Lunar Eclipse of June, 15, 2011: Three-color umbra surface photometry

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The paper contains the preliminary result description of the photometric observations of the Moon surface during the total lunar eclipse of June, 15, 2011 conducted in southern Russia and Ukraine in three narrow spectral bands with effective wavelengths equal to 501, 673, and 867 nm. The photometric maps of umbra are built, the radial dependencies of relative brightness are compared with the theoretical ones for gaseous atmosphere. Dark anomalies of umbra are shown and related with the aerosol air pollution of the definite regions above the surface of Earth.

1. Introduction

Lunar eclipses are the object of theoretical and observational interest over the centuries and until the present time [1, 2]. The radiation coming to the Moon during the totality is transferred through the dense layers of the atmosphere of the Earth. The atmospheric path length exceeds thousand kilometers, and the emission is sufficiently refracted, scattered, and absorbed. All processes strongly depend on the atmospheric conditions, presence of aerosol [3, 4] and optically active gases (O_3, NO_2, H_2O [5], etc., if observations are held in the absorption spectral bands of these gases). This makes the lunar eclipse observations the tool for the atmospheric optical components investigations.

Theoretical analysis [6] had shown that the scattered fraction of emission reaching the Moon's surface is noticeable only in the case of strong volcanic atmosphere perturbation (as after the Mt. Pinatubo eruption in 1992) or at the wavelengths shorter than 400-450 nm. In the other cases the observed emission is the direct solar radiation refracted in the atmosphere. The lower the path of light propagation above the surface of Earth, the stronger the refraction and the deeper the umbra region where this emission can be detected. Holding the surface photometry of the Moon, we cover the interval of altitudes in troposphere and lower stratosphere and wide range of locations along the Earth's limb where refraction occurs. Variations of atmosphere conditions along the limb can lead to the radial asymmetry of the umbra with the dark spots far from the center, especially in infrared part of spectrum, as it was observed during the eclipse of March, 4, 2007 and related with equatorial region with increased aerosol and water vapor concentration above Indonesia [5].

The basic light extinction mechanism in the atmosphere is the Rayleigh scattering that strongly depends on the wavelength ($\sim\lambda^{-4}$). Short-wave emission disappears traveling along the low trajectory above the Earth's surface, but the longer-wave radiation can pass the atmosphere by almost the same trajectory and reach the Moon. It is the explanation of red color of the eclipsed Moon and choice of red and infrared spectral bands for most of the eclipse photometric observations. If the observations are hold in a number of different spectral bands, it helps to separate the emission from different parts of the solar disk refracted by the different angles and come to the same point of the Moon. Thus, it is the way to increase the altitude resolution of the remote sounding of the atmosphere.

2. Observations

Lunar eclipse of June, 15, 2011 was the deepest total eclipse of the first two dozens of years of 21st century, having the maximum magnitude 1.71. The Moon was crossing the umbra close to its diameter almost horizontally from the west to the east. Optical structure of the eclipse was basically formed by equatorial and tropical atmosphere above the Atlantic ocean between Brazil and Spain (in the beginning of totality) and China & western Pasific ocean (in the end of totality).

The photometric measurements of the eclipsed Moon were held close to local midnight in Crimean Laboratory of Sternberg Astronomical Institute (Crimea, Ukraine, 44.7°N, 34.0°E) and Special Astrophysical Observatory (SAO, Russia, 43.7°N, 41.4°E). The observations in Crimea were conducted by CCD-camera with narrow spectral IR-filter with effective wavelength equal to 867 nm. SAO observations were conducted by two CCD-cameras with narrow filters with the effective wavelengths 501 and 673 nm. Both SAO spectral ranges fall on the different slopes of Chappuis bands of ozone absorption, and Crimean IR-range is out of atmospheric gases absorption bands.

