ABSOLUTE PHOTOMETRY OF THE MOON IN WIDE PHASE ANGLE RANGE. Yu. I. Velikodsky, N. V. Opanasenko, L. A. Akimov, V. V. Korokhin, Yu. G. Shkuratov, and V. G. Kaydash, Institute of Astronomy, Kharkiv National University, 35 Sumskaya Street, Kharkiv, 61022, Ukraine, dslpp@astron.kharkov.ua.

Introduction: The purpose of this work is to obtain the absolute value of lunar albedo and study the phase dependence of lunar brightness. This information is very important for calibration of new Chandrayaan-1 and LRO data and finally to determine the composition and structure of the lunar regolith. Moreover, the new photometric system gives an opportunity to use the Moon as a photometrical standard for observations of planets and the Earth's surface from space.

Observations: In 2006 we carried out a two-months series of quasi-simultaneous imaging photometric observations of the Moon and the Sun at a 15-cm refractor – the guide of the Kharkov 50-cm telescope at Maidanak Observatory (Uzbekistan) [1]. During 42 observational dates we have acquired with a Canon EOS 300D camera about 20,000 images of the Sun and the Moon in 3 spectral bands ("R": 0.61 μm, "G": 0.53 μm, "B": 0.47 μm) in a wide range of phase angles (1.6–168°) and zenith distances. Observations of the Moon were performed by night as well as by day in parallel with solar observations when the Moon's and the Sun's zenith distances were equal. The day observations in the filter "R" have been processed in [1], and here we have processed the night observations in the filter "R".

Absolute calibration: For absolute calibration the brightnesses of solar and lunar surfaces have been converted into the same photometric system that allows us to calculate the lunar albedo. Procedure of this calibration has been described in [1]. As a piece of the calibration we have taken into account the extinction in the atmosphere that weakens the brightness of celestial bodies (see below).

Albedo calculation. We use the albedo A(α,*i*,ε) which is defined as a function of the phase angle α, incidence angle *i*, and emergence angle ε. It is equal to the well-known bidirectional reflectance r(α,*i*,ε) multiplied by π [2]. The albedo known as the normal albedo is A(0,0,0). To describe the phase dependence, it is convenient to use the so-called equigonal albedo A(α)=A(α,α/2,α/2) [3]. The albedo A(α,*i*,ε) can be calculated from the ratio of lunar and solar brightnesses [1].

Atmospheric extinction. Unfortunately, we could not observe star standards for calculating the night atmospheric transparency, because the mosaic polarimetry at the main telescope focus took all the rest of observational time. Therefore, we used overnight observations of the Moon (a detail in Sinus Medii) to obtain the coefficient of transparency. If the zenith distance changes, the phase angle and brightness of the Moon changes as well. Thus, a reliable simultaneous obtaining of the transparency coefficient and the phase slope from one-night lunar survey without observation of standard stars is practically impossible. Therefore, we apply the following method of sequential approximations: (1) to obtain the coefficient of transparency with an approximate phase slope for each night; (2) to calculate albedo for each night (and phase angle); (3) to build a phase dependence using all phases; (4) to obtaine the phase slope for each night; and then repeat the procedure from the beginning until convergence is reached.

Processing. We have processed in such a manner the data obtained at moonrise and moonset (at large zenith distances) and then using the average coefficient of transparency for a night, we have calculated albedo using lunar images registered near culmination, where transparency errors have minimal effect.

Results: Using this algorithm we have mapped the albedo A(α,*i*,ε) for the visible and illuminated portion of the lunar surface at phase angles from 1.6° to 73°. The albedo A(α,*i*,ε) can be converted to the equigonal or normal albedo using lunar photometric function [3,4]. On the other hand, analysis of our albedo maps allows study of the photometric function with higher accuracy.

Phase dependence. Examples of phase dependences of the equigonal albedo of lunar areas are shown in Fig. 1 (closed symbols). The phase dependence has a steep and narrow opposition peak at phase angles <5°. We note that fitting the curve with this peak with one (or a combination of two) exponent was not successful, because of the strong nonlinearity of the phase function at small phase angles. Moreover, the slope of this peak is determined not reliably form albedo data only. Therefore the approximation was performed simultaneously for phase dependences of albedo and phase slope (bold curves in Figs. 1 and 2, respectively) using a model phase function that is a combination of 3 exponents $f(\alpha) = m_1 e^{-\mu_1 \alpha} + m_2 e^{-\mu_2 \alpha} + m_3 e^{-\mu_3 \alpha}$. For this approximation we obtained the phase slope at small phase angles using images acquired near two oppositions at phase angles 2–3°. During these series the direction "sub-observer point – subsolar point" changed up to perpendicular one. This permits us to separate the phase angle trend of brightness over the lunar disk and albedo variations over it. This method yields the relative phase slope that can be expressed by the logarithmic derivative of phase function $-f'(\alpha)/f(\alpha)$. Four values of the phase slope obtained for narrow phase angle ranges are presented in Fig. 2. Note that the values of phase slope are obtained for the “average” Moon, but have a good agreement with relative position of points on the phase dependence of all studied lunar areas (Fig. 1).

