The Vegetation Red Edge Spectroscopic Feature as a Surface Biomarker

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The search for Earth-like extrasolar planets is in part motivated by the potential detection of spectroscopic biomarkers. Spectroscopic biomarkers are spectral features that are either consistent with life, indicative of habitability, or provide clues to a planet’s habitability. Most attention so far has been given to atmospheric biomarkers, gases such as O\textsubscript{2}, O\textsubscript{3}, H\textsubscript{2}O, CO, and CH\textsubscript{4}. Here we discuss surface biomarkers. Surface biomarkers that have large, distinct, abrupt changes in their spectra may be detectable in an extrasolar planet’s spectrum at wavelengths that penetrate to the planetary surface. Earth has such a surface biomarker: the vegetation “red edge” spectroscopic feature. Recent interest in Earth’s surface biomarker has motivated Earthshine observations of the spatially unresolved Earth and two recent studies may have detected the vegetation red edge feature in Earth’s hemispherically integrated spectrum. A photometric time series in different colors should help in detecting unusual surface features in extrasolar Earth-like planets.

1. Introduction

One hundred extrasolar giant planets are currently known to orbit nearby sun-like stars. These planets have been detected by the radial velocity method and so, with the exception of the one transiting planet, only the minimum mass and orbital parameters are known. Many plans are underway to learn more about extrasolar planets’ physical properties from ground-based and space-based observations and via proposed or planned space missions. Direct detection of scattered or thermally emitted light from the planet itself is the only way to learn about a variety of the planet’s physical characteristics. Direct detection of Earth-size planets, however, is extremely difficult because of the proximity of a parent star that is $10^6$ to $10^{10}$ times brighter than the planet.

Terrestrial Planet Finder (TPF), with a launch date in the 2015 timeframe, is being planned by NASA to find and characterize terrestrial-like planets in the habitable zones of nearby stars. The ESA mission Darwin has similar goals. The motivation for both of these space missions is the detection and spectroscopic characterization of extrasolar terrestrial planet atmospheres. Of special interest are atmospheric biomarkers—such as O\textsubscript{2}, O\textsubscript{3}, H\textsubscript{2}O, CO and CH\textsubscript{4}—which are either indicative of life as we know it, essential to life, or can provide clues to a planet’s habitability (Des Marais et al. 2002). In addition, physical characteristics such as temperature and planetary radius could be constrained from low-resolution spectra.

We have shown (Ford, Seager & Turner 2001) that planet characteristics could also be derived from photometric measurements of the planet’s variability at visible wavelengths. A time series of photometric data of a spatially unresolved Earth-like planet could reveal a wealth of information such as weather, the planet’s rotation rate, presence of large oceans or surface ice, and existence of seasons. The amplitude variation of the time series depends on cloud-cover fraction; more cloud cover makes a more photometrically uniform Earth and so reduces variability. The signal-to-noise necessary for photometric
study would be obtained by a mission capable of measuring the sought-after atmospheric biomarker spectral features. Furthermore the photometric variability could be monitored concurrently with a spectroscopic investigation, as was done for the transiting extrasolar giant planet HD209458b (Charbonneau et al. 2002).

To detect and study surface properties only wavelengths that penetrate to the planetary surface are useful. Visible wavelengths are more suited than mid-IR wavelengths for such measurements for several reasons. First, the albedo contrast of surface components is much greater than the temperature variation across the planet’s surface. Second, at visible wavelengths the planet’s flux is from scattered starlight and hence at some configurations the planet is only partially illuminated. This allows a more concentrated signal from surface features, such as continents, as they rotate in and out of view. Furthermore, the non-uniform illumination and non-isotropic scattering of different surface components mean much of the scattered light can come from a small part of the planet’s surface. At mid-IR wavelengths the planet has, to first order, uniform flux across the planet hemisphere. In addition, the narrow transparent spectral window at 8-12 µm will close for warmer planets than Earth and for planets with more water vapor than Earth. However, further study at the mid-IR “window” needs to be investigated.

