On the Spectroscopy Study of the Earthshine Spectra

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ABSTRACT

We obtain a low-resolution optical spectrum of the faint glow from the dark side of the Moon, *i.e.,* the Earthshine. We extract the Earth's spectrum from it and observe absorption features of ozone, molecular oxygen, and water. The spectra is fitted to five well-known models for the atmosphere and the ground of a planet with life content. At short wavelengths, the largest contribution to this spectra comes from Rayleigh scattering. At long wavelengths, enhancements with values of $4 \pm 5\%$ starting at 740 nm were found, corresponding to the red reflectivity edge of vegetation.

Subject headings: Earthshine · Earth's Spectrum · biosignature

1. Introduction

The detection of *exolife* is one of the most important goals for future space missions. Current space missions used to identify exoplanets include `COROT`, `Spitzer` and `the Hubble Space Telescope`, as well as the secondary extended mission of `Deep Impact (EPOCh)` which will observe the light reflected from exoplanets (1). `ESAs Darwin` mission (estimated launch 2015) will aim to find and study the properties and composition of Earth-like exoplanets in the infrared. Over 300 giant exoplanets already have been detected, and hundreds, perhaps thousands more, are anticipated in the coming years. The nature of these planets, including their orbits, masses, sizes, constituents, and likelihood that life could develop on them, can be probed by a combination of observations and modeling.

Our observations tie in with current and future missions to observe and search for life on exoplanets. By looking at the spectra of Earth, we can characterize what makes it suitable for sustaining life - information that can be related to present and future exoplanet observations. This search is characterized by the detection of possible *biomarkers* on Earth-like exoplanets. On a first approach, they are simple molecules present in the planet's atmosphere, such as O_2, O_3, CO_2, and H_2O (see Fig.1-a). Further studies aim for the detectibility of a proper signature of life from the planet's surface, considering, for instance, green vegetation as a biormaker (2).

Solar's photon flux reaches the ground after absorption through Earth's atmosphere. In this case, vegetation reflects or transmits almost all incident radiation at wavelengths where sunlight has about 40% of its energy. The *vegetation reflectance* (vegetation spectral signature) has a well know spectrum, with a sharp edge of $\lambda = 700$ nm in the visible electromagnetic spectra due to the missing photons used in photosynthetic process. This is detected as a *positive shift* above the continuous spectra, starting at this wavelength, also known as the *Vegetation Red Edge* (VRE) (see Fig. 1-b).

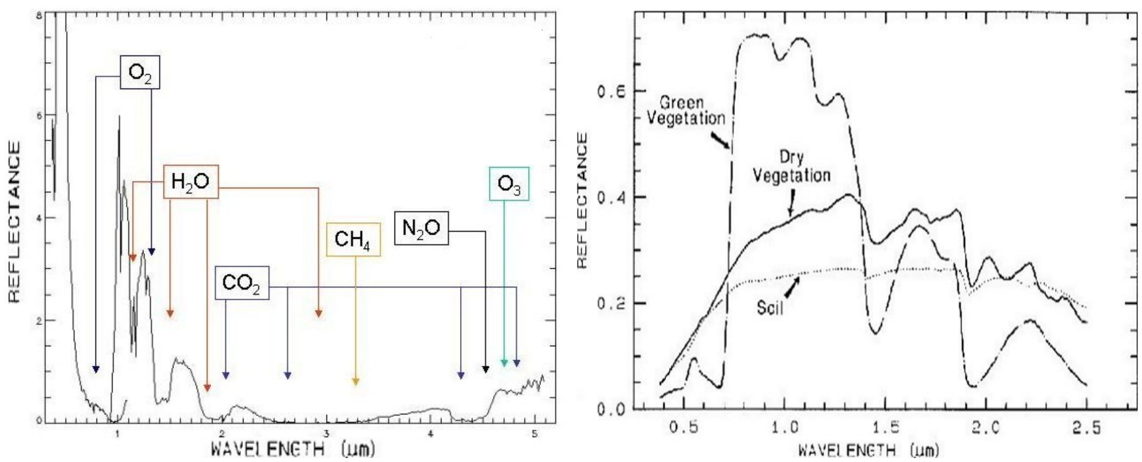

Fig. 1.— (i) Mars Express record of Earth spectrum on the visible, (ii) The vegetation spectral signature.

The Earthshine as a Tool to the Study of other Earth-like Systems

The observation of the spectrum of *Moon Earthshine*, *i.e.,* the reflection of the Earth's light on the non-sunlit Moon, allows one to observe the Earth as any distant planet, and to perform studies on the detectibility of biomarkers (*e.g.* VRE) in its spectrum. Extracting the Earth albedo from the Earthshine spectrum requires the measurement of moonlight spectra (lit side of the moon) and the Earthshine spectra (unlit portion of the moon) in the visible wavelength (3) (see Fig. 2).

The spectrum of the light reflected by the planet, when normalized to the Sun (parent star spectrum), gives the planet reflectance spectrum revealing its atmospheric and ground color (if this is visible by a transparent atmosphere). Quantitatively, the Earth spectrum from the Earthshine depends on the following variables:

- the Sun spectrum as seen from outside of Earth's atmosphere, $S(\lambda)$,
- the Earth's atmospheric transmittance, $AT(\lambda)$,
- the moonlight (sunlight reflected by the Moon's surface), $MS(\lambda)$,