Albedo of the Moon. Albedo maps for different phase angles allow us to build a new photometric system and calibrate existing data of lunar photometry. We have compared our maps for filter "R" with other existing photometric systems (with taking into account wavelength difference): (1) Sytinskaya-Sharonov’s system [5] that was used for absolute calibration of Akimiov’s photometric catalog [6]; (2) Wildey-Pohn’s system [7]; (3) two systems of Gehrels [8]: 1956/57 and 1963/64; (4) Clementine UVVIS camera data that have been calibrated using laboratory measurements of lunar samples [9].

Fig. 1 shows albedo differences between photometric systems for several lunar areas. Average ratios of albedo in old photometric systems to our albedo are presented in Table 1. The ratio for Sytinskaya-Sharonov’s system changes from 0.71 at α=10° to 0.78 at α=40°. The ratio for Clementine has been obtained for α=30°; it is significant as has been earlier noted [10]. The ratios for other photometric systems obtained in a wide range of phase angles and have no notable phase dependence.

Table 1

Photometric system	Ratio to our albedo
Sytinskaya-Sharonov	0.71 – 0.78
Wildey-Pohn	0.85
Gehrels 1956/57	0.81
Gehrels 1963/64	0.66
Clementine	1.64

Conclusions: Our new albedo turns out about 20% higher, than that in the most previous photometric systems (Gehrels 1963/64 system and Clementine data reveal questionably extremal albedo). Relative accuracy of our data is higher; their standard deviation from the phase curve is 2% against 5% and 10%, respectively, for Gehrels’ and Wildey-Pohn’s observations. Our phase curves show good argeement with Gehrels’ and Wildey-Pohn’s ones.

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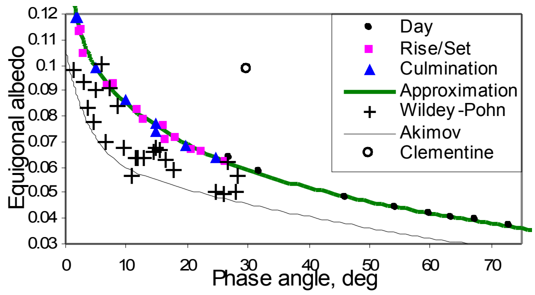
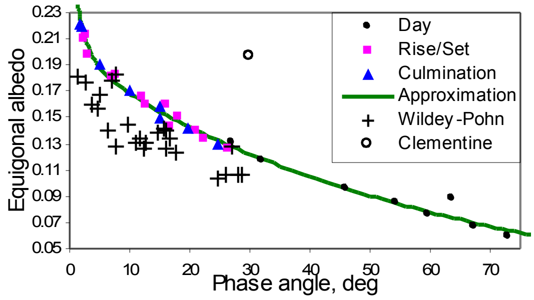
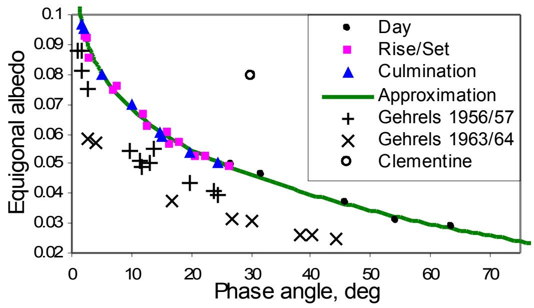
a. Mare Vaporum (l=1°55', b=14°50')



b. Godin (*l*=10°00', *b*=2°00')



c. Mare Tranquill. near Palus Somni (*l*=39°10', *b*=11°34')



d. Copernicus, NNW of central peak (*l*=-20°08', *b*=10°11')

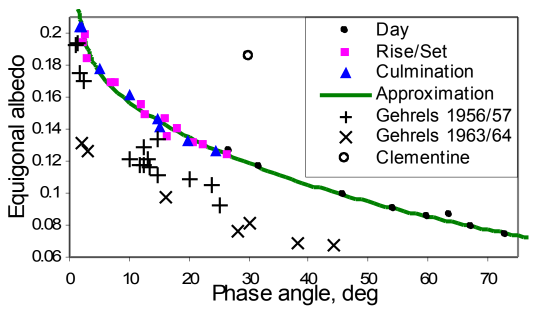


Fig.1. Phase dependence of albedo of lunar areas. Crosses, open symbols, and thin line (see panel **a**) are data of other authors.

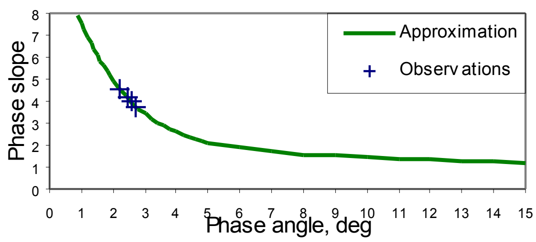


Fig.2. Phase slope $-f'(\alpha)/f(\alpha)$.