The Spectrum of Earthshine: Detecting Earth’s Biosignatures from Afar

1. Scientific Background

Can we detect life on an unresolved Earth-like extrasolar planet? Future space missions will provide us with the first images and low-resolution spectra of exo- Earths, and the question of the presence of biogenic spectral signatures in these data will undoubtedly feed an animated debate. Our only reference point at present is our own planet. In this lab you will measure the integrated spectrum of the Earth and assess the evidence for biogenic signatures.

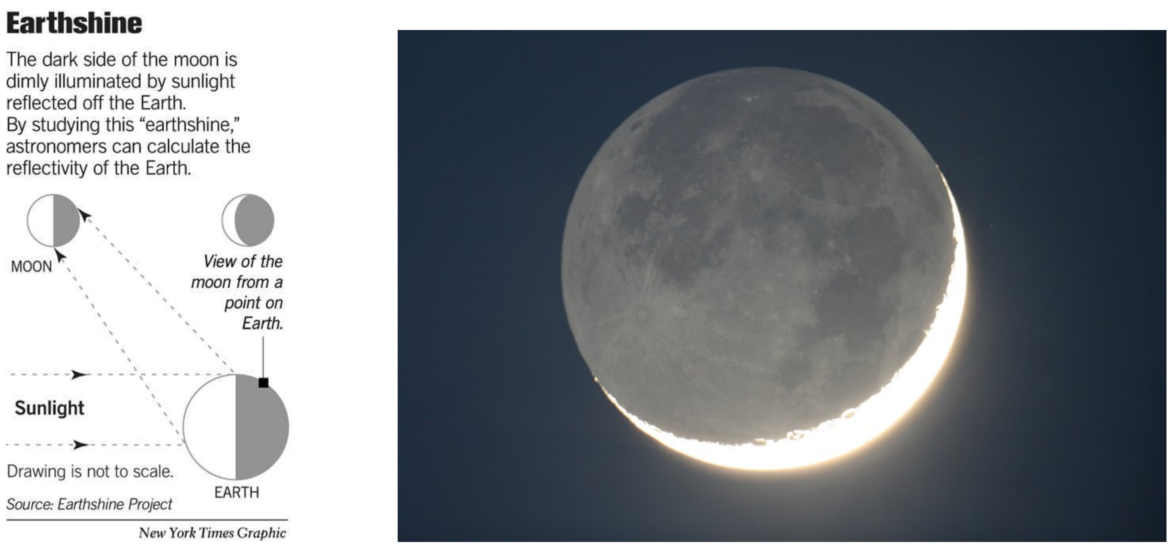

Fig. 1.— **Left:** A schematic description of Earthshine from the May 28, 2004 issue of the New York Times. **Right:** The Moon on May 7, 2008, displaying its crescent, i.e., the sunlit part of the Moon (here overexposed), and a bright Earthshine over the rest of the Moon disk: the visible part of the dark side of the Moon illuminated by a gibbous Earth. (*Photo credit: Matthew Cook, http://www.mattastro.com.*)

While one way to obtain an unresolved spectrum of the Earth would be by observing it from a distant spacecraft, an alternative and easier method is to obtain a spectrum of the lunar earthshine, i.e., of Earth light backscattered by the non-sunlit Moon (Fig. 1). A spectrum of the lunar Earthshine directly gives the disk-averaged spectrum of the Earth at the phase seen from the Moon; the roughness of the lunar surface washes out any spatial information about the Earth’s color.

What would the spectrum of an unresolved Earth-like planet look like? You will look for sets of molecules in the planet’s atmosphere that may be biologic products or by-products, such as molecular oxygen and ozone. Water, while not a product of living organisms, is also abundant in Earth’s atmosphere, and has several prominent absorption bands in the red-optical. Finally, dependent on the amount of dryland visible on the gibbous Earth from the Moon, you may be able to detect the effect of the missing $<$700 nm photons used in the photosynthetic process (Fig. 2), otherwise known as the vegetation “red edge.”

To extract the spectrum of earthshine, we need to consider the various contributing factors in the overall signal from the visible part of the dark side of the Moon. Let us call the Sun spectrum as seen from outside the Earth's atmosphere $S(\lambda)$, Earth's atmospheric transmittance $AT(\lambda)$, moonlight (i.e., sunlight reflected by the Moon's surface) $MS(\lambda)$, earthshine $ES(\lambda)$, lunar reflectance $MR(\lambda)$, and the Earth's reflectance $ER(\lambda)$. We then have (e.g., Arnold 2008):

$$MS(\lambda) = S(\lambda) \times MR(\lambda) \times AT(\lambda) \times g_1, \quad (1)$$

$$ES(\lambda) = S(\lambda) \times ER(\lambda) \times MR(\lambda) \times AT(\lambda) \times g_2 \quad (2)$$