An extremely exciting possibility, aided by a photometric time series, is the detection of surface biomarkers in the spectrum of an extrasolar planet. This would be possible at wavelengths that penetrate to the planet’s surface, and for surface features that have large, distinct, abrupt changes in their spectra. Although most surface features (e.g., ice, sand) show very little or very smooth continuous opacity changes with wavelength, Earth has one surface feature with a large and abrupt change: vegetation (Figure 1). In this paper we discuss Earth’s vegetation red-edge spectroscopic feature as a surface biomarker.

2. The Vegetation Red Edge Spectral Feature

All chlorophyll-producing vegetation has a very strong rise in reflectivity at around 0.7 µm by a factor of five or more. This red-edge spectral signature is much larger than the familiar chlorophyll reflectivity bump at 0.5 µm, which gives vegetation its green color. In fact, if our eyes could see a little further to the red, the world would be a very different place: plants would be very red, and very bright. The glare from plants would be unbearably high, like that of snow. The red edge is caused both by strong chlorophyll absorption to the blue of 0.7 µm, and a high reflectance due to plant cell structure to the red of 0.7 µm. Figure 2 shows a deciduous plant leaf reflection spectrum. The high absorptance at UV wavelengths (not shown) and at visible wavelengths is by chlorophyll and is used by the leaf for photosynthesis. Photosynthesis is the process by which vegetation and some other organisms use energy from the sun to convert H₂O and CO₂ into sugars and O₂. The primary molecules that absorb the light energy and convert it into a form that can drive this reaction are chlorophyll A (0.450 µm) and B (0.680 µm).

As seen in Figure 3, between 0.7 µm and 1 µm the leaf is strongly reflective. Not shown in Figure 3 is that the leaf also has a very high transmittance at these same wavelengths, such that reflectivity plus transparency is near 100%. Interestingly, the bulk of the energy of solar radiation as it reaches sea level is at approximately 0.6 to 1.1 µm. If plants absorbed with the same efficiency at these wavelengths as at visible wavelengths they would become too warm and their chlorophyll would degrade. A specific plant must balance the competing requirements of absorption of sunlight at wavelengths appropriate for photosynthesis reactions with efficient reflectance at other wavelengths.
Figure 1. Reflection spectrum of a deciduous leaf. The small bump near 0.5 μm is a result of chlorophyll absorption (at 0.45 μm and 0.68 μm) and gives plants their green color. The much larger sharp rise (between 0.7 and 0.8 μm) is known as the red edge and is due to the leaf cell structure.

To avoid overheating (Gates et al. 1965). Therefore the exact wavelength and strength of the red edge depends on the plant species and environment. Although negligible from the TPF view point, it is interesting to note that the specific wavelength and strength of the red edge feature is used for remote sensing of specific locations on Earth to identify plant species and also to monitor a field of vegetation’s (such as crops) health and growth as the red edge changes during the growing season.

In the near-infrared, as shown in Figure 1, plants have water absorption bands. The band strength depends on plant water content, weather conditions, plant type, and geographical region. These absorption features can be quite strong, but are not very useful for identifying life, since they would only be indicative of water and would not be distinguishable from atmospheric water vapor.

Plant leaves are very reflective away from chlorophyll absorption and water absorption wavelengths due to the internal leaf structure (Gates et al. 1965). Light partially scatters off of the leaf surface but also scatters efficiently inside the leaf. Light reflects off of and refracts through cell walls from the surrounding air gaps between cells. Inside cells themselves the high change in the index of refraction from 1.33 for water to 1.00 for air causes an efficient internal reflection at the interface between cell walls and the surrounding air gaps. Also, inside cells light can Mie or Rayleigh scatter off of cell organelles which have sizes on the order of the wavelength of light. The overall reflectance and transmittance is a complex function of the cell size and shape and the size and shape of the air gaps between the cells (see, e.g., Govaerts et al. 1996). Because there is little absorption away from the chlorophyll and water absorption wavelength regions, light will eventually scatter out of the leaf at the top (reflection) or bottom (transmission).

