Opposition effect of the Moon from ground-based and space observations

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We study phase ratio images of the lunar nearside at low phase angles (1.6° and 2.7°) using ground-based telescope observations. The ratio appears highest for highlands of intermediate albedo, while bright craters have lower values. An average phase curve obtained with ground-based and spacecraft photometry of the Moon at phase angles 0.25–73° is presented.

INTRODUCTION

The brightness opposition effect (BOE) is a rapid increase of surface brightness seen when the phase angle α approaches zero. There are two mechanisms governing the BOE of planetary regoliths: the shadow-hiding effect and coherent backscattering enhancement [e.g. 1,2]. The relative contribution of each mechanism depends on α, albedo, and surface structure. Coherent backscattering can be significant only if the surface is rather bright. The BOE is observed for many atmosphereless celestial bodies including the Moon at α below 5–10° [1]. There are so far discrepant data about the role of coherent backscattering in the formation of the lunar BOE. Low-phase-angle observations of the Moon are difficult. Absolute photometry has low accuracy [3], spacecraft data are scarce, and ground-based observations cannot be carried out at α<1° because of the lunar eclipse. Relative lunar photometry can be performed by dividing one image obtained at α_1 by another image acquired at a generally larger α_2. This method can be very effective and was applied to select Clementine [4] and SMART-1 [5] data. Similar phase ratio technique was applied to Earth-based telescope data [6,7]. We use this method to produce a phase ratio (1.6°/2.7°) image of the lunar disk.

OBSERVATIONS

During a two-month campaign in 2006, we carried out quasi-simultaneous imaging photometry of the Moon and the Sun using a 15-cm refractor at Maidanak Observatory (Uzbekistan) [3,8]. We have presented results of absolute photometry [3], in particular, phase dependencies at α = 1.6 … 73° for several lunar areas acquired at 603 nm. We also obtained a series of lunar images near opposition suitable for phase-ratio analysis. The series covers the range of α = 1.6 … 3.1° (hereafter, α values correspond to the lunar disk centre). During the observations near opposition the photometric equator, the direction from the sub-observer point to

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sub-solar one, was continuously rotated around 180°, and the direction of the phase-angle trend over the lunar disk was also rotated. Using this rotation we may separate the phase-angle trend from the albedo distribution on the lunar disk. Below we present results of processing the opposition series of lunar images at 603 nm.

PHASE RATIOS

A phase-ratio image is the quotient of coregistered brightness images of the same scene acquired at different phase angles. Before calculation of the phase-ratio image, the brightness images should be corrected for the global limb-terminator darkening using a disk function. We here apply Akimov's theoretical disk function [1,9]

$$D(\alpha,\beta,\gamma)=(\cos\beta)^{\frac{\alpha}{\pi-\alpha}}\,\frac{\cos\frac{\alpha}{2}}{\cos\gamma}\cos\left(\frac{\pi}{\pi-\alpha}\left(\gamma-\frac{\alpha}{2}\right)\right), \qquad (1)$$

where β and γ are the photometric latitude and longitude, respectively. The observed brightness (radiance factor) divided by a disk function (e.g., Eq. (1)) is called the equigonal albedo A_{eq} because it corresponds to the mirror geometry of observation/illumination when the incidence and emergence angles are equals to $\alpha/2$ [e.g., 10].

The ratio of equigonal albedo images obtained at 1.6° and 2.7° is shown in Fig. 1. One can see that the phase ratio is lower for maria than for highlands, though the difference is small (≤1%). Meanwhile, bright craters (e.g., Tycho and Copernicus) are clearly visible as dark spots; these are areas having smaller phase-function slopes. Both mare and highland craters have phase ratios about 5% lower than their neighbourhood. This is an unexpected result, as the craters are rather bright and we could anticipate a manifestation of the coherent backscattering effect resulting in BOE increasing at so small α. Thus, either the albedo is not high enough to provide the coherent spike or it is too narrow to be revealed at 1.6° … 2.7°. The global brightness trend on the image relates to the variations of α over the lunar disk.

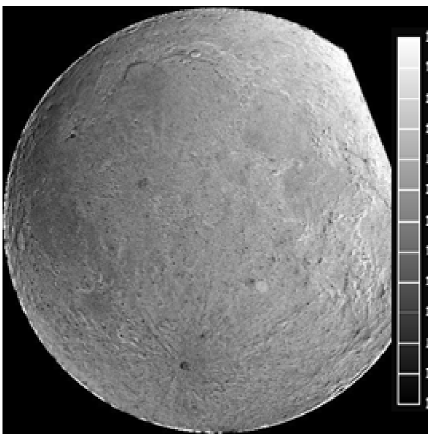

Figure 1. Phase ratios 1.6°/2.7°.

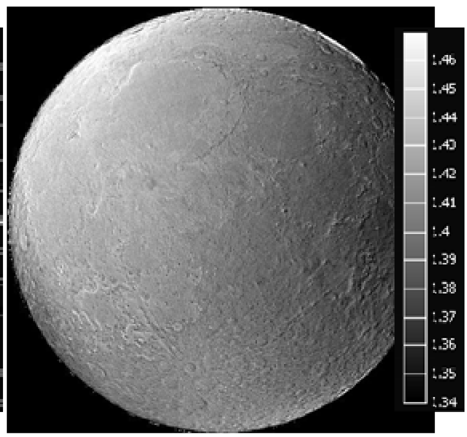

Figure 2. Phase ratio 2.59°/−2.59°.