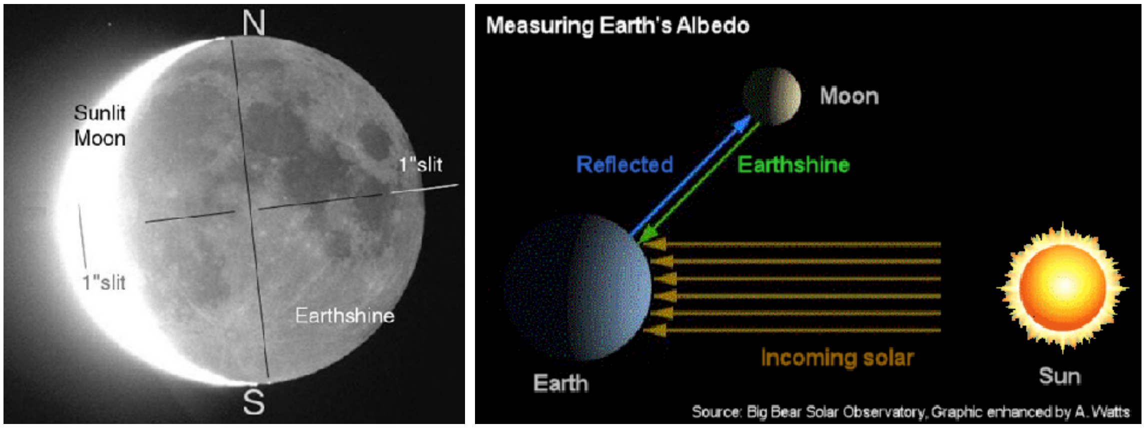

Fig. 2.— (i) Moon's Earthshine and the schematic illustration of the dark and bright side of the moon, (ii) Schematic illustration of the sunlight reflected from the the Earth.

- the earthshine, $ES(\lambda)$,
- the lunar reflectance, $MS(\lambda)$,
- the Earth's reflectance, $ER(\lambda)$.

So we can write

$$MS(\lambda) = S(\lambda) \times MR(\lambda) \times AT(\lambda) \times g_1,$$

and

$$ES(\lambda) = S(\lambda) \times ER(\lambda) \times MR(\lambda) \times AT(\lambda) \times g_2.$$

The Earth's reflectance is given by the ratio of the two equations,

$$ER(\lambda) = \frac{ES(\lambda)g_1}{MS(\lambda)g_2}, \tag{1}$$

where $EM(\lambda)$ and $MS(\lambda)$ should be recorded simultaneously to avoid airmass variation, and g_1, g_2 are geometric factors related to the position of Sun, Moon and Earth, and they can be set to unity.

The *vegetation red edge* is extracted from $ER(\lambda)$,

$$VRE = \frac{r_I - r_R}{r_R}, \tag{2}$$

where r_I and r_R are the near infrared and red reflectance integrated over the spectral domains (~ 10 nm width) (1) (4) (5).

2. Observations

This experiment aims to obtain an optical spectrum of Earthshine and test for the presence of biomarker features,*e.g.,* O_2, O_3, H_2O, and the presence of the vegetation red edge through fits of several models' components to the observed spectrum. The observations were performed on the **Mt. Stony Brook 14-inch telescope**, with the **DADOS optical spectrograph** (6), and the **SBIG STL-402 CCD camera** (7), on the date of April 17th, from 1:30 am to 5:30 am. The sky was clean and the temperature was around 55° F. The overall cloud cover from the archival satellite imagery and the Earth seen from the moon, can be seen in the figures 12 and 13, in the appendix.

2.1. Setting up the Spectrometer

A spectrometer splits the incoming light of Earthshine by wavelength, having previously been focused by the optical section of the instrument. The intensity of light at each wavelength is measured and recorded by the detector, and it is then plotted against light intensity, which is analyzed to find a number of features. In order to pick up the key features of oxygen, water and vegetation red edge, we investigate the visible and near infrared sections of the electromagnetic spectrum, with light of wavelengths between 500 to 800 nm.

Earthshine is brightest when most of the Earth as seen from the Moon is illuminated, *i.e.*, when the Moon is only a thin crescent. However, if the Moon is too close to the Sun, there are difficulties separating the glow of Earthshine from the bright twilight sky (3). We select a night of waxing crescent moon when the angular separation from the Sun to the moon (from the moonrise to the sunrise) is suitable for the experiment. This means that the moon is sufficiently high above the horizon ($> 20°$), yet sufficiently close to the Sun ($< 90°$)

so that the Earthshine signal is bright. The observations cease at sunrise, since when the Sun reaches about 5° below the horizon, the sky will be too bright to measure Earthshine.

We set the optical wavelength range of the spectrograph to cover our chosen set of Earthshine absorption by molecular O_2, O_3, H_2O. This was done before mounting the spectrograph on the telescope with the help of the Neon light source. We looked up the wavelengths of the strongest Neon gas transitions in the optical, adjusting the wavelength range of the spectrograph. We use the DADOS spectrograph with long integration times. To maximize the spectral resolution the narrowest width slit $25\mu m$ is to be used. This gives a spectral resolution of $\lambda/\Delta\lambda \sim 500$.

Setting the telescope tracking rate to lunar (`Autostar II` keypad), we obtain sequences of spectra of the **bright** (moonshine) and **dark** (earthshine) sides of the facing Moon, each of them together with the adjacent **sky** (in the adjacent slit). We also take calibration exposures of the Neon light source and darks with duration matched to the duration of all of the science exposures.

2.2. Estimative of Exposure Times

The Earthshine usually has low S/N (signal to background) ratio because the observations are obtained with Moon low above the horizon, and consequently a high airmass and low Earthshine fluxes with respect to the sky. Moreover, the detector can be quickly saturated when recording the spectrum of the sunlit Moon crescent. When it comes to the vegetation signal, the Earthshine data reduction becomes even more difficult: past works (2) have shown that it is only a few percent (less than 5%) above the continuum. Two reasons for this are pointed in the literature: (i) the variable amplitude, induced by a variable cloud cover and the Earth phase, (ii) the strong astmospheric bands which need to be removed to access the surface reflectance.

Assuming that the signal is limited to photons, the signal to background ratio for each of the sciences can be written as

$$S/N = \sqrt{N_\gamma t}, \tag{3}$$

where t is the time of integration ans N_γ the number of photon counts.

