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THE SPECTRUM OF EARTHSHINE: A PALE BLUE DOT OBSERVED FROM THE GROUND

N. J. Woolf and P. S. Smith
Steward Observatory, University of Arizona, Tucson, AZ 85721; nwoolf@as.arizona.edu, psmith@as.arizona.edu
and
W. A. Traub and K. W. Jucks
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; wtraub@cfa.harvard.edu, kjucks@cfa.harvard.edu
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ABSTRACT

We report the visible reflection spectrum of the integrated Earth, illuminated as it would be seen as a spatially unresolved extrasolar planet. The spectrum was derived from observation of lunar earthshine in the range 4800–9200 Å at a spectral resolution of about 600. We observe absorption features of ozone, molecular oxygen, and water. We see enhanced reflectivity at short wavelengths from Rayleigh scattering and apparently negligible contributions from aerosol and ocean water scattering. We also see enhanced reflectivity at long wavelengths starting at about 7300 Å, corresponding to the well-known red reflectivity edge of vegetation because of its chlorophyll content; however, this signal is not conclusive because of the breakdown of our simple model at wavelengths beyond 7900 Å.

Subject headings: astrobiology — Earth — Moon — planetary systems

1. INTRODUCTION

Earthshine is sunlight that has reflected from the Earth onto the dark side of the Moon and back again to Earth. Here " dark side " refers to that portion of the lunar surface that, at any instant, faces the Earth but does not face the Sun. Both earthshine, from the dark side of the Moon, and moonlight, from the bright side of the Moon, are transmitted through the same air mass just prior to detection and thus suffer the same extinction and imposed absorption features. Their ratio is the reflection coefficient of the Earth multiplied by a geometric factor and by the ratio of phase effects of the Moon. (We ignore weak additive Raman-shifted spectra from both bodies, i.e., the Ring effect.) We report here the results of our effort to obtain a spectrum of the Earth as it would be seen from outside the solar system. Our goal is to pave the way for interpreting extrasolar terrestrial planet spectra that might be obtained in the future, for example, as part of the Terrestrial Planet Finder (TPF) program.

2. OBSERVATIONS

We observed the spectrum of earthshine and moonlight soon after sunset on 2001 June 24/25 (25/26 UT) from Kitt Peak, Arizona, using the Steward Observatory 2.3 m telescope with its Boller & Chivens spectrograph, a CCD detector, and a 300 line mm^{-1} grating. The raw spectrum is shown in Figure 1. A spectral range from 4800 to 9200 Å was recorded at a resolution of about 600, or a spectral width of about 8–9 Å. The telescope drive was set to lunar rate and was guided in right ascension, keeping the limb in the same position on the slit to within about an arcminute in declination between the different observations. At the time of these observations, about $\frac{1}{4}$ of the Moon appeared sunlit, and $\frac{3}{4}$ was nominally dark.

The 1$''$.5 wide spectrograph slit has a length of about 200$''$. It was set perpendicular to the lunar limb, with approximately half of its length on the limb and half on adjacent sky. Both the sunlit and Earth-lit limb spectra were corrected for scattered light in the telescope by subtracting the adjacent sky spectrum; this amounted to about $\frac{2}{3}$ of the total signal in the earthshine spectrum. Each earthshine spectrum was bracketed by moonlight spectra.

Both nights were partly cloudy, and the observations were made during breaks in the clouds. Data from the first night have more noise than data from the second night but are in qualitative agreement. The second night produced two independent sets of observations; the first was taken under more clear conditions and is the one reported here.

The measured reflectivity of the integrated Earth is shown in Figure 2. The reflectivity is the ratio of the earthshine to moonlight spectra, both sky-subtracted. We have also corrected for the color effect of the lunar phase (Lane & Irvine 1973), which makes the apparent reflectivity about 16% too strong in the blue; this color bias was removed by multiplying the apparent reflectivity by an eight-segment piecewise linear factor, which ranged from 0.835 at 5000 Å to 1.00 at 9000 Å.