3. Plants as an Earth Surface Biomarker

The red-edge spectroscopic feature is very strong for an individual plant leaf, at a factor of five or more. Averaged over a (spatially unresolved) hemisphere of Earth, however, the vegetation red-edge spectral feature is reduced from this high reflectivity down to a few percent. This is because of several effects including the forest canopy architecture, soil
characteristics, the non-continuous coverage of vegetation across Earth’s surface, and the presence of clouds which prevent viewing the surface. In addition the reflectance of vegetation is anisotropic and so the illumination conditions and viewing angle are important. Nevertheless at a signal of a few percent Earth’s vegetation red edge may be a viable surface biomarker to a distant, telescope-bearing civilization. The chlorophyll bump at 0.5 µm, however, is negligible in a hemispherically averaged spectrum. The spectral signature of oceanic vegetation or plankton is also unlikely to be detectable, due to strong absorption by particles in the water and also by the strong absorptive nature of liquid water beyond red wavelengths.

Using vegetation’s red edge as a surface biomarker is not a new idea. Early last century the high near-infrared reflection signature was used to test the hypothesis that the changing dark patches on Mars were due to seasonal changes of vegetation (Slipher 1924; Millman 1939; Tickhov 1947; Kuiper 1949). Not surprisingly, only negative results were obtained.

More recently Sagan et al. (1993) used the Galileo spacecraft for a “control experiment” to search for life on Earth using only conclusions derived from data and first principle assumptions. En route to Jupiter, the Galileo spacecraft used two gravitational assists at Earth (and one at Venus). During the December 1990 fly-by of Earth, the Galileo spacecraft took low-resolution spectra of different areas of Earth. In addition to finding “abundant gaseous oxygen and atmospheric methane in extreme thermodynamic disequilibrium”, Sagan et al. (1993) found “a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum” that “is inconsistent with all likely rock and soil types”. Observing ∼100 km² areas of Earth’s surface the vegetation red edge feature showed up as a reflectance increase of a factor of 2.5 between a band centered at 0.67 µm and one at 0.76 µm. In contrast there was no red-edge signature from non-vegetated areas.

A new area of extrasolar planet research is now emerging: using Earthshine to study the spatially unresolved Earth. Earthshine is light from the sun that has been scattered off of Earth onto the moon and then back to Earth. It appears as a faint glow on the otherwise dark part of the moon during the crescent phase, but can be studied with a CCD camera and specialized coronagraph even as the moon waxes (Good et al. 2001). Satellite data of Earth is not as useful as Earthshine because it is highly spatially resolved and limited to narrow spectral regions. Also, since most satellite data is collected by looking straight down at specific regions of Earth hemispherical flux integration with lines-of-sight through different atmospheric path lengths is not available. Recent spectral observations of Earthshine have tentatively detected the red-edge signature at the few percent level. Woolf et al. (2002) observed the setting crescent moon from Arizona which corresponds to Earth as viewed over the Pacific Ocean. Nevertheless their spectrum (Figure 2) shows a tantalizing rise just redward of 0.7 µm that is tentatively the spectroscopic red-edge feature. Figure 2 also shows other interesting features of Earth’s visible-wavelength spectrum, notably O₂ and H₂O absorption bands (note that that spectral lines of both O₂ and H₂O cut into the red-edge signature.) Arnold et al. (2002) have made observations of Earthshine on several different dates. With observations from France the Earthshine is from America and the Pacific Ocean (the evening moon) and Europe and Asia (the morning moon). After subtracting Earth’s spectrum to remove the contaminating atmospheric absorption bands they find a vegetation red edge signal of 4 to 10 %.
4. Temporal Variability to Detect Surface Biomarkers