First, we make an estimate of the exposure time for the dark and the bright side of the waxing crescent moon, supposing that their S/N are similar. Considering that the *full moon* has magnitude $m_{full} = -12.7$ and the *new moon* has magnitude $m_{new} = -2.5$, the ratio of *photon fluxes* for the dark and bright side of the moon (7) is

$$\begin{aligned} R_{d/b} &\sim \frac{F_{dark}}{F_{bright}}, \\ &\sim 0.1 \times 10^{(m_{full}-m_{new})/2.5}, \\ &\sim 10^3. \end{aligned}$$

We can then derive the exposures times for each side,

$$t_{bright} \times N_{\gamma\, bright} \sim t_{dark} \times N_{\gamma\, dark} \times R_{d/b}^{-1}.$$

The last result means that if we keep the number of counts constant for the dark and bright sides, we should aim for calibration dark exposure times of around 1000 larger than those for bright, *e.g.,* we should have at least 90 minutes of net observation of the dark side for a 5 seconds exposure of the bright side. However, due the observational constrains, we ended up collecting only 1/4 of this value, as it is shown in the Table 1 of the appendix.

2.3. Steps of Data Acquisition

The data acquisition was performed by the following steps, based on the exposure times in the Table 1 in the appendix:

1. We record the spectrum of the Neon lamp on all the slits.

2. We record a non-saturated spectrum of a *bright stellar point source* (Altair) at *two distinct positions on the slit*. We trace their spectrum, which gives the direction along which we extract the spectrum of the Earthshine.

3. We track the *dark side of the Moon*, positioning the *dark limb* in one slit and the adjacent on the other and recording the spectra.

4. We measure the *illuminated limb of the moon* in the same way, with a much smaller time to avoid saturation.

5. We repeat the above three procedures while the Sun is still not close enough to the Moon.

6. We obtain sets of dark frames for all the exposure times of our sciences.

3. Data Reduction

The CCD observations are registered as astronomical images (FITS, Flexibble Image Transport System). All the analysis was done in IDL and ATV (8) - the source codes are included in the appendix.

3.1. CCD Dark Frame Calibration

The first step of the data reduction is to remove the various instrumental artifacts of the CCD, by calibrating the science images. We create *dark master frames* for every exposure times, *i.e.,* median combined frames of the CCD closed, the high signal-to-noise dark. We subtract these frames from the respective science frames with same exposure times and median combine these last to form a deep exposure frame.

3.2. Spectra Trace Calibration

Spectra are arranged on the CCD in a manner that most efficiently makes use of the detector size/area. Before these spectra can be extracted, their exact positions on the CCD must be mapped. This is the process of *aperture tracing.* To this, we calculated the spectra's *trace* from two methods:

1. Method 1: From a standard point source;

2. Method 2: By integrating the 1 + 1/2 strips.

The trace of the point source, *e.g.,* a bright (standard) star in the sky, is taken by positioning this star in each of the three slits. With ATV (8), it is possible to extract the *spectral flux distribution* [1], F_λ, as shown in the Fig. 3.

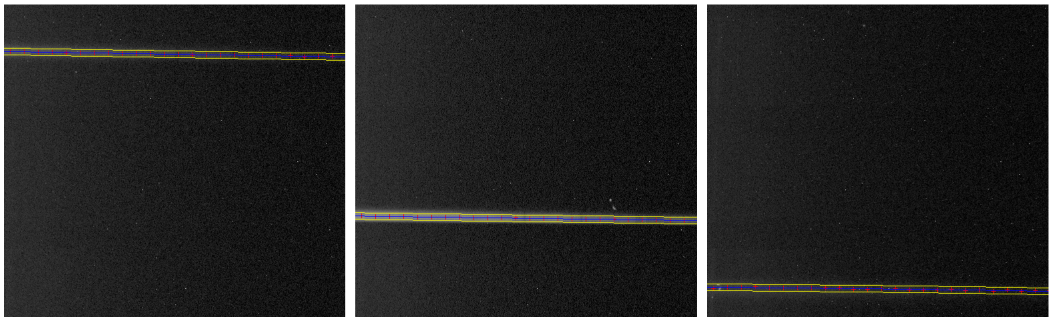

Fig. 3.— Trace extraction from a point source star in each of the three slits (from ATV).

For the Moonshine, the flux is very high and using only the the point source trace (method 1) was enough. (see Figs. 4).

Only for the Earthshine, due to their much lower signal (in the same order of the adjacent sky), we determine a second set of data (method 2), aiming to extract more statistics from the data. We proceeded integrating over the whole Earthshine strip and adding half of the middle strip (which has the adjacent sky on the other half).

3.3. Adjacent Sky Subtraction

Both the dark and bright side of the Moon are corrected for scattered light in the telescope by subtracting the adjacent sky spectrum. The adjacent skies were always extracted in the same way the their respective set of data. The sky-subtracted spectra can been in the see Figs. 5.

After these reductions we were able to calculate the signal to background for the Earthshine (methods 1 and 2) and for the Moonshine spectra, obtaining $S/N_{earth}^{point} = 1.8$,

[1]Loading the image with `decomposed, device=0` option and pressing `x` on it.