The reflectivity in Figure 2 has also been corrected for CCD fringing. Dome flats were not adequate to exactly match the lunar spectrum fringing in the thinned CCD chip because flexure in the instrument and/or telescope changed the position of the fringes slightly. Use of a quartz lamp internal to the spectrograph ensured that fringes were at the same location on the chip as for the lunar observations, but their amplitude was suppressed because the lamp does not illuminate the slit with an f/9 beam as does light that passes through the telescope. We used the internal lamp to partially correct the fringes by dividing by the lamp spectrum, but a noticeable fringe pattern remained. Five residual interference fringe packets in the red part of the spectrum were least-squares fitted with smooth Gaussian envelope sinusoids and subtracted from the data. The fitting procedure removed most of the remaining fringing, but a residual noise remains that is larger in this region than elsewhere in the

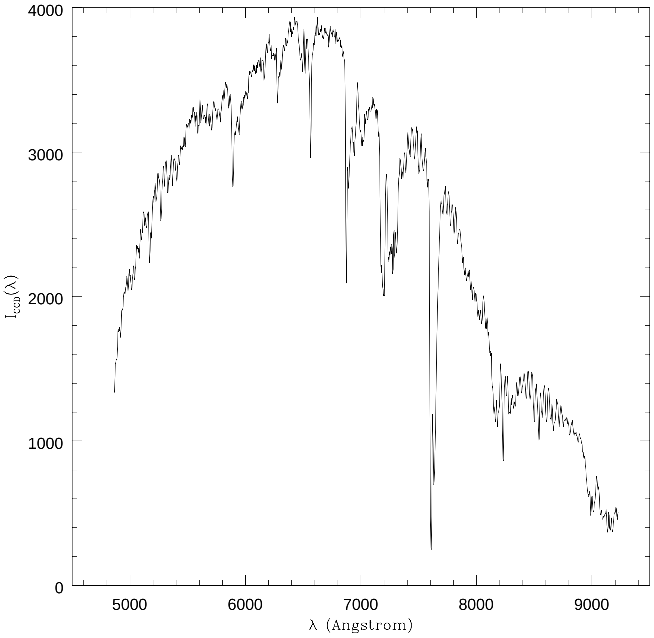

FIG. 1.—Spectrum of earthshine, after sky subtraction. Ordinate is CCD data units. A mix of solar features such as Na D line and Hα is seen, along with terrestrial oxygen A and B bands and many water vapor features. CCD fringes disturb the spectrum from about 7200 to 9200 Å.