A small but sharp spectral feature from a component of the planet’s surface should be more easily identified by temporal variation. As the continents rotate in and out of view, the planet’s reflectivity will change, causing a change in the measured spectrum. Recent Earthshine measurements have shown that detection of Earth’s vegetation-red edge is tricky due to smearing out by other atmospheric and surface features. Trying to identify such small features at unknown wavelengths in an extrasolar planet spectrum may be very difficult. We propose that such spectral features could be much more easily identified by the increased temporal variability at a carefully chosen color. In particular, any changes associated with a rotational period would be highly relevant. Since the wavelength of any surface biomarkers would not be known apriori, flexible data acquisition is essential. For example low-resolution spectra could be later integrated into narrow-band photometry of many different bands. Here we discuss simulations of Earth’s temporal variability, including preliminary calculations of Earth’s vegetation red-edge variability.

We model the photometric flux from a rotating Earth by a Monte Carlo code using a spherical map of Earth which specifies the scattering surface type at each point on the sphere and a set of wavelength-dependent bidirectional reflectance distribution functions which specify the probability of light incident from one direction to scatter into another direction for each type of scattering surface (see Ford et al. 2001 for details). We use a map of Earth from a one-square-degree satellite surface map that classifies each pixel as permanent ice, dirty/temporary ice, ocean, forest, brush, or desert. We consider cloudy models using the scattering properties of Earth clouds and we also include an approximation of atmospheric Rayleigh scattering. We focus our attention to quadrature (a
Figure 3. A light curve for a cloud-free Earth model for one rotation. The $x$-axis is time and the $y$-axis is the reflectivity normalized to a Lambert disk at a phase angle of 0°. The viewing geometry is shown by the Earth symbols, and a phase angle of 90° is used. Note that a different phase angle will affect the reflectivity due to a larger or smaller fraction of the disk being illuminated; because of the normalization the total reflectivity is $\ll 1$ in this case of phase angle of 90°. From top to bottom the curves correspond to wavelengths of 0.75, 0.65, 0.55, and 0.45 $\mu$m, and their differences reflect the wavelength-dependent albedo of different surface components. The noise in the light curve is due to Monte Carlo statistics in our calculations. The images below the light curve show the viewing geometry (cross-hatched region is not illuminated) and relative contributions from different parts of the disk (shading ranges from < 3% to > 40%, from white to black) superimposed on a map of the Earth. At time = 0.5 day, the Sahara desert is in view and causes a large peak in the light curve due to the reflectivity of sand which is especially high in the near-infrared (top curve).

phase angle of 90°) for which the planet-star separation is largest and the observational constraints thus least severe.

The existence of different surface features on a planet may be discernable at visible wavelengths as different surface features rotate in and out of view. Considering a cloud-free Earth, the diurnal flux variation caused by different surface features rotating in and out of view could be as high as 200% (Figure 3). This high flux variation is not only due to the high contrast in different surface components’ albedos, but also to the fact that a relatively small part of the visible hemisphere dominates the total flux from a spatially unresolved planet. Clouds interfere with surface visibility and in the presence of clouds the diurnal light curve shown in Figure 3 becomes that shown in Figure 4. It is very interesting to note that an extrasolar Earth-like planet certainly could have a lower cloud cover fraction than Earth’s 50% cloud cover. The cloud pattern and cover fraction are influenced by a variety of factors including the planet’s rotation rate, continental arrangement, obliquity, and presence of large bodies of water.

A time series of data in different colors (Figure 5) may help make it possible to detect a small but unusual spectral feature, even with variable atmospheric features. Most of Earth’s surface features, such as sand or ice, have a continuous increase or minimal change with wavelength, in contrast to the abrupt vegetation red edge spectral feature.
We have generated spectrophotometric variability of Earth by using theoretical spectra (for a cloudy and non-cloudy atmosphere from Traub (private communication) as included in (Des Marais et al. 2002)) modulated by our Earth rotational surface and cloud model. We use cloud data from the ISCCP database (Rossow & Schiffer 1991) such that the rotating Earth also has changing cloud patterns. We have chosen to integrate the spectrum into colors, the first \[\frac{I(0.75-0.8)-I(0.7-0.65)}{I(0.75-0.8)}\] chosen to emphasize variability of vegetation’s red edge and the second, for comparison, a color \[\frac{I(0.85-0.8)-I(0.75-0.8)}{I(0.75-0.8)}\], which is less sensitive to vegetation. Figure 4 shows that Earth is more variable in a color across the red edge than for colors with similar wavelength differences in other parts of Earth’s spectrum. For extrasolar planet measurements spectra or spectrophotometric data would be most useful in the form of a spectrum so that the photometric bands can be chosen after data acquisition.