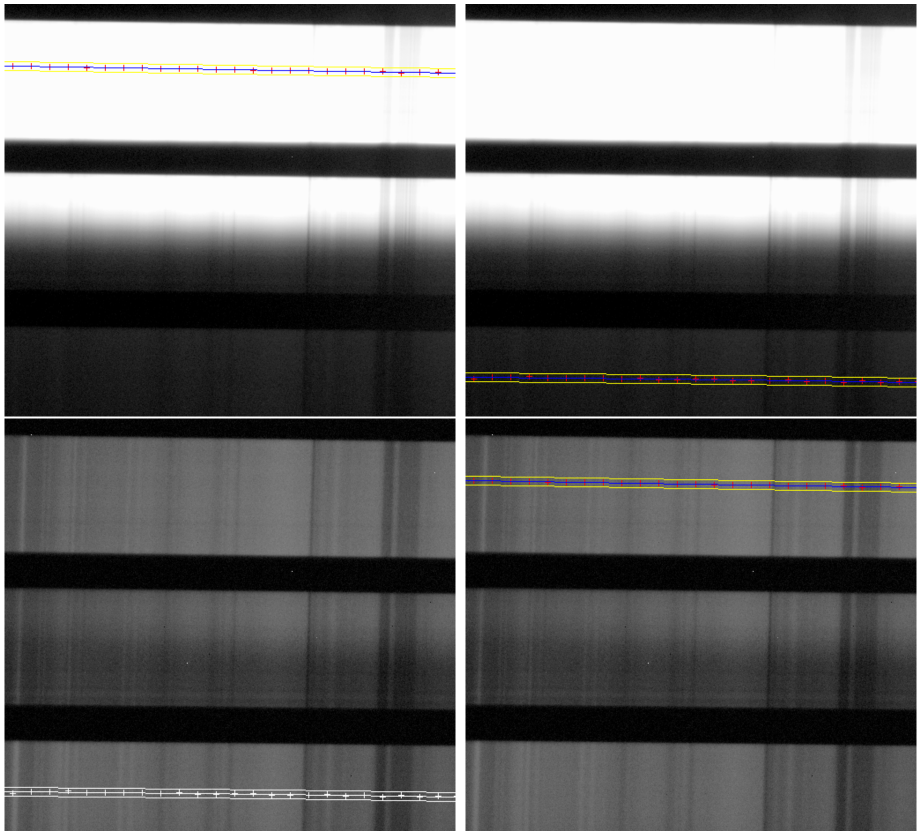

Fig. 4.— Extraction of the point source spectra for the bright (above) and dark (below) side of the waning crescent moon and its adjacent sky (from ATV).

$S/N^{strip}_{earth} = 3.4$ and $S/N_{moon} = 148$, respectively.

3.4. Obtaining the Reflectivity of Earth

The reflectivity of Earth is the ratio of the Earthshine to the Moonlight spectra, *i.e.*, by reducing the contribution of the extra passage of the Sun through the Earth's atmosphere in the spectrum of the Earthshine. Dividing the dark side by the bright side (the earthshine by the moonshine) for methods 1 and 2, we obtain the Fig. 6. We confirm that they show a very good agreement, with a very small enhancement from the method 2. We shall use

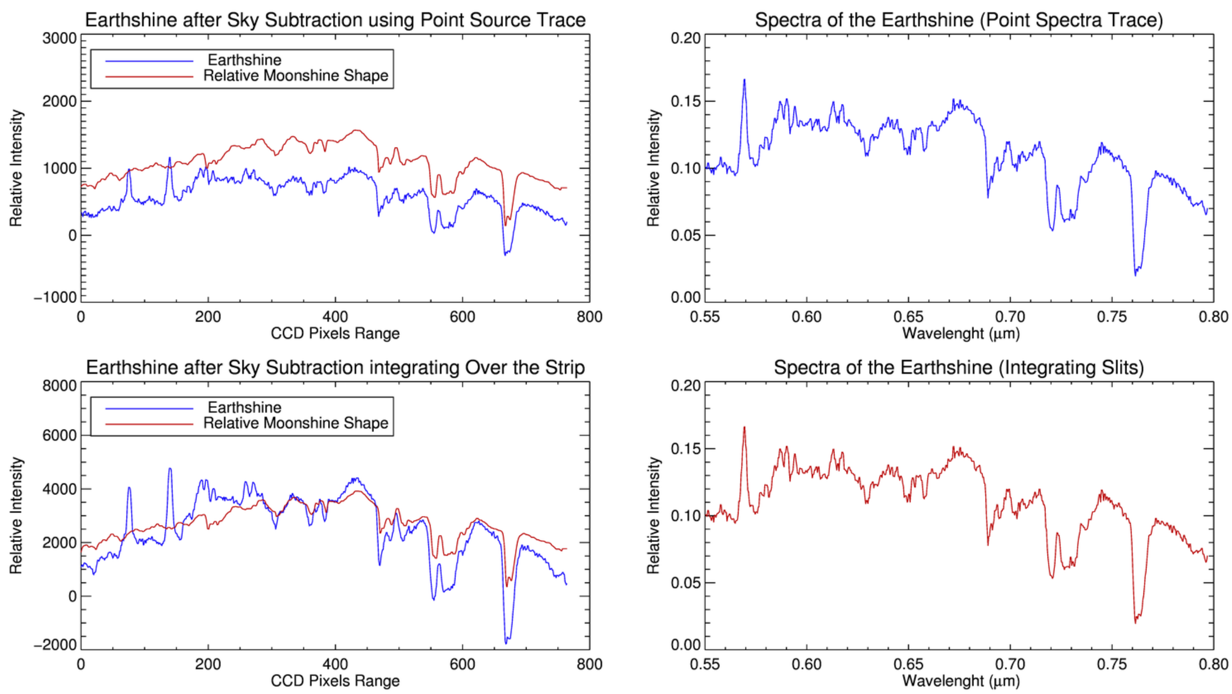

Fig. 5.— Earthshine spectra from method 1(top) and method 2 (down), comparing to the scaled Moonshine spectra, in function of CCD pixel counts, and wavelength calibrated.

only this spectra on the following analysis and refer to it as the Earthshine reflectivity.

3.5. Absolute Spectra Calibration

To obtain the absolute wavelengths of the Earthshine spectrum, we measure the spectrum of a neon calibration lamp and compare it to the well-known wavelengths of neon transitions, see Fig. 7.