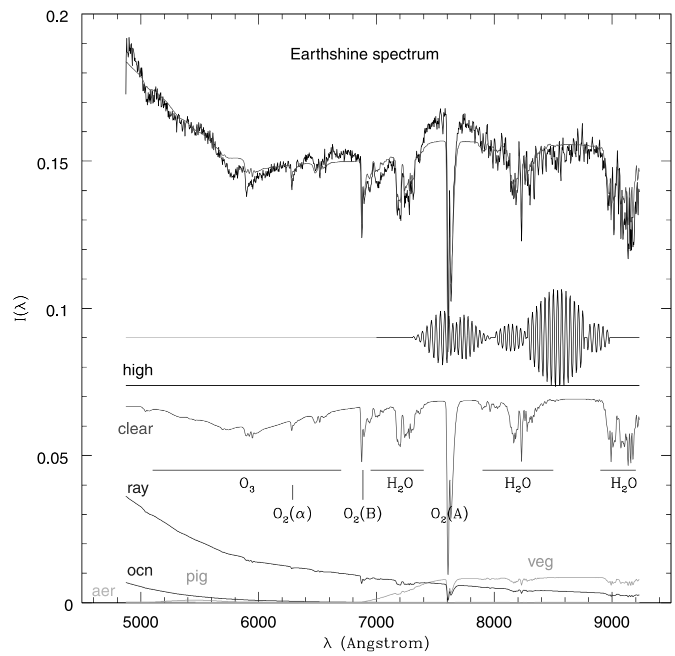

FIG. 2.—Observed reflectivity spectrum of the integrated Earth, as determined from earthshine, is shown at the top, with a model spectrum superposed. The reflectivity scale is arbitrary. Five interference fringe packets (inset, offset but otherwise to scale) simulating CCD fringing were subtracted from the data. Seven component spectra (*bottom*) were fitted and summed to produce the model spectrum. "High": reflectivity from a high cloud. "Clear": the clear-atmosphere transmission. "Ray": Rayleigh-scattered light. "Veg": the vegetation reflection spectrum from land chlorophyll plants. "Ocn": the blue spectrum from subsurface ocean water. "Aer": aerosol scattered light, here negligible. "Pig": the green-pigmented phytoplankton reflection of ocean waters, also negligible here.

spectrum. The zero-mean subtracted component is explicitly displayed (offset in intensity) beneath the data in Figure 2.

3. SPECTRUM MODEL AND ANALYSIS

Our model of the Earth's reflection spectrum is a simple box model in which each box represents a potentially major contributor to the final spectrum. By using a box model, we ignore the interactions between components (e.g., reflections between clouds and ground, multiple scattering, etc.); in other words, we focus on the net resulting spectrum, not the interplay of generating mechanisms. The model has nine independent parameters, each of which scales an independent physical component. The standard atmosphere component is discussed in Traub & Jucks (2002), and the other components are discussed briefly here:

1. Optical depth of standard atmospheric species H_2O, O_2, and O_3. The optical depth is calculated at very high spectral resolution, using a model atmosphere with thin layers from 0 to 100 km altitude, standard mixing ratio profiles of species, and Doppler and pressure broadening. The resulting spectrum is smeared and sampled to match the experimental wavelength grid and resolution.
2. Optical depth of stratospheric O_3. Here O_3 is the only absorber, and atmospheric layers are limited to stratospheric altitudes, otherwise similar to the full standard atmosphere component.
3. Rayleigh scattering. This is a source term with λ^{-4} functional form.
4. Aerosol scattering. This is also a source term but with $\lambda^{-1.3}$ form.
5. Reflectivity of high clouds. This is a constant reflectivity term, independent of wavelength, as from a very high cloud.
6. Reflectivity of ocean water. This is light that has penetrated the surface and has been scattered out of the water. It has a $10^{-(\lambda-\lambda_0)/\Delta\lambda}$ form, giving the ocean its blue color, where $\lambda_0 = 5500$ Å and $\Delta\lambda = 1300$ Å here.
7. Reflectivity of ocean pigment. This is ocean pigment resulting from chlorophyll and its products, here represented by a Gaussian centered at 5500 Å, and with FWHM 650 Å, giving waters with phytoplankton a green color. The longer wavelength chlorophyll feature (item 8) is not seen in practice; water absorbs quite strongly at these wavelengths (item 6).
8. Reflectivity of vegetated land. This is the reflectivity of vegetation containing chlorophyll, on land, dominated by a sharp rise in reflectivity for wavelengths longer than about 7200 Å, plus some smaller bumps at shorter and longer wavelengths. It is modeled here by functional forms approximating these features. (If our eyes were sensitive to wavelengths longer than 7200 Å, all vegetation would appear to be infrared bright, not green!)
9. Reflectivity of low clouds and surface, below the bulk of atmosphere. The nominally featureless reflectivity of land, low clouds, and the 2% Fresnel reflectivity of the air-ocean interface are lumped into this single term, independent of wavelength.

In terms of our model, the two dominant components in the spectrum are the "high cloud" continuum and the "clear atmosphere" spectrum of water, ozone, and oxygen. All components are displayed in Figure 2, where the linear sum of the seven-component spectra is equal to the smooth model function superposed on the data. The main features of water, ozone, and oxygen are labeled; weak bands of water are not labeled. The relative strength of each spectral component is proportional to the intrinsic reflectivity times the effective projected area on Earth of that component. For example, suppose that the clear atmosphere spectrum arises entirely over water, which has a Fresnel reflectivity of 0.02, and that the continuum spectrum is from clouds, with a nominal reflectivity of 0.30. Then the fact that we observe these components to have similar strengths indicates that the clear atmosphere area is roughly 15 times greater than the cloudy area; i.e., the model Earth has a relatively clear sky.

