PHOTOMETRIC INVESTIGATIONS USING THE SIR-2 DATA OF THE CHANDRAYAAN-1 MISSION.

U. Mall[1], V. Korokhin[2], Yu. Shkuratov[2] and the SIR-2 collaboration [1]Max Planck Institute for Solar System Research, Katlenburg-Lindau, D-37191, Germany, mall@linmpi.mpg.de , [2]Institute of Astronomy of Kharkiv National University, Sumska ul. 35, Kharkiv, 61022 Ukraine, dslpp@astron.kharkov.ua.

Introduction: Lunar mineral abundance determinations based on remote sensing observations are usually made through the analysis of spectra or images taken under different illumination/observation conditions that impact the result of these measurements. Knowledge of a photometric function that transforms the different measurements to the same photometric conditions is therefore of paramount importance for retrieving accurate results. While new instruments are producing data in a wider wavelength range, it is important to study available photometric functions over the wavelength dependence.

The SIR-2 instrument is one of these newer instruments. It is a compact high-resolution pointing spectrometer [1], which has observed the Moon in the spectral range 0.9–2.4 μm, with a spectral resolution of about 0.06 μm on board Chandrayaan-1, the first Indian mission to the Moon. The high quality of the SIR-2 data is intrinsically linked to a thermally actively stabilized InGas detector which delivered unique data from orbit heights of 100 and 200 km above the lunar surface during its operation between January and August 2009. The spectrometer field of view translates into a ground sampling distance of approximately 200m at 100km altitude. Thanks to high spatial and spectral resolution, SIR-2 observations are expected to have a large impact on our understanding of the mineral composition of the lunar soils, particularly on the far side and the polar regions of the Moon.

While different photometric functions are in wide spread use all of them have shortcomings. The SIR-2 data are important, because they allow for testing and validation of photometric functions and their wavelength dependence. The Chandrayaan-1 mission provides lunar spectroscopic data that were not available to the scientific community before, neither at their wavelengths nor with their spatial and spectral resolution.

Photometric analysis: Photometric conditions can be described by three angles: the incidence angles i, the reflection angle e, and the phase angle α. To bring SIR-2 data into a photometric system, where the photometric conditions are fixed, we follow the widespread use of reducing the SIR-2 data into the RELAB photometric system ($i = 30°$, $e = 0°$, $\alpha = 30°$) [2], in which the mosaics generated from the Clementine UVVIS data [3] and the LSCC spectra of lunar samples [4] are presented.

Measurements of reflectivity (brightness) distribution over the lunar surface $A(\alpha,i,e)$ can be transformed into another photometric conditions as follows:

$$A(\alpha_0,i_0,e_0) = A(\alpha,i,e)F(\alpha_0,i_0,e_0)/F(\alpha,i,e), \quad (1)$$

where F is the photometric function, (α_0,i_0,e_0) are the angles of the chosen illumination/observation geometry and (α,i,e) are the angles under which the observations were carried out. The function F can be written as [5]:

$$F(\alpha,\beta,\gamma) = f(\alpha)D(\alpha,\beta,\gamma), \quad (2)$$

where f denotes the phase function of the surface, D is the disk function, describing for Earth-based observations the global brightness distribution over the lunar disk, γ and β are the photometric coordinates (photometric longitude and latitude, respectively) related to the angles i, e [e.g., 5]. Due to the transition from α,i,e to α,β,γ the disk function can be factorized:

$$D(\alpha,\beta,\gamma) = D_\gamma(\alpha,\gamma)D_\beta(\alpha,\beta), \quad (3)$$

where D_γ and D_β represent the longitudinal and latitudinal components, respectively. We use here an accurate disk function suggested by Akimov [6,7]:

$$D_\gamma(\alpha,\gamma) = \cos(\alpha/2)\cos[(\gamma-\alpha/2)\pi/(\pi-\alpha)]/\cos\gamma, \quad (4)$$

$$D_\beta(\alpha,\beta) = (\cos\beta)^{q(\alpha)}, \quad (5)$$

where $q(\alpha) = \nu\alpha/(\pi - \alpha)$, ν is termed the roughness factor; $\nu = 0.34$ for maria and $\nu = 0.52$ for highlands. We use the mean value $\nu = 0.43$ [7]. We note that Eqs. (4) and (5) can be derived as a particular case from the rigorous photometric model of pre-fractal rough surfaces of low albedo with Gaussian statistics of slopes [8].

