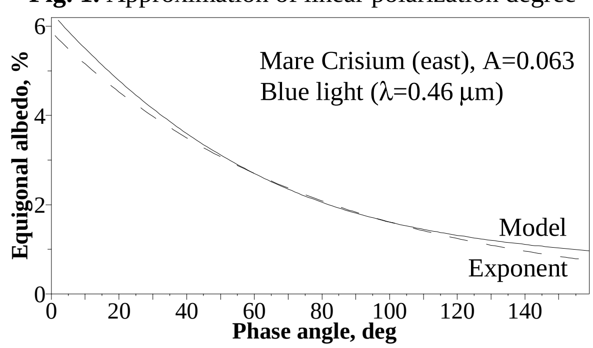

Fig. 2. Approximation curves of phase dependence of lunar brightness (at area with mirror reflectance geometry): model curve (1) and exponential function (3)