Rayleigh-scattered light from molecules is the next largest component. In our box model, this component is multiplied by the transmission of the clear atmosphere, as displayed in Figure 2. The remaining components are relatively small and carry less significance than the dominant three.

The vegetation "red edge" signal in Figure 2 is the well-known signature of chlorophyll in land vegetation, described above. The earthshine spectrum shows increased reflectivity in the 7200–7900 Å region, suggestive of a vegetation signal in this range. However, the data do not show continued high reflectivity at longer wavelengths (7900–9200 Å), as would be expected for a vegetation reflection profile, making the interpretation ambiguous. Nevertheless, on the basis of the abrupt reflectivity increase at 7200 Å, we suspect that the vegetation signal is indeed present and that either the data or the model fail at longer wavelengths, masking this signal.

The three remaining components are weakest. The ocean clear water signal, the aerosol signal, and the ocean phytoplankton signal all make relatively small contributions to the spectrum. Note that there is a superficial similarity between each of the blue continuum spectra (Rayleigh, ocean, and aerosol); however, their wavelength variations are quite different when viewed over a wide range of wavelengths, and this allows the components to be independently determined with relatively small correlation.

In summary, the earthshine spectrum shows strong evidence for cloud, ozone, water, oxygen, Rayleigh scattering, and very probably vegetation signals. Apparently weak components are aerosols, ocean water, and phytoplankton signals.

4. DISCUSSION

In order to characterize an extrasolar terrestrial planet using visible light, there are three main avenues of approach:

1. The diurnal photometric variability could be measured. Ford, Seager, & Turner (2001) have shown that for an earthlike planet, variation on the order of 100% may be expected.
2. The spectral reflectivity of the atmosphere could be measured. As shown here and in Traub & Jucks (2002), absorption features resulting from ozone, water vapor, and molecular oxygen could be seen, as well as enhanced reflectivity resulting from Rayleigh and aerosol scattering.
3. The spectral reflectivity of the surface could be measured. As we have shown in Figure 2, this potentially includes the reflectivity of clear ocean water (*blue*), phytoplankton in the ocean (*green*), and land vegetation (*red*).

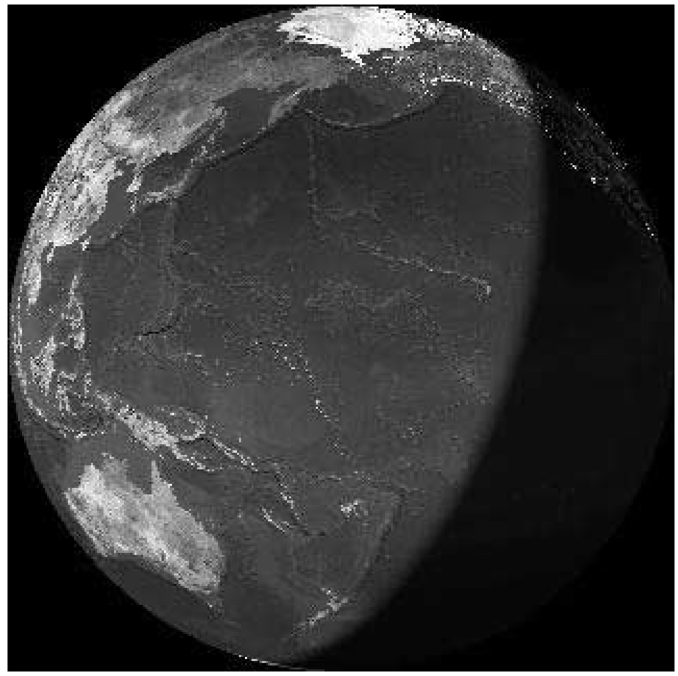

Fig. 3.—Simulated image of the cloud-free, illuminated Earth as seen from the Moon at the time of the observations reported here, centered on the Pacific Ocean. For reference, the illuminated appearance of the Moon from the Earth would be approximately the inverse; i.e., the illuminated and dark fractional areas would be exchanged.