In the analysis, the concept of the equigonal albedo [6] of the lunar surface becomes important. The equigonal albedo $A_{eq}(\alpha)$ of a lunar point equals the observed reflectivity $A(\alpha)$; if this point is placed on the photometric equator at $i = e = \alpha/2$, this corresponds to the "mirror" illumination/observation geometry. The function $A_{eq}(\alpha)$ results from a division of the observed reflectivity $A(\alpha,i,e)$ by function (3). A conversion of the observed data to the equigonal albedo allows one to bring all visible points of the lunar surface to the same photometric conditions. The lunar function $A_{eq}(\alpha)$ for the range $1° < \alpha < 120°$ can be approximated as [9,10]:

$$A_{eq}(\alpha) = m_1\exp(-\mu_1\alpha) + m_2\exp(-\mu_2\alpha) + m_3\exp(-\mu_3\alpha), \quad (6)$$

where the first term describes the opposition effect, m_1 denotes the amplitude of the opposition peak, μ_1 its width; the second term describes the peak of the shadow effect produced by regolith particles, μ_2 depends on the albedo; and the third term describes the shadow effect from the meso-scale topography ($m_1 + m_2 + m_3 = A(0)$ is the normal albedo). As the different physical effects more or less dominate in specific ranges of phase angles, individual terms can be conditionally considered alone: the second term of (6) for $10° < \alpha < 40°$, the third one for $40° < \alpha < 120°$, and the 2-nd and 3-rd terms for $10° < \alpha < 120°$. In general, the parameters m and μ vary from site to site. A photometric transformation requires knowledge of these values over the lunar surface. However, our previous analysis has shown that in the wavelengths range 0.35–1.07 μm the value μ_3 is independent of the albedo and is equal to 0.7 [9, 10]. Moreover, in the NIR range the second term in (6) is small [9], because of the secondary illumination of the shadows by light propagated through regolith particles. Thus, the phase dependence of the lunar surface brightness in the NIR range at $10° < \alpha < 120°$ may be described as

$$A_{eq}(\alpha) = m_3 \cdot \exp(-0.7\alpha). \quad (7)$$

Thus, the photometric correction for SIR-2 data is:

$$A_0 = A\exp(-0.7(\alpha_0-\alpha))D(\alpha_0,\beta_0,\gamma_0)/D(\alpha,\beta,\gamma). \quad (8)$$

We note that this formula contains no parameters dependent on the surface properties.

Comparison with Clementine's UVVIS data: We compare SIR-2 measurements in the spectral channel #10 ($\lambda = 997$ nm) with data obtained in the Clementine UV-VIS channels ($\lambda = 0.95$ and 1 µm). In particular, such a comparison allows us to perform an absolute calibration of the SIR-2 spectra. For orbit #721 the results of comparison are shown in Fig. 1 (without photometric correction) and Fig. 2 (after correction). The calibration coefficient for converting the SIR-2 readouts into RELAB system albedo is $4.65 \cdot 10^{-5}$. It's seen that formula (8) works properly for photometric correction of the SIR-2 data. However, there are high-frequency discrepancies corresponding to small craters. This is caused by a difference in data resolution and conditions of illumination. Errors in pointing of the SIR-2 spectrometer also are possible.

The phase function of Mare Serenitatis area: The function (7) has been obtained with analysis of integral photometry of the Moon [7] performed for $\lambda < 1$ µm. It is interesting to check the fidelity of this function using SIR-2 data. Although during the Chandrayaan-1 mission, special experiments to investigate the phase function of the lunar surface were not carried out, the SIR-2 data give a unique opportunity to perform such a study. We use observations of lunar areas with uniform albedo; fragments of 28 orbits passing over Mare Serenitatis are used. In Fig. 3 we show first results of the determination of lunar phase function with SIR-2 data. We remind one that the equigonal albedo A_{eq} was calculated through a division of the observed reflectivity by Akimov's disk function (see Eqs. (3)-(5)).