Unfortunately, weather conditions restricted the totality observation periods and umbral area covered by measurements. Atmospheric transparency was stable and suitable for observations during the initial 15 minutes of totality in all spectral bands. In addition, Crimean observations at 867 nm had also included last 15 minutes of totality. Owing to last angular size of the Moon, it allowed to hold the IR-measurements on the majority of umbral area passed by the Moon. The observational data were calibrated by the measurements of nearby standard stars and lunar surface observed right before or after the eclipse.

3. Results and Discussion

The basic measured value is the brightness ratio of the lunar surface element in the definitive point of the umbra and the same surface element outside the umbra and penumbra. The procedure of ratios calculation with account of variable sky background from brighter parts of the Moon is described in [4]. The distribution maps of measured value for three spectral bands are shown in Figure 1. As it was told above, measurements had covered two umbral areas for 867 nm and one western area for both 501 and 673 nm bands.

The most remarkable feature seen in the 867 nm map is the sufficient asymmetry of the umbra. While western parts show the regular structure and typical relative brightness values observable during the other eclipses in this band [5, 7], eastern part is dark as a whole and contains even darker spot to the North-East from the center. The solar radiation transfers to this point through the middle troposphere (about 5-6 km and above) of the eastern China, and the spot can be related with the aerosol pollution of this atmosphere region. The brightness difference of eastern and western umbra parts was noticed by many observers worldwide [8], and the brightness values recorded during the second half of totality at 867 nm were the lowest among the observed eclipses of the last years [7]. It does not completely follow the assumption of French astronomer A. Danjon in 1920s, who had stated the gradual increase of lunar eclipses brightness during and after the solar activity maximum epoch.

At the shorter waves, 673 and especially 501 nm, the western umbra brightness is smaller. It is native since lower atmosphere layers have less influence on the umbra brightness due to their lower transparency. The emission background is basically formed by the outer solar edge radiation transferring above. The 501 nm relative brightness value falls down to about 10^{-6} near the umbra center, but it is still higher than the theoretically estimated scattering fraction contribution (about 10^{-7}, [6]).