The Earth's reflectance is simple given by the ratio of Equation (2) to (1), i.e.,

$$ER(\lambda) = \frac{ES(\lambda) g_1}{MS(\lambda) g_2}. \quad (3)$$

The cancellation of $AT(\lambda)$ in Equation (3) means that $ES(\lambda)$ and $MS(\lambda)$ should ideally be recorded simultaneously to avoid significant airmass variation and thus an incorrect Rayleigh scattering measurement. The mean of two MS spectra bracketing $ES(\lambda)$ is thus used to compute $ER(\lambda)$. The g_i terms are geometric factors related to the mutual positioning of the Sun, Earth and Moon system. For simplicity, g_1 and g_2 are set to unity, equivalent to spectrum normalization. Equations (1–3) assume that the sky background has been properly subtracted from the spectra. The vegetation red edge is extracted from $ER(\lambda)$ and defined by the ratio

$$VRE = \frac{r_I - r_R}{r_R}, \quad (4)$$

where r_I and r_R are the near-infrared and red reflectance integrated over given spectral domains (≈50 nm width).

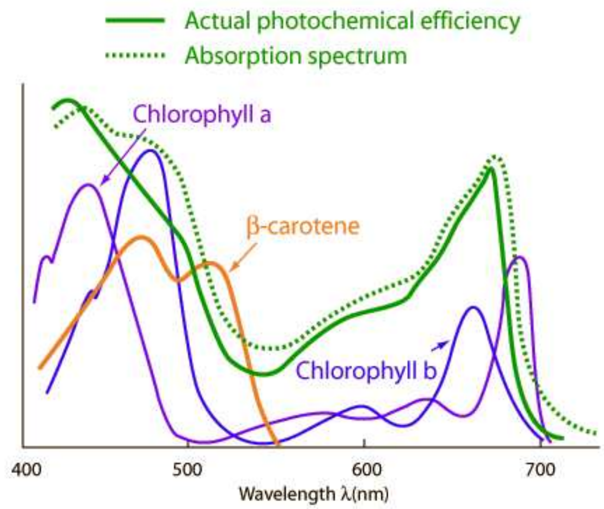

Fig. 2.— Photosynthesis depends on the absorption of light by pigments in the leaves of planets. The most important of these is chlorophyll-a, which together with chlorophyll-b and β-carotene account for most of the photochemical efficiency and the resulting absorption spectrum from photosynthesis. The unabsorbed >700 nm light leads to a sharp rise in reflectivity, creating the vegetation "red edge" in the Earth's spectrum. (*Figure credit: http://hyperphysics.phy-astr.gsu.edu/hbase/biology/ligabs.html*.)

2. Experiment Goals and Plan

The experiment aims to detect the spectroscopic signature of Earth's atmosphere and surface through low-resolution optical spectroscopy of earthshine.

Actions marked with "*PHY 517*" are required only of graduate students. All students are responsible for all other actions.

2.1. Experiment Goals

- obtain an optical spectrum of earthshine;
- test for the presence of expected biomarker features, such as O_2, O_3, and of H_2O;
- *PHY 517:* test for the presence of the vegetation red edge through the simultaneous fit of several model components to your observed spectrum.

2.2. Experiment Plan

1. Decide when you will conduct your observations. 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 on the sky, you may encounter difficulties with separating the glow of earthshine from the bright twilight sky. Also, note that observations over the western horizon from the Mt. Stony Brook telescope are hindered by the elevator shaft adjacent to the telescope dome.
2. Set the desired wavelength range of your spectrograph to cover your chosen set of earthshine absorption features by molecular oxygen, ozone, and water. This should be done before mounting the spectrograph on the telescope, with the help of the Neon light source. Look up the wavelengths of the strongest Neon gas transitions in the optical[1], and adjust the wavelength range of the spectrograph accordingly.
3. Decide which of the three slits in the DADOS spectrograph to use. The narrowest (25 μm) slit offers the highest resolution ($\lambda/\Delta\lambda \approx 500$) but has the lowest throughput. The widest (50 μm) slit offers half the spectral resolution, but has higher throughput.
4. Acquaint yourself with how to operate the Mt. Stony Brook 14-inch telescope, the DADOS optical spectrograph, and the SBIG STL-402 CCD camera.
5. Plan to arrive at the telescope at least 2 hours before the start of your observations. Assemble the spectrograph and the CCD, perform an initial focusing, mount them on the telescope, and finalize focusing on a bright star.
6. Point to the Moon and set the telescope tracking rate to lunar. This is done from the Autostar II keypad. Obtain sequences of spectra of the night and day sides of the Moon, interspersed with spectra of the adjacent sky. Carefully set the exposure times to ensure high signal but to avoid saturation.
7. Take calibration exposures. If you haven't already, take wavelength calibration exposures of the Neon light source. Take darks with durations matched to the durations of all of your science exposures.