Figure 2 shows the phase ratio (2.59°/−2.59°) of equigonal albedo images obtained before and after opposition. Albedo variations in Fig. 2 are almost suppressed, but due to variations of α over the lunar disk (in limits of 0.5°) a gradient of phase ratio is seen very well.

RELATIVE PHOTOMETRY

The global trends seen in Figs. 1 and 2 allow us to estimate the lunar phase function at small α. We clipped the edges of the equigonal albedo images to avoid errors of the disk function (1) near the limb and terminator. Then, applying the least-squares method we fit an equigonal albedo distribution at a fixed α and simultaneously relative phase dependence (the values in the range of α = 1.4° … 3.2° with step 0.1°) using whole series of lunar images. In Fig. 3 the relative phase dependence is shown together with data of absolute photometry of the Sinus Medii area (latitude 0°35', longitude −1°17') at large α [3] and with data of relative photometry (averaged different lunar types) of Clementine [4] and SMART-1 [5] for very small α. All equigonal albedo data were fitted (Fig. 3) by the expression [3]:

$$A_{eq}(\alpha) = a_1 e^{-\mu_1 \alpha} + a_2 e^{-\mu_2 \alpha} + a_3 e^{-\mu_3 \alpha}, \quad (2)$$

where a_1=0.0244, μ_1=30.1, a_2=0.0384, μ_2=5.55, a_3=0.0842, μ_3=0.633 with α measured in radians. Simultaneously, normalizing factors for the three sequences of phase function relative values were fitted to convert these values to absolute equigonal albedo of Sinus Medii at 603 nm [3]. Figure 3 shows that the lunar BOE is very prominent; its amplitude is almost 40% in the range of α = 0.25° … 5.0°. At α = 0.5° … 2.0° the phase function of the Moon is almost linear. It appears that the main factor determining the lunar BOE is the shadow-hiding effect. At α<0.25° a slight tendency to flatten the phase curve is revealed; this relates to the angular size of the solar disk.

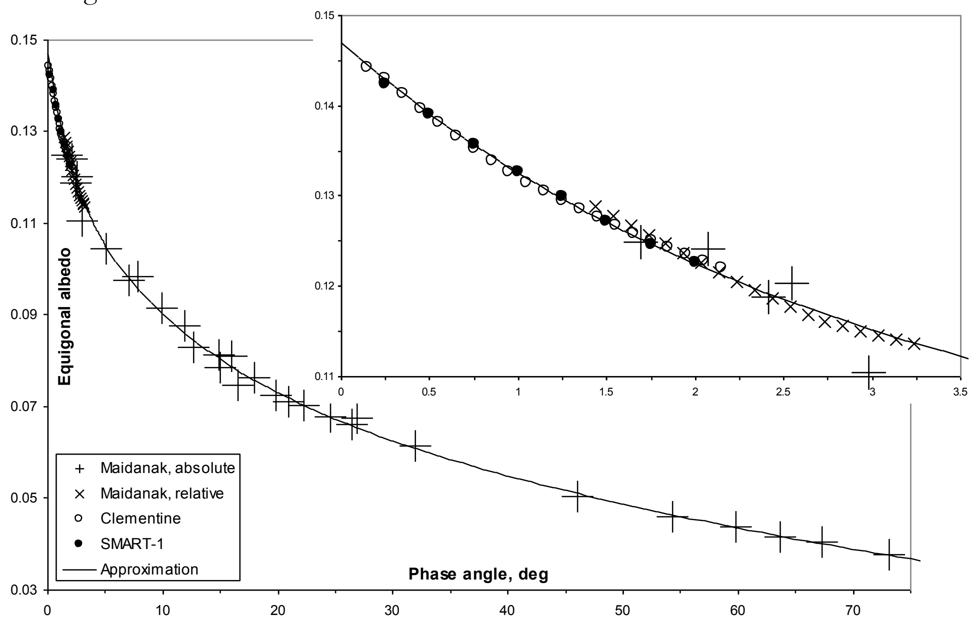

Figure 3. Phase dependence of lunar equigonal albedo.

CONCLUSIONS

The phase dependencies averaged over different areas of the lunar surface, obtained by ground-based, Clementine and SMART-1 observations, are in agreement with each other and compose the integrated phase curve of absolute equigonal albedo. The integrated dependence at $\alpha = 0.25° \ldots 75°$ can be described by the smooth function in Eq. (2), which has neither inflection nor corner points, suggesting a single mechanism of the BOE formation. The phase ratio (1.6°/2.7°) is slightly lower for maria than for highlands, which can be related to greater roughness of the highland surface. Bright craters have smaller phase-function slopes. This is unexpected, as the craters should manifest themselves in coherent backscattering. This suggests that either the albedo is yet not high enough or the spike is too narrow to be revealed at 1.6° … 2.7°. The latter is consistent with the regolith of bright young craters being immature and, hence, consisting of larger particles, resulting in a narrower coherent peak.

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