We find the $\lambda/pixels$ *scale dispersion* and we reduce the Earthshine spectra from it.This results on the Earthshine spectra correlation to light wavelengths, *i.e.,* the reflectivity of the Earth.

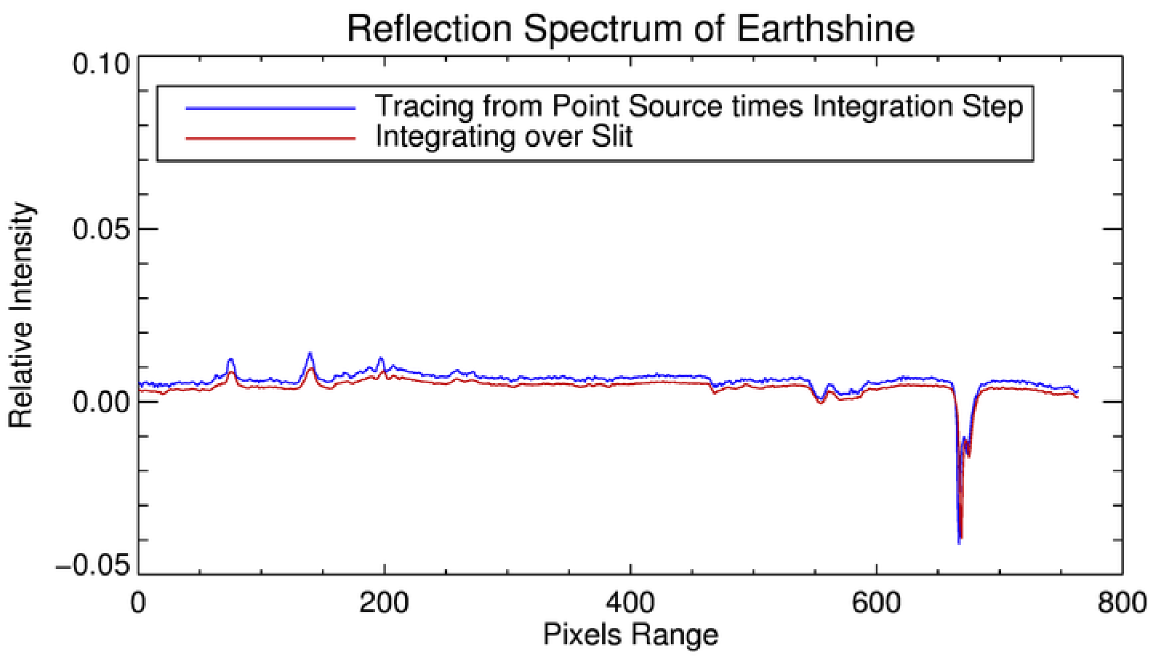

Fig. 6.— Earthshine reflectivity from method 1 and 2, scaled to each other.

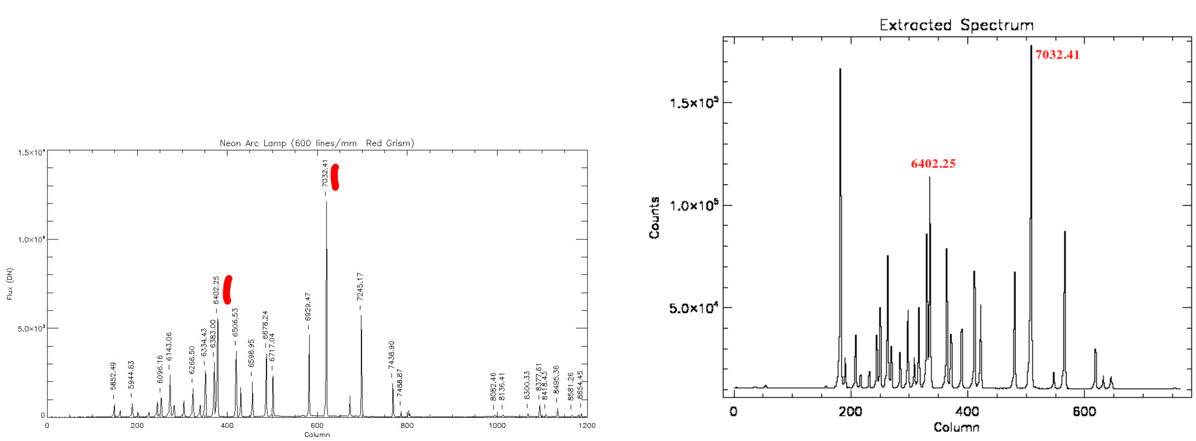

Fig. 7.— Wavelength transitions of neon: (left) from the literature (10), (right) experimentally obtained.

