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The earthshine spectrum

P. Montañés Rodriguez [a,*], E. Pallé [a], P.R. Goode [a], J. Hickey [b], J. Qiu [a], V. Yurchyshyn [a], M.C. Chu [c], E. Kolbe [d], C.T. Brown [e], S.E. Koonin [e]

[a] Big Bear Solar Observatory, New Jersey Institute of Technology, Newark, NJ 07102, USA
[b] Palomar Observatory, California Institute of Technology, Pasadena, CA 91125, USA
[c] Department of Physics, The Chinese University of Hong Kong, Shatin N.T., Hong Kong
[d] Department für Physik and Astronomie, Universität Basel, Basel, Switzerland
[e] W.K. Kellogs Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

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Abstract

Since 1998 the Earthshine Project has been a collaborative effort between Big Bear Solar Observatory/New Jersey Institute of Technology and California Institute of Technology. Cyclic spectroscopic observations of the dark and bright sides of the moon (or earthshine and moonshine, respectively) have been carried out in the visible region at Palomar Observatory. From these data, the ratio of the earthshine to moonshine characterizes the globally averaged Earth's spectrum. Information concerning the search for extra-solar, terrestrial planets can be also obtained from these observations.

Keywords: Earthshine; Earthshine spectrum

1. Introduction

The advantage of measuring terrestrial atmospheric parameters by observing the light of the Earth reflected from the moon, instead of through the most direct way, by satellite observations, arises from the capability of obtaining global-scale information.

With this premise in mind, photometric observations of the dark and bright side of the moon have been routinely taken at Big Bear Solar Observatory for the last four years to determine variations in the Earth's albedo, an important input for climate models. The albedo has been considered until now to have a constant value of about 0.3. First results were reported by Goode et al. (2001). More detailed explanations of the techniques and results obtained up to March 2002 are being reported in Qiu et al. (2003) and Pallé et al. (2003), and a summary of the present stage of the project can be found in this volume in Pallé et al. (2004).

In addition to the albedo, but using the same basic method, other global-scale parameters may be also determined through spectroscopy. Variations in the global Earth's spectrum provide information about atmospheric gasses, such as water vapor, which are difficult to obtain by other techniques.

Global observations of the Earth's spectrum will also be of interest for the detection of extra-solar, small-mass planets. They can provide complementary information for future space missions, since the current methods for the detection of small planets, such as radial velocity measurements by ground-based telescopes, are not sensitive enough.

In this paper, we present preliminary results of the spectra taken at Palomar Observatory with the 60-inch telescopes echelle spectrograph. We targeted the region between 0.4 and 1 μm of the electromagnetic spectrum, which includes oxygen A, oxygen B, water bands and the Hα line. The first three are typical terrestrial molecular bands. The Hα line is used mainly for spectral calibration.

* Corresponding author. Fax: +1-909-866-5791.
E-mail address: pmr@bbso.njit.edu (P. Montañés Rodriguez).