5. Extrasolar Plants?

It is difficult to speculate on extrasolar plants and we will not do so here. Some might argue that the vegetation red edge differences among coniferous, deciduous, and desert plants are meaningful. However, all Earth vegetation has almost certainly evolved from the same ancestor and it is not a fair evolutionary experiment. Nevertheless a few interesting facts are suggestive and useful to those who wish to speculate on the possible existence extrasolar plants or light harvesting organisms:

- Plants absorb very efficiently throughout the UV and the visible wavelength regions
Figure 5. Variability of Earth’s color. The solid line shows a color \[ \frac{I(0.75-0.8)-I(0.70.65)}{I(0.75-0.8)} \] chosen to emphasize variability of vegetation’s red edge. For comparison, the dotted line shows a color \[ \frac{I(0.85-0.8)-I(0.75-0.8)}{I(0.75-0.8)} \], which is less sensitive to vegetation. These colors include theoretical spectra from Des Marais et al. 2002 modulated by our Earth rotational surface and cloud model. The cloud cover for the model in the left panel is from the ICSSP database from 17 August 1986 and in the right panel from 14 April 1986. Earth is more variable in the color sensitive to the red edge vegetation feature.

of the spectrum where the energy is required for photosynthesis (involving molecular electronic transitions):

- At sea level (after atmospheric extinction) the solar energy distribution peaks at 1 \( \mu \text{m} \) and approximately 50% of the energy is redward of 0.7 \( \mu \text{m} \);
- Plants reflect and transmit almost 100% of light in the wavelength region where the direct sunlight incident on plants has the bulk of its energy;
- Considering these last three points, Earth’s primary “light harvesting organism”, vegetation, has evolved to balance the competing requirements of absorption of sunlight at wavelengths appropriate for photosynthesis reactions with efficient reflectance at other wavelengths to avoid overheating (Gates et al. 1965);
- Other pigments involved in vegetation’s light harvesting process also absorb in the 0.44 \( \mu \text{m} \) wavelength regime (but only chlorophyll B absorbs near 0.68 \( \mu \text{m} \)). However, some other organisms have pigments that absorb at other wavelengths. For example, the light-harvesting pigments carotenoids and phycobilins are used by red algae.

6. Summary and Conclusions

The vegetation red edge spectroscopic feature is a factor of 5 or more change in reflection at \( \sim 0.7 \mu \text{m} \). This red edge feature is well-used in satellite remote sensing studies of Earth’s vegetation. Earthshine observations have been used to detect the vegetation red
edge signature in the spatially unresolved spectrum of Earth where it appears at the few percent level.

When discovered, observations of extrasolar Earth-like planets at wavelengths that penetrate to the planet’s surface will be very useful, especially for planets with much lower cloud cover than Earth’s 50%. A time series of spectra or broad-band photometry could reveal surface features of a spatially unresolved planet, including surface biomarkers. Earth’s hemispherically integrated vegetation red-edge signature is weak (a few to ten percent), but Earth-like planets with different rotation rates, obliquities, land-ocean fraction, and continental arrangement may well have lower cloud-cover.

While it is near impossible to speculate on spectral features of light harvesting organisms on extrasolar planets, flexible data acquisition will maximize scientific return. The detection of an unusual spectral signature that is inconsistent with any known atomic, molecular, or mineralogical signature would be fantastic. Combinations of unusual spectral features together with strong disequilibrium chemistry would be even more intriguing and would certainly motivate additional studies to better understand the prospects for such a planet to harbor life.

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