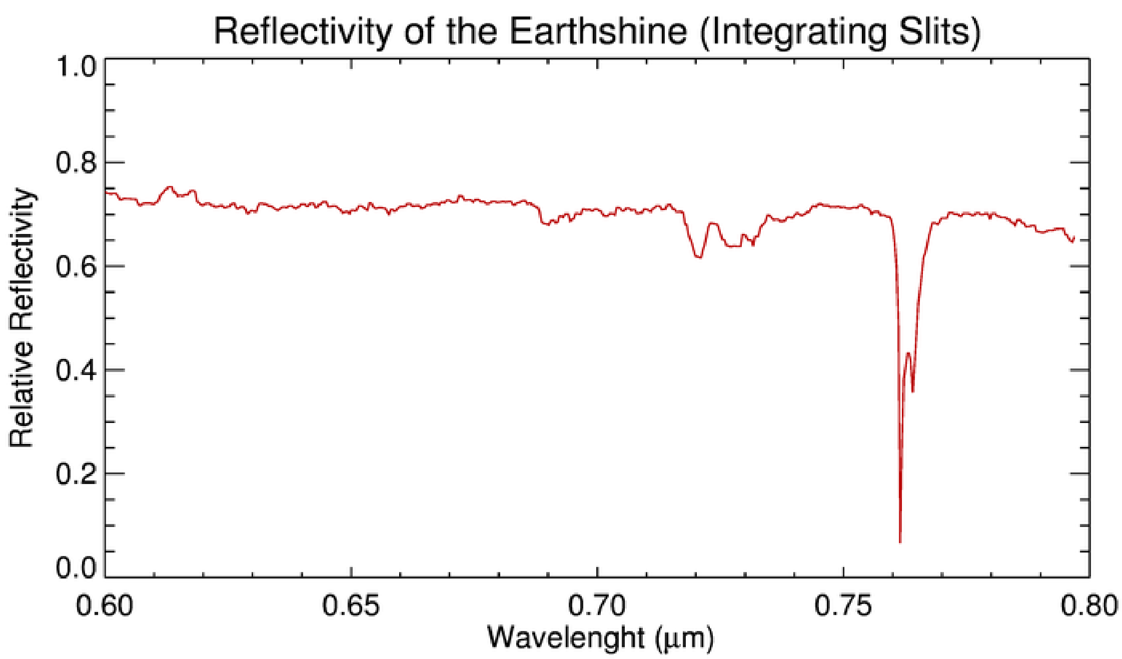

Fig. 8.— The Reflectivity of the Earth.

4. Data Analysis and Results

4.1. Detecting Molecular Gas Features

We compare the final sky-subtracted and wavelength calibrated spectrum of the Earthshine to predictions and existing measurements. First, we detect the molecular bands of O_2, O_3, and H_2O by comparing the absorption lines obtained from (9). We verify that the abundance of those components are compatible to the literature (see Fig. 9).

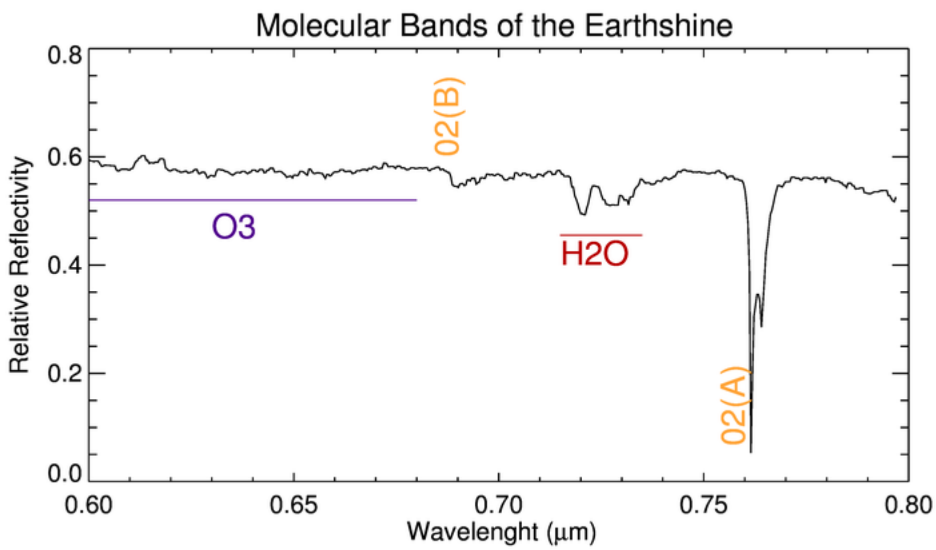

Fig. 9.— Atmospheric molecular bands detected in the Earthshine spectrum.

The presence of strong absorption lines in the near infrared when comparing to shorter regions (blue) of the spectra indicates that if human vision were sensitive a little further toward the red, the natural world would be very red and exceeding bright. In the next session we also see that the blue spectrum from the subsurface ocean water has a very small contribution ranging for wavelengths around 500 to 600 nm.

4.2. Detecting the Vegetation Red Edge

The main contributors to the optical spectrum of Earthshine (5) (12) are

1. The **neutral reflectivity from high clouds** (same as the Sun (blackbody) with $T \sim 5700$K and independent of the wavelength).

2. The blue spectrum of subsurface **ocean water** (see Fig. 10 (right)) .

3. The **transmission of Earth's clear atmosphere**.

4. The **Rayleigh scattering** (proportional to $1/\lambda^4$).

5. The **vegetation** reflection spectrum from land chlorophyll plants (see Fig. 10 (left)).

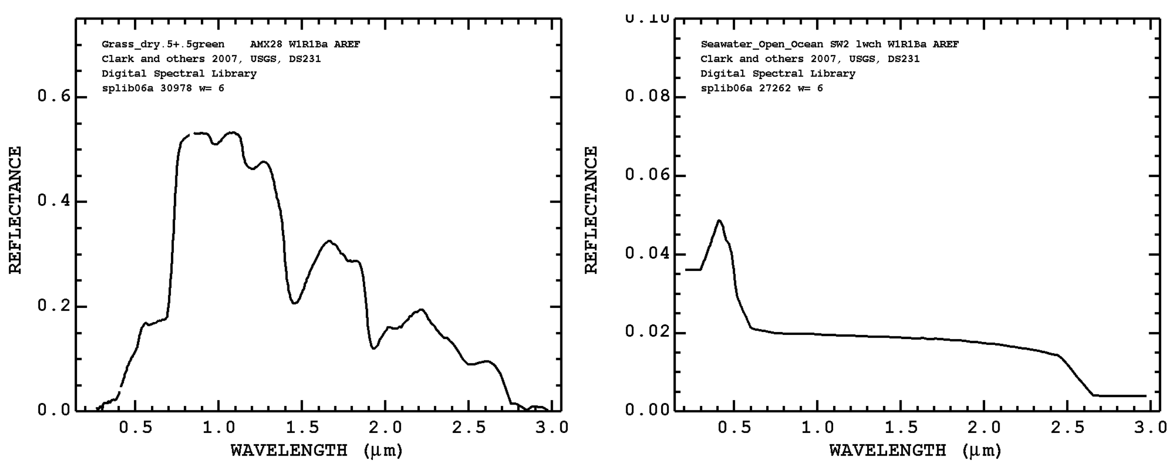

Fig. 10.— Some of the models we fitted our spectra: (left) Vegetation reflection and (right) Ocean Surface.