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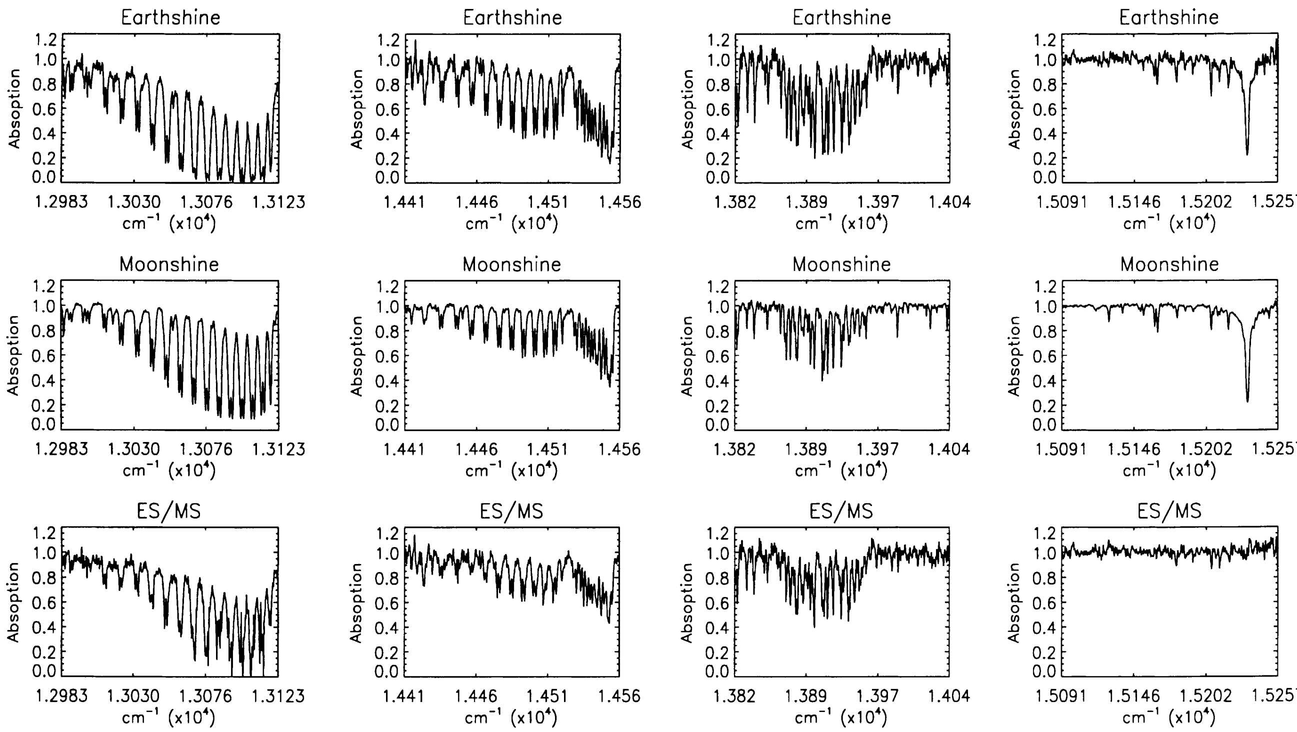

Fig. 1. From the left to the right: oxygen A, oxygen B, 13,900 cm^{-1} water vapor band, and Hα line (solar line utilized for calibration). They are shown for the earthshine (top), moonshine (middle), and for the ratio earthshine/moonshine (bottom). Note how the Hα is eliminated in the ratio spectrum (bottom panel).

2. Methodology

The observational method consists of alternatively observing the earthshine, the moonshine and the nearby sky, the last being used to eliminate scattered light. The moonshine spectrum contains information on the local atmosphere above the observatory. The earthshine spectrum has also gone once through the same path in the local atmosphere as the moonshine, but also has gone through the global atmosphere on the sunlit part of the Earth. The ratio of the earthshine to the moonshine eliminates the effect of the local atmosphere as well as the solar and lunar spectra, and contains global information about the illuminated part of the Earth (Fig. 1).

3. Observations, data analysis and preliminary results

Several observational campaigns have been performed at Palomar Observatory with the 60-inch telescope echelle spectrograph. The observations, presented here as an example of the methodology and possibilities of this technique, were taken on 4th September 1999, when the lunar phase angle was about +109°. Sets of the moonshine, earthshine and sky spectra were cyclically taken every half and hour, with exposure times of 5, 600 and 600 s, respectively. The slit was oriented parallel to the lunar rotation axis and the spectrum of the sky was taken 200″ away from the dark side lunar limb.

The resolving power of the echelle spectrograph at the observed spectral range, between 0.4 and 1 μm, is 19,000. This allows us to observe the oxygen A and B bands at 12,960–13,120 cm^{-1} and 14,450–14,560 cm^{-1}, respectively, and the water band at 13,620–13,960 cm^{-1} with a resolution of about 0.35 cm^{-1} (or ∼0.18 Å). The solar lines contained in our spectra are utilized for calibration purposes. The degree of cancellation can be appreciated in Fig. 1.

As the images were not taken simultaneously, the intensity I_i of each wavelength, λ_i, of the sky frames are fit to Beer's law,

$$I_i = I_{0i} e^{\alpha_i z}, \qquad (1)$$

with α_i being the atmospheric extinction coefficient at λ_i, z is the local airmass and I_{0i} is the intensity at λ_i and zero airmass.

The images for the sky were then interpolated from this fit to the corresponding airmass where both earthshine and moonshine images were taken; and subtracted from the lunar images. Most of the data reduction was carried out through IRAF, nevertheless a reduction of the entire spectrum was also performed, where all the echelle orders were extracted at once, using IDL tools.