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[1] http://www.nist.gov/pml/data/asd.cfm

8. Shut down all equipment and transfer the recorded data onto a memory stick.

3. Data Acquisition

Before or after you take your science observations of the Moon, record a non- saturated spectrum of a bright stellar point source at two distinct positions on the slit. Tracing the spectrum of the point source will give you the direction along which to extract your spectra of earthshine.

With the telescope pointed at the Moon and set to track it, position the dark limb of the Moon half-way across your chosen slit, so that you can record spectra of the Moon and the night sky simultaneously. The slit should be oriented perpendicularly to the limb of the Moon. If placing the slit across the edge of the Moon in a reproducible manner proves difficult, take separate equal-exposure time spectra of the Moon and of the adjacent sky.

Take several non-saturated but high-signal spectra. Repeat the procedure on the illuminated limb of the Moon. Note that you will need a much shorted exposure time on the bright side of the Moon to avoid saturation.

Make sure that you obtain sets of "dark" frames with exposure durations corresponding to those of all of your calibration and science images. Darks can be obtained automatically by the CCD after each exposure, with the saved image file being the difference between the "light" and the dark exposure, or can be obtained separately at the end of your observations. Taking darks immediately after each exposure effectively doubles the time to get any single exposure, but may be convenient for short observations. For long ($\gtrsim$30 sec) exposures you may find it more practical to take a single set of darks at the end of the night.

Make sure to keep a good observing log in your lab book. In particular, proper records of target names, exposure numbers, start times, durations, and sky conditions are essential. Keep a current record of, or infer at a later time for each exposure, the elevation of the Moon above the horizon. You will find this information useful at a later time in judging the quality of your data.

4. Data Reduction

Briefly, you will:

1. determine of the "trace" of point source spectra, i.e, $y(x)$ functional relation of the dispersed light;

2. extract of your science spectra with the same spectral trace at the corresponding y offsets and with an appropriately chosen width perpendicular to the trace;

   Note: If you obtained separate spectra of the night sky, or you are reducing spectra of a point source taken at two different (nodded) locations along the slit, your best approach to sky subtraction is to do it before the spectral extraction. Simply subtract the image of the sky spectrum from the image of the lunar spectrum, or for the point source nodded along the slit, mutually subtract the images of the spectra taken at different positions on the slit.

3. sky-subtract (if you haven't already) and median-combine your spectra of the night- an day-side of the Moon. Divide the night-side by the day-side spectra to account for the contribution of the solar spectrum and the extra passage through the Earth's atmosphere in the spectrum of earthshine.

4. use the same trace to extract a spectrum of the neon calibration lamp. By comparing that spectrum to the known wavelengths of neon transitions, solve for the wavelength dispersion equation on the detector (i.e., solve for $\lambda(x, y)$). Apply this wavelength dispersion relation to your extracted earthshine spectrum.

All of the data reduction is done in IDL with ATV v. 2.3 or higher. Once you load an image of each spectrum, you can access the spectral extraction toolbox by pressing 'x'. A brief description of how to do spectral extraction with ATV is given on Aaron Barth's ATV site.[2]

5. Analysis and Discussion

5.1. Detecting Molecular Gas Features

Compare your final sky-subtracted and wavelength calibrated spectrum of earthshine to predictions and existing measurements of it. Can you detect the molecular bands of O_2, O_3, and H_2O? Is "blue" the correct description of Earth's optical broadband color (as in "pale blue dot")? Why?

5.2. Detecting the Vegetation Red Edge (*PHY 517*)

The main contributors to the optical spectrum of earthshine are:

1. neutral reflectivity from high clouds,

2. the transmission of Earth's clear atmosphere,

3. Rayleigh scattering,

4. the spectrum of subsurface ocean water, and

5. the vegetation reflection spectrum from land chlorophyll plants.

Find appropriate models in the literature for each of these components, and fit them simultaneously to your data to infer their partial contributions to the combined spectrum.

5.3. Discussion (*PHY 517*)

How well does the combination of reflectance, scattering, and transmission models fit your data, as expressed by the reduced χ^2 value of the fit? Do your data enable you to detect the

[2] http://www.physics.uci.edu/ barth/atv/instructions.html.

vegetation red edge? If so, at what significance? If not, then why not? (Consider what fraction of the Earth as seen from the Moon during your observations is covered by ocean vs. landmass and check what the overall cloud cover may have been from archival satellite imagery.)

REFERENCES

Arnold, L. 2008, Space Sci. Rev., 135, 323