We fit together each of the previous five models to our spectra of the Earthshine, inferring the partial contributions to the combined spectrum (see Fig. 11), *i.e.,* our model has 5 parameters. We calculate the best values for these parameters to minimize χ^2_{point} on each point then integrate to an acceptable final value of $\chi^2 = 7.8$ (see fitting code in ROOT in the appendix). We assume the data are normally distributed with a variance equal to the mean and the data points are independent from each other, so we can use the level of significance of $\alpha > 0.1$ for the fit. For five parameters, the χ^2_5 should be less than 9, so we see that our fit is indeed significant: χ^2 is not too large for a good fit and it is large enough to reject the *null hypothesis* (5).

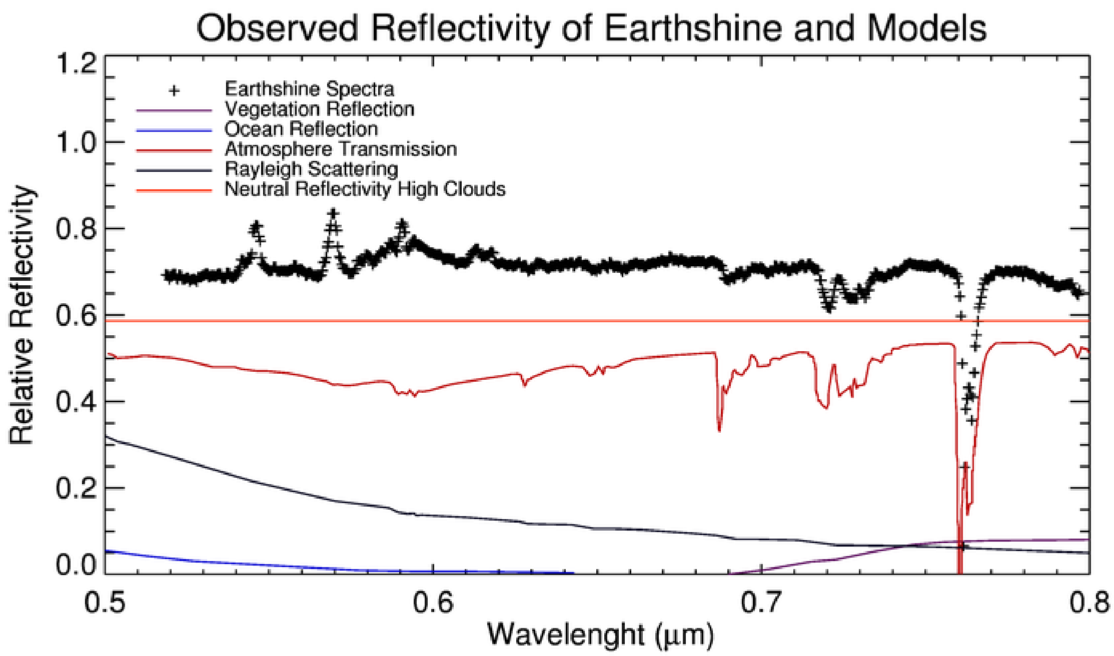

Fig. 11.— The main models to the optical spectrum of Earthshine which we fit to our data. They are scaled in the plot for a better display.

The most important components in the fitting are the Rayleigh scattering (high cloud continuous) in the beginning of the spectra and the clear atmosphere (molecular spectrum) in the whole range.

We calculate the vegetation edge from equation 2. With mean reflectances in the [600, 670 nm] and [740, 800 nm] windows in the spectrum, we obtain $VGE = 4 \pm 5\%$, which was small but compatible with the literature (12). The errors were estimating by looking at the standard deviation during a “flat” part of the spectra and dividing by the mean in that region.

5. Conclusion

The spectrum of the Earth as it would appear to an extrasolar observer is useful for learning how to analyze the spectra of extrasolar planets. It illustrates both atmospheric and surface reflectivity features.

The main contribuition for the spectra comes from the atmosphere transmission. We also see enhanced reflectivity at short wavelengths from Rayleigh scattering and apparently negligible contributions from aerosol and ocean water scattering. We see enhanced reflectivity of $4 \pm 5\%$ at long wavelengths starting at about 740 nm, corresponding to the well-known vegetation red-edge. Our fittings for the Earth's reflection spectrum shows good agreement with the combination of reflectance, scattering, and transmission models.

The vegetation signal was not very significant mostly because of the difficulties of the observation - we had a signal-to-background ratios of $S/N < 5$. Although the observations had great part of reflecting land and had not much high clouds in the atmosphere (see figures 12 and 13), the low signal is due to the fact that we only had 20 minutes of net observation for the Earthshine (less than one fourth of the minimum we had estimated in the beginning of the report).

In conclusion, we have shown that an observer in a nearby stellar system, with the same or better resources used in this experiment, would be able to use the oxygen, water and ozone absorption features to suspect the presence of life on Earth. The small chlorophyll red-edge reflection feature might also help to confirm the presence of life.

REFERENCES

Arnold, L., et al. 2008, ApJ, 135, 323

Seager, R., et al. 2005, ApJ, 5, 3

Woolf, E., et al. 2002, ApJ, 574, 433

Arnold, L., et al. 2002, astro-ph:02063

Metchev, *The Spectrum of Earthshine: Experiment Writeup*, 2012.