The vegetation signal in Figure 2 is relatively small, about 6% above the nearby continuum. But at the time of observation only about 17% of the projected area was land, as shown in the simulated cloud-free Earth image[1] in Figure 3. Of this fraction of land, only part is cloud-free and vegetated, so in principle the vegetation signal could be at least 6 times larger than we observed. An infrared view of the whole Earth[2] showed little or no cloud cover over the land masses illustrated in Figure 3, so it is reasonable to expect that we might be seeing a large part of the available vegetation signal in our spectrum.

For example, this expectation is borne out in data taken by the *GOME* satellite[3] in which the spectral region from about 3100 to 8000 Å was observed in a nadir-pointing mode, and the field of view was relatively small and filled with vegetated land in northern Italy. In that reflection spectrum, the vegetation signal is about 2.4 times larger than the adjacent continuum, showing that this is a potentially very large differential signal on a similarly vegetated extrasolar planet.

The residual spectral mismatch in Figure 2 in the range 7300–7900 Å suggests that yet more vegetation signal could be accommodated in the model but that this may be thwarted by a bias in either the data or the model in the 7900–9200 Å region. Although a more detailed reflectivity

[1] Earth simulation images are available at http://www.fourmilab.ch/earthview/vplanet.html.

[2] Infrared view of the Earth is available at http://www.ssec.wisc.edu/data/comp/ir/.

[3] For a sample spectrum, see http://earth.esa.int/symposia/participants/popp.html.

model of the composite Earth has yet to be developed, we believe that the enhancement of reflectivity redward of 7300 Å is significant and is an indicator of vegetation.

5. COMMENTS

Our spectrum of the Earth as it would appear to an extrasolar observer will be useful for learning how to analyze the spectra of extrasolar planets, discovering the key spectral features of Earth analogs, and determining the necessary spectral resolution and signal-to-noise ratios. This spectrum illustrates both atmospheric and surface reflectivity features. It was not feasible to look for variability because of the limited observing period.

We note that the reflectivity of the Earth has not been static throughout the past 4.5 Gyr. In particular, oxygen and ozone become abundant perhaps only 2.3 Gyr ago, affecting the atmospheric absorption component of the reflection spectrum. Then perhaps about 2.0 Gyr ago, a green phytoplankton signal developed in the oceans. About 0.44 Gyr ago, an extensive land plant cover developed, generating the red chlorophyll edge in the reflection spectrum (Lunine 1999).

An observer in a nearby stellar system would have been able to use the oxygen and ozone absorption features to suspect the presence of life on Earth anytime during the past 50% of the age of the solar system. The extrasolar observer would have been able to use the chlorophyll red-edge reflection feature to confirm the presence of life on Earth anytime during the most recent 10% of the age of the solar system.

As the Earth evolved, there have also been significant changes in the temperature structure, the abundances of H_2O, CO_2, CH_4, and perhaps the character of cloud coverage. Some of these changes may have been sudden and even oscillatory, as opposed to gradual. Thus, the spectrum of the evolving Earth has shown dramatic changes (e.g., Traub & Jucks 2002), and we may expect that similar signatures will be found on extrasolar terrestrial planets.

We suggest that further observations of earthshine should be made; one group has already done so (Arnold et al. 2002). One purpose is to validate our ability to characterize extrasolar terrestrial planets using visible wavelengths. In particular, it would be valuable to make earthshine observations from space as well as ground, to remove the complicating factor of observing through the Earth's atmosphere. It would also be valuable to observe different types of land, ocean, and cloud cover on Earth and, furthermore, to do so for a full diurnal cycle in order to test the spectroscopy and the prediction of variable photometry.

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[4] An earlier version of Des Marais et al. (2002) is also available as JPL Publication 01-008.

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