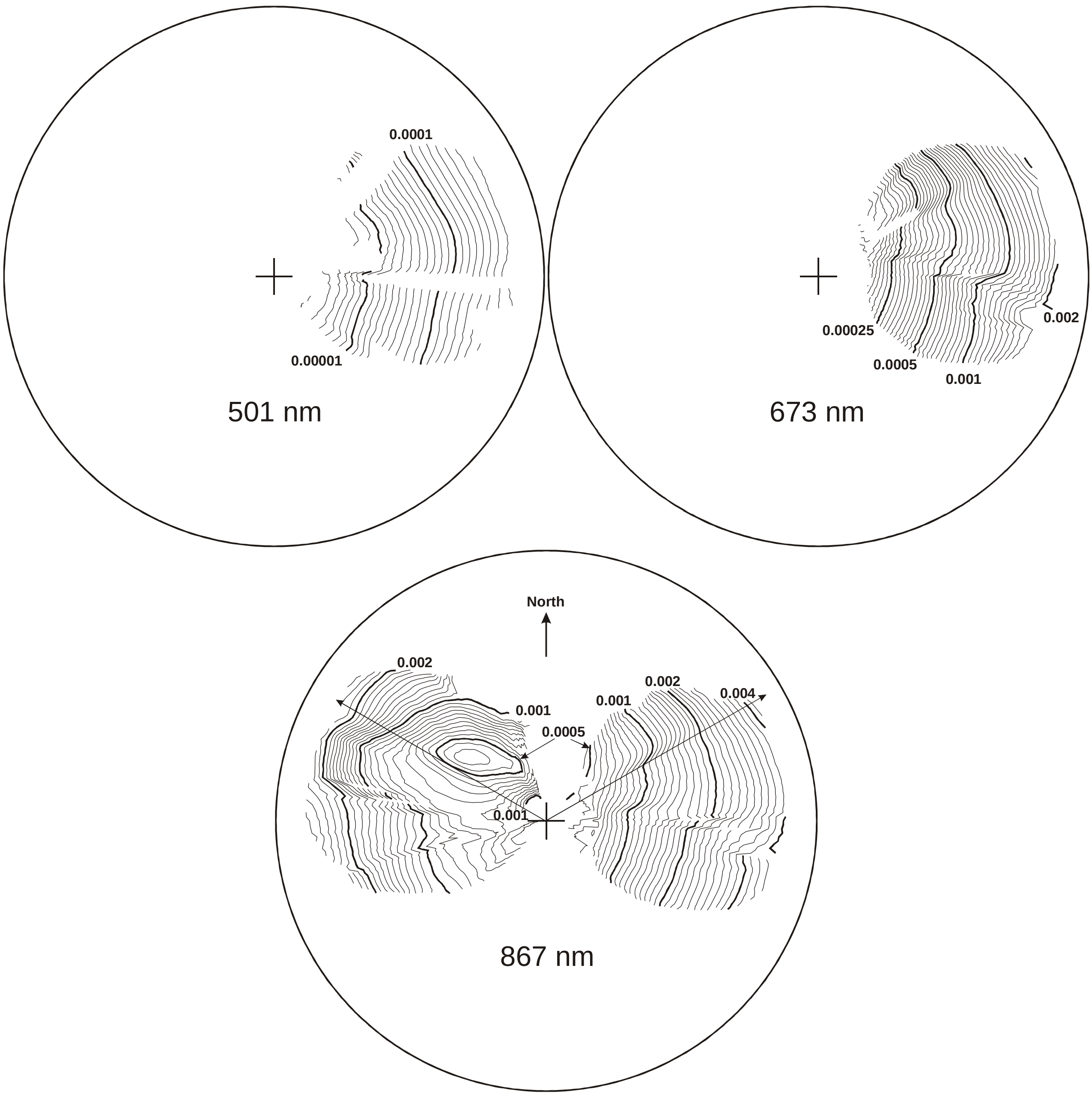

Figure 1. Relative brightness of Moon surface inside the umbra in three spectral bands. The step between the neighbor isophotes is $10^{0.1}$ *for 501 nm and* $2^{0.1}$ *for other bands.*

Figure 2 shows the radial dependencies of umbra relative brightness for the directions shown by arrows in the Figure 1 (30° to the north from equator). They are signed as W and E for 867 nm, and only western ones are available for other wavelengths. The dependencies are compared with the ones calculated using simple equatorial gaseous atmosphere model (ground temperature 300 K, lower stratosphere temperature 220 K, and total ozone content 250 Dobson units).

Observational curves for outer western umbra (0.6° from the center) coincide with the theoretical ones in all three bands, showing the clear conditions of Atlantic atmosphere above 10 km. Aerosol extinction appears only below, causing the difference between observational and theoretical curves. This fact can be used for aerosol investigation [4, 5].