DADOS, Spectrograph Manual, 2008

ccd, *Visible-light CCD Camera Manual*, 2012

ATV.PRO, *http://www.physics.uci.edu/ barth/atv/*, as in 04/2012

NIST Atomic Spectra Database, http://www.nist.gov/pml/data/asd.cfm, as in 04/2012

NEON spectrum, http://www.astro.sunysb.edu/metchev/, as 04/2012

Parameters for spectrum simulation, http://hitran.iao.ru, as in 04/2012

Resource for spectra of vegetation and ocean water, http://speclab.cr.usgs.gov/spectral.lib06/ds231/datatable.html, as in 04/2012

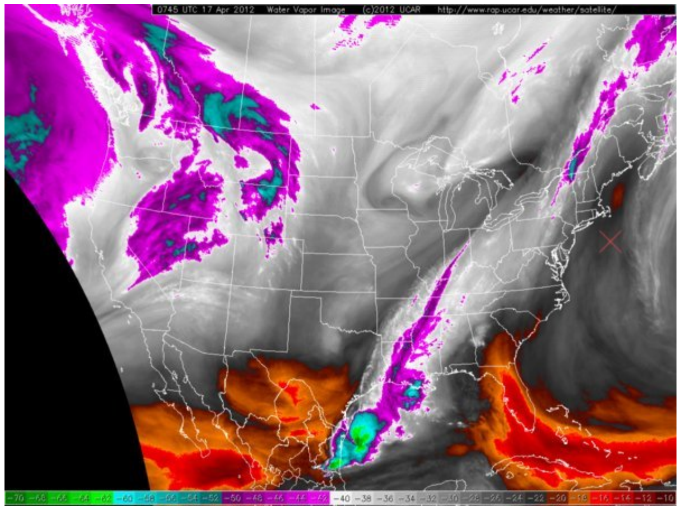

Fig. 12.— Cloud coverage on Earth for the period of observations.

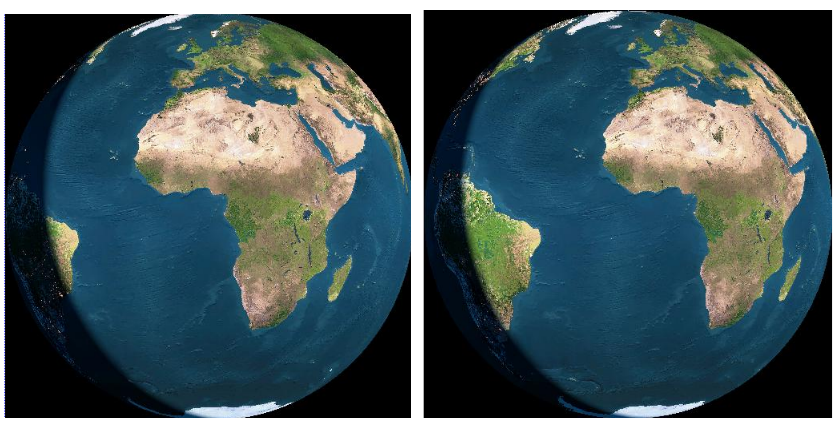

Fig. 13.— Earth seen from the Moon in the begin and the end time of our observations.

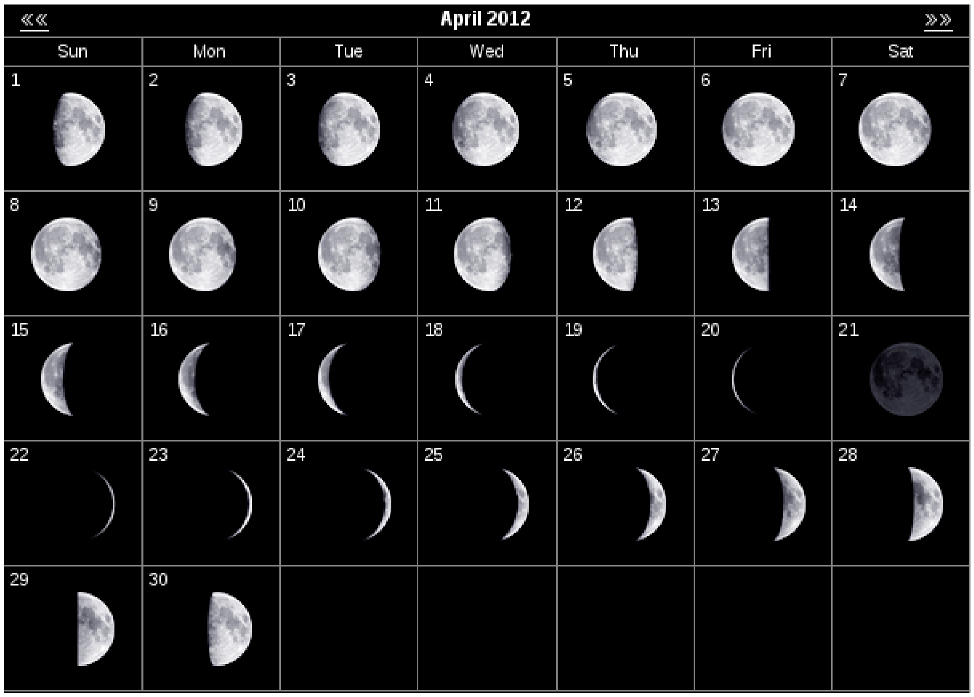

Fig. 14.— Phases of the moon for the month we were observing. The data was taken on the 17th, a waning crescent moon.

Table 1. DADOS Spectrograph Observations Log Sheet

File	Object	Exp. Time (s)	Position in the Slit	Slit (μm)
cal/1	Neon	1	in all of them	200
cal/2	Star - Altair	30	middle	200
cal/3	Star - Altair	30	bottom	200
cal/4	Star - Altair	60	top	200
bright/15/1-5	Moonshine	15	Sky on top	200
bright/30/1-5	Moonshine	30	Sky on top	200
dark/1-10	Earthshine	120	Sky on bottom	200