The one-exponent approximation of the obtained phase dependence (solid curve in Fig. 3) suggests: m = 0.14 and μ = 0.53, with σ_y= 6%. The value of the μ is somewhat less than the expected 0.7. This is probably caused by an uncertainty in the BIAS and/or dark signal. For example, increasing the BIAS only on 6% gives μ = 0.7.

Conclusions: (1) a technique of photometric correction of SIR-2 data is proposed; (2) we show that SIR-2 data allow for estimates of the phase function of lunar maria.

References: [1] Mall U. et al. (2009), *Current Sci., 96,* 486–491. [2] http://www.planetary.brown.edu/relab/ [3] Nozette S. et al. (1994), *Science, 266*, 1835–1839. [4] http://www.planetary.brown.edu/relabdocs/LSCCsoil.htm [5] Shkuratov Y. et al. (1999), *Icarus, 141*, 132-155. [6] Akimov L. (1988), *Kinemat. Phys. Celest. Bodies, 4(1),* 3-10. [7] Akimov L., et al. (2000), *Kinemat. Phys. Celest. Bodies, 16(2)*, 181-187. [8] Shkuratov Y. et al. (2003), *JOSA. 20.* 2081-2092. [9] Korokhin V. et al. (2007), *Solar System Res., 41(1)*, 19-27. [10] Velikodsky Y. et al. (2009), *this issue*.

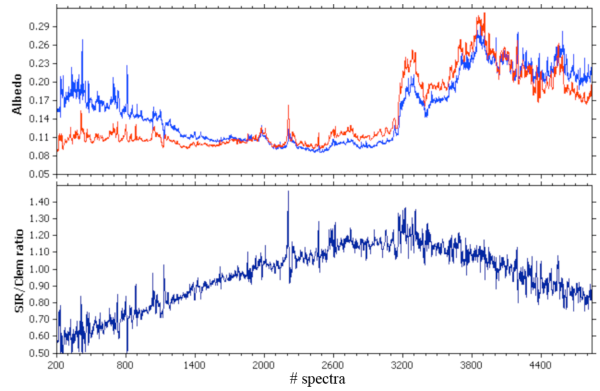

Fig.1. Upper: comparison of the initial SIR-2 profile for 0.997 µm channel (red) with the Clementine's UVVIS profile for 1.0 µm (blue). Bottom: SIR-2/Clementine ratio.

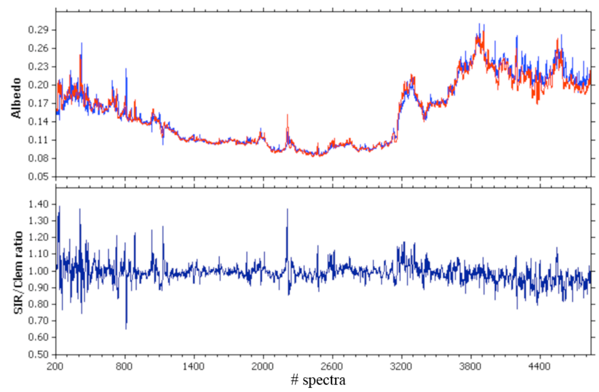

Fig.2. The same as in Fig.1, but for photometrically corrected SIR-2 data.

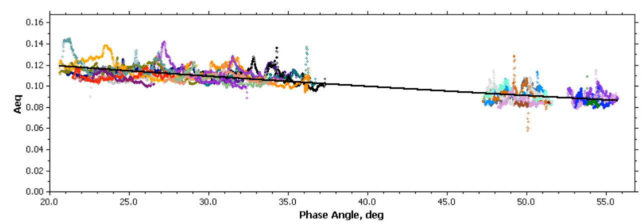

Fig.3. Phase dependence of equigonal albedo of Mare Serenitatis at $\lambda = 1.003$ µm (different orbits are shown by different colors).