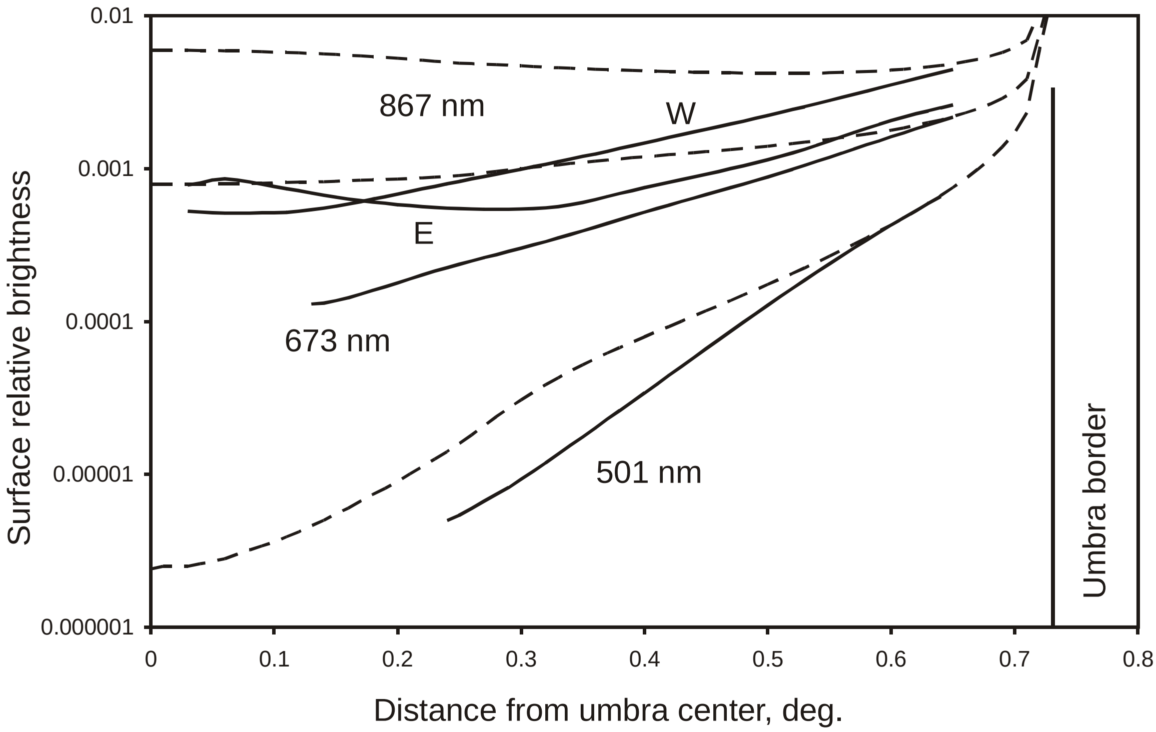

Figure 2. Theoretical (gaseous atmosphere, dashed lines) and observed brightness of umbra in the directions shown by an arrows in the Figure 1 (W – western direction, E – eastern direction, 30° north from the equator). Observational data for 501 nm and 673 nm are in the same western direction.

On the contrary, western umbra is darker from the center to the edge, that can be related with the increased tropospheric aerosol concentration along the eastern limb over the wide range of altitudes. Umbra becomes brighter just at the south edge of the lunar path. This umbra region was emitted by the solar radiation transferred above the Pasific ocean far from Asian shores. The maritime atmosphere (as an Atlantic one for the western umbra half) contains less amount of aerosol particles.

The data obtained can be the basis of the calculations of aerosol tangent optical depths and extinction coefficients as the function of location, altitude and wavelength.

References

1. Link F. Lunar eclipses, in *Physics and Astronomy of the Moon*, ed. Z. Kopal. New York, Academic Press, 1962.
2. Mallama A. Eclipses, atmospheres and global change, 1996.
3. Keen R.A. Volcanic aerosols and lunar eclipses. *Science*, 1983, V.222, P.1011.
4. Ugolnikov O.S., Maslov I.A. Atmospheric aerosol limb scanning based on the lunar eclipses photometry. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 2006, Vol. 102, P.499.
5. Ugolnikov O.S., Maslov I.A. Altitude and latitude distribution atmospheric aerosol and water vapor from the narrow-band lunar eclipse photometry. *Journal of Quantitative Spectroscopy and Radiative Transfer,* 2008, Vol. 109, P.378.
6. Garcia Munoz A., Palle E. Lunar eclipse theory revisited: Scattered sunlight in both the quiescent and the volcanically perturbed atmosphere. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 2011, Vol. 112, P.1609.
7. Ugolnikov O.S., Maslov I.A. Remote sensing of the Earth's atmosphere based on lunar eclipse observations. *Atmospheric and Oceanic Optics*, 2009, V.22, P.365.
8. Keen R.A., 2011, private conversation.