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Trajectory retrieval and component investigations of the southern polar stratosphere based on high-resolution spectroscopy of the totally eclipsed moon surface

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ABSTRACT

In this paper we present the high-resolution spectral observations of the fragment of lunar surface during the total lunar eclipse of December 10, 2011. The observations were carried out with the fiber-fed echelle spectrograph at the 1.2-m telescope in Kourovka Astronomical observatory (Ural mountains, central Russia). The observed radiation is transmitted by tangent trajectory through the southern polar stratosphere before the reflection from the Moon and the spectra contain a number of absorption bands of atmospheric gases (O_2, O_3, O_4, NO_2, H_2O). High-resolution analysis of three O_2 bands and O_4 absorption effects is used to trace the effective trajectory of solar emission through the stratosphere and to detect the contribution of scattered light. Bands of other gases allow us to measure their abundances along the trajectory.

1. Introduction

A lunar eclipse is an astronomical event characterized by a unique geometry of the radiation transfer [1]. Direct solar emission cannot reach the surface of the Moon immersed in the umbra (shadow) of the Earth. But it can be refracted in the Earth's atmosphere and enter the geometrical shadow area. That is why the Moon does not fade in the sky during total eclipses. Along with the refraction, light scattering and absorption take place in the atmosphere. Since these processes can depend on the wavelength, the color of the eclipsed Moon changes and strong atmospheric lines appear in the lunar spectrum. The situation is similar to the spectrum of a distant star of sun-like spectral class during the transit of the planet with a dense and optically thick atmosphere [2,3]. In the case of the lunar eclipse, these lines are sensitive to the component concentration near the ray perigee altitude. Normally, tangent transmission spectrum of the Earth's atmosphere can be observed from space, which became the basis of satellite techniques of atmosphere composition measurements [4,5]. Lunar eclipses provide the unique opportunity to carry out such measurements from the ground.

The basis of radiation transfer theory during the lunar eclipses is established in Ref. [1]. Refracted solar emission makes the principal contribution to the brightness of the lunar surface. This simplifies the theory and makes it possible to retrieve the additional aerosol and trace gas extinction in the different layers above the limb [6–8]. However, the emission scattered in the atmosphere can also be noticeable. The theoretical estimation of its contribution is performed in Ref. [9]. It is found to be sufficient for the wavelengths below 450 nm or in the volcanically perturbed atmosphere, which is not a rare case: the signs of scattered light were found during the

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eclipse of August 16, 2008 [10]. The authors relate these signs to the Kasatochi volcano eruption in Alaska (quite close to the limb) which occurred just before the eclipse.

Photometric analysis of a number of eclipses [6–8] in the red and near-infrared spectral range out of atmospheric gases absorption bands had shown that the brightness of the outer umbra part (less than 0.2° from the umbra edge) is usually close to the theoretical value for the gaseous atmosphere model without the aerosol extinction, revealing the clear atmosphere conditions above 10 km. The exceptions occur in the equatorial and tropical atmosphere. The most remarkable one is the eastern tropical umbra part illuminated through the South-Asian troposphere during the eclipse of June 15, 2011, the darkest through the last years [11].

Results of spectral measurements of lunar eclipses are interesting since they are sensitive to the variations of atmospheric components along the tangent path above the limb. This path is long (about several hundreds kilometers), and its sufficient and optically thick fraction lies in the horizontal layer with almost constant altitude. It provides high accuracy and good vertical resolution of limb atmosphere spectroscopy. It is especially true for stratospheric components, first of all, stratospheric ozone. The Chappuis lines of ozone define the general brightness and color characteristics of the eclipsed Moon, although they seem to be quite weak in a transmission spectrum in a vertical atmosphere column.

The spectrum of the lunar surface was obtained with high resolution during the partial eclipse of August 16, 2008 [3], but in the penumbra, where the Moon is partially illuminated by direct solar radiation transmitted above the atmosphere. The umbral area was measured once during the same eclipse in a wide spectral range [2], but with lower spectral resolution (about 1000). In this paper we analyze a number of high-resolution spectra of the lunar surface in the umbra obtained during the total eclipse of December 10, 2011. This time the moonlight did not strongly increase the flux from the surrounding sky background. This eclipse is especially interesting since the solar radiation was transferred through the Antarctic stratosphere not far from the seasonal ozone depression. The long duration and less depth of the eclipse allowed a thorough investigation of the Antarctic stratosphere.

The rest of the paper is organized as follows. Section 2 contains the description of observations. In Section 3 a low-resolution analysis is performed, the atmospheric species with broad absorption bands (O_3, O_4, and NO_2) are studied. High-resolution analysis of O_2 lines and trajectory retrieval is presented in Section 4. Investigations of water vapor are discussed in Section 5. Finally, Section 6 contains a conclusion.

2. Observations

Spectral observations of the total lunar eclipse of December 10, 2011 were conducted at the Kourovka Astronomical Observatory, Russia (57.0°N, 59.5°E). The observations were carried out with an optical fiber-fed echelle spectrograph at the Nasmyth focus of a 1.2-m telescope. The spectral resolution was about 30,000. The fiber diameter corresponds to the angular size 5″. The instrumental band covers the wavelength range from 410 to 780 nm.

The calibration frames (bias, flat field, ThAr spectrum) were collected once per hour. We used the ThAr lamp spectrum for wavelength scale calibration. The accuracy of this procedure is 0.0003 nm. The narrow lines of the ThAr lamp were used to build the instrument point-spread function (PSF) of the spectrograph. We did not obtain the spectra of the sky because it is not necessary for high-resolution spectra. The sky emission lines are weak during the totality and their flux is negligible (the exposure must be about ten times more than the totality duration to observe the sky lines with a high-resolution spectrograph). All frames were processed with an IRAF/echelle package [12]. Ambient temperature and humidity were recorded at about five-minute intervals to control the weather condition stability during the observations.

We acquired the spectra of the region of the lunar surface with selenographic coordinates 50°S, 5°W, south-eastwards from bright crater Tycho. This place is characterized by almost uniform albedo. During the eclipse, the place was traversing the southern edge of umbra. The radiation transmitted through the lower Antarctic stratosphere contributed the major portion of brightness of the observed spot. Eight frames (exposure is 300 s for the each one) were obtained as this surface moved through the umbra. The frames were not combined to improve the signal-to-noise ratio (S/N). The spectra with eclipsed Moon have the S/N ratio up to 65 in different orders, which is sufficient for this study. The S/N ratio near the Hα line (656.3 nm) is about 45. The observational parameters of the recorded spectra are presented in Table 1. The positions of the observed spot in the umbra during the exposures are shown in Fig. 1. The limb point was moving eastwards along the Antarctic shore. The mid-exposure positions of the limb point are depicted in Fig. 2.

To take the lunar albedo spectral dependency into account, we obtained the spectra of the same spot on the lunar surface after the end of the eclipse. The Moon was ascending during the observations. Throughout the eclipse the zenith angle decreased from 70° to 60° and after the end of the eclipse it was about 40°. The transparency of the atmosphere over the observatory depends on the wavelength too. To take it into account, the spectra of a standard star were obtained between the

Table 1
Parameters of the observed spectra of the lunar eclipse.

Spectrum no	UT (middle) hr	UT (middle) min	Zenith distance (deg.)	Distance to the umbra edge (deg.)
1	14	14.2	68.2	0.086
2	14	20.2	67.4	0.095
3	14	26.3	66.7	0.101
4	14	32.2	65.9	0.102
5	14	38.1	65.1	0.100
6	14	44.4	64.3	0.093
7	14	50.2	63.5	0.083
8	14	56.1	62.7	0.069