Spectroscopic observations of the unsaturated lines, as shown in Fig. 2, provide critical information about

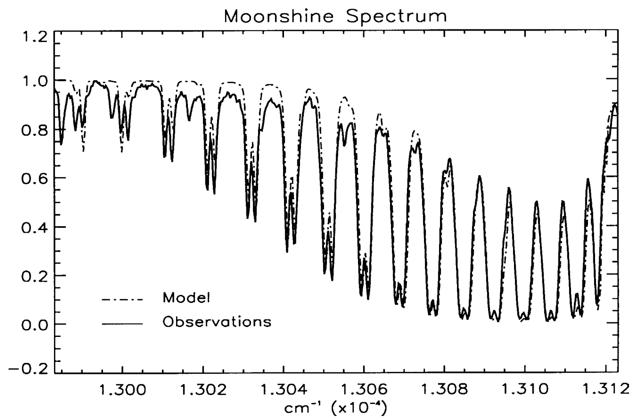

Fig. 2. Observed oxygen A molecular band (solid line) and comparison with the synthetic molecular band (broken line) at optimal temperature and column density. From these analysis a mean column density of 3.38×10^{24} mol/cm^2, for the local atmosphere, was found for 4th September 1999. This value is comparable to the one using International Standard Atmosphere table, which after corrections for the altitude of Palomar Observatory, gives a column density of 3.43×10^{24} mol/cm^2.

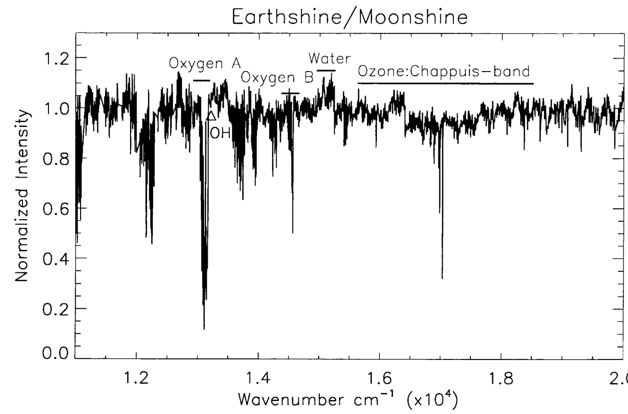

Fig. 3. Preliminary high-resolution earthshine/moonshine spectrum over the visible region. Solar and lunar spectra, and the effects of the local atmosphere have been eliminated.

the column abundances of these species in the global atmosphere. These parameters can be estimated by comparison with atmospheric molecular databases such as HITRAN (high-resolution transmission molecular absorption database), which provides models of the line profiles per molecule for a range of temperatures (Fig. 2). To do this, we introduce a Lorentzian absorption profile to the synthetic lines and convolve this with the Gaussian instrument profile. We calculate the residual, $\mathrm{Res}(T,S)$, between the synthetic spectrum and the observed spectrum,

$$\mathrm{Res}(T,S) = \sum_i \left| P(v_i,T,S)_{\mathrm{obs}} - P(v_i,T,S)_{\mathrm{syn}} \right|, \quad (2)$$

where P represent each absorption spectrum, T is the temperature and S is the column density. The profile with a minimum residual value is taken as the best fit.

4. Applications

4.1. Greenhouse gases and hydroxyl radical monitoring

The earthshine spectrum can give us global column abundances of greenhouse gases by retrieving column density information over a long period of time. These species can be monitored on a global scale, which can potentially provide us with a powerful tool to test climate models. Our column density results can be contrasted, for the case of well-mixed atmospheric gasses such as oxygen, with ground-based measurements.

Nevertheless, global monitoring of non-well-mixed greenhouse gases in the atmosphere, such as water vapor or ozone (Fig. 3), is not an easy task to do from satellite or ground-based measurements and their global concentrations are usually determined by model simulations. Therefore, our results may provide information applicable to climate models.

For the same reason global measurements of hydroxyl radicals column density through a few lines around 13,200 cm^{-1} can provide useful information. OH plays an important role in atmospheric chemistry since it is the dominant oxidizing chemical in the atmosphere, destroying a variety of greenhouse gases, such as CH_4, CO and SO_2, and ozone-depleting trace species.

4.2. Extra-solar terrestrial planets

The information retrieved from earthshine spectra is useful not only for the study of the Earth's climate system, but also for the search for extra-solar terrestrial like planets. The Earthshine Project can also help to identify and characterize important signatures on the Earth's spectrum and, by extrapolation, in extra-solar terrestrial-like planets.

5. Overall

Observations of the earthshine spectrum provide us with a powerful tool to test climate models by comparison with laboratory databases. This information is also applicable to the search for extra-solar, terrestrial-like planets.

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