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Review Article

Optical measurements of the Moon as a tool to study its surface

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A B S T R A C T

This survey is a general overview of modern optical studies of the Moon and their diagnostic meaning. It includes three united parts: phase photometry, spectrophotometry, and polarimetry. The first one is devoted to the progress in the photometry of the Moon, which includes absolute albedo determination to refine the albedo scale (e.g., to connect lunar observations and the data of lunar sample measurements) and mapping the parameters of a lunar photometric function (e.g., the phase-angle ratios method) with the aim of making qualitative estimates of regolith structure variations. This part also includes observations of the lunar opposition effect as well as photogrammetry and photoclinometry techniques. In particular, available data show that because of the low albedo of the lunar surface, the coherent backscattering enhancement hardly influences the lunar opposition spike, with the exception of the brightest lunar areas measured in the NIR. The second part is devoted to chemical/mineral mapping of the Moon's surface using spectrophotometric measurements. This section also includes analyses related to the detection of water ice or hydroxyl, prognoses of maturity, and helium-3 abundance mapping. In particular, we examine the relationship between superficial OH/H_2O compounds spectrally detected recently and bulk "water ice" found earlier by the *Lunar Prospector* GRS and *LRO* LEND, assuming that the compounds are delivered to cold traps (permanently shadowed regions) with electrostatically levitated dust saturated by solar wind hydrogen. Significant problems arise with the determination of TiO_2 content, as the correlation between this parameter and the color ratio C(750/415 nm) is very non-linear and not universal for different composition types of the lunar surface; a promising way to resolve this problem is to use color ratios in the UV spectral range. The third part is devoted to mapping of polarization parameters of the lunar surface, which enable estimates of the average size of regolith particles and their optical inhomogeneity. This includes considerations of the Umov effect and results of spectropolarimetry, negative polarization imagery, and measurements of other polarimetric parameters, including the third Stokes parameter. Although these three research divisions have not been developed equally and the numbers of proper references are very different, we try to keep a balance between them, depicting a uniform picture. It should be emphasized that many results presented in this review can be applied to other atmosphereless celestial bodies as well.

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1. Introduction

The Moon has fascinated mankind throughout the ages. In the time since the existence of civilization, the surface of the Moon can be considered almost unchanged. Much of the lunar surface carries information about events that took place millions or even billions of years ago. In the next decades and centuries, intensive utilization of the Moon may commence. For example, it may become profitable to use its natural resources, in particular, ^{3}He as nuclear fuel. The face of the Moon will gradually change due to human activity. Therefore, the collection of information on the original face of the Moon is of mankind importance for the historical record. Aside from their universal appeal, lunar explorations are interesting for fundamental and applied science.

The aim of lunar explorations is to comprehend the origin and evolution of the Moon, as well as to describe the state of its surface and its interaction with the environment. It is necessary to estimate the chemical compositions of basic geologic formations and the structure of their regolith layers. It is not feasible to obtain enough samples from the Moon to provide global information for this; therefore, planetary scientists search for ways to extrapolate characteristics of lunar samples to any lunar site using remote sensing that includes global optical studies.

The Moon is unique as an astrophysical object in that its samples have been delivered and used for verification and calibration of remote-sensing techniques. For instance, if we believe that some lunar samples are representative of given landing sites, correlations between spectral parameters and chemical/mineral contents can be established and used for estimating the lunar surface composition of non-sampled areas. Optical methods are the most effective in the arsenal of remote sensing. Optical measurements with Earth-based telescopes or spacecraft in lunar orbit would allow the global chemical/mineral mapping of the lunar surface and determination of the surface roughness. The history of such measurements is long and interesting in the context of modern lunar studies.

About 40 years ago during the lunar race, when the American and Soviet lunar missions were being realized, astronomers studying the Moon became witnesses and victims of a great invasion of allied sciences into their field, which was unprecedented in its extent. At that time, many lunar astronomers wished to turn their attention to other astronomical objects; they were justifying the decision that the Moon had become the subject of geology and other sciences. Nevertheless, optical investigations of the Moon continued. In our time the Moon is a topical object of space exploration and still remains attractive for ground-based telescope observations. The methodology of ground-based measurements is often used in space-born experiments.

At present, there is considerable activity in optical studies of the Moon using spacecraft. These studies carried out by the probes *Clementine*, *Lunar Prospector*, *Smart*-1, *Kaguya* (*Selena*), *Chandrayaan*-1, *Chang'E*-1, and *Lunar Reconnaissance Orbiter* (*LRO)* significantly extend our knowledge about the Moon. It is enough to say that *Chandrayaan*-1 (Pieters et al., 2009a), *Deep Impact* (Sunshine et al., 2009), and *Cassini* (Clark, 2009) observations of the Moon in the NIR spectral ranges have allowed the determination of water ice and/or hydroxyl near the lunar poles. In modern planetology this perhaps is one of the most resonant discoveries.

The number of different methods for making optical measurements of the Moon is not too large. Electromagnetic radiation scattered from any atmosphereless celestial body, e.g., from the Moon, can be described with four characteristics that are named the Stokes parameters (e.g., Bohren and Huffman, 2004). The first one is the intensity of scattered radiation I. This is the most important parameter, which provides our principal knowledge about the Moon. The second parameter $Q=I_{\perp}-I_{\parallel}$ where $I_{\perp}$ and $I_{\parallel}$ are the intensities of light passing through an analyzer oriented perpendicular and parallelly, respectively, to the scattering plane. Usually Q is used in its normalized form, as the linear polarization degree $P=(I_{\perp}-I_{\parallel})/(I_{\perp}+I_{\parallel})=Q/I$, which characterizes the ability of a surface to polarize the incident, initially unpolarized, solar light. This parameter is potentially useful to analyze the lunar surface structure; however, it is not popular in the planetary-science community. The third Stokes parameter $U=I_{\pi/4}-I_{3\pi/4}$ characterizes the orientation of the polarization plane relative to the scattering plane. The angle of orientation is defined as $\vartheta=(1/2)\arctan(I_{\pi/4}-I_{3\pi/4})/(I_{\perp}-I_{\parallel})$. This parameter may potentially be useful to indicate the surface anisometry and anisotropy. Ground-based polarimetric observations have shown that the third Stokes parameter of the lunar surface is negligibly small. The fourth parameter $V=I_R-I_L$ is responsible for the circular polarization. The indexes R and L correspond to right and left circular polarization. The degree of circular polarization is defined as $P_C=(I_R-I_L)/(I_R+I_L)=V/I$. Unfortunately, the degree of circular polarization is too small to be studied and used as a tool of surface diagnostic; moreover, this signal is dominated by geometrical factors rather than the physical properties of the lunar surface.

Thus, only the first two Stokes parameters I and P have been used to characterize the lunar surface. These parameters depend on the wavelength λ and phase angle α. This angle is the most important variable in planetary photometry. Measurements of the functions $I(\alpha,\lambda)$ and $P(\alpha,\lambda)$ or their parameters are the gist of lunar optical remote sensing. Accordingly, we distinguish phase photometry (phase polarimetry) from spectrophotometry (spectropolarimetry). Among these four directions, spectrophotometry is the most elaborate as a tool of optical remote sensing. Recently, a