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The Earthshine observations: from climate change to Astrobiology

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Abstract

The earthshine observations on the dark side of the Moon provide us with the opportunity to study the light reflected to space by the Earth in a globally-integrated manner. Accurate measurements of this relected light and its variability in time and space have been very useful for the study of the readiative balance of the planet and its implications for global climate change, but also to the study of the fingerprints of the biomarkers that signal the presence of life on Earth from space. Of special interest is also the study of a particular type of earthsine, that which is observable during a lunar eclipe. Here we make a brief review of the earthshine observation carried out during the pase decades and what we have learned from them.

1 Introduction

Earthshine is sunlight that has reflected from the dayside Earth onto the dark side of the Moon and back again to Earth. The term *dark side* refers to the portion of the lunar surface that, at any instant, faces the Earth but not the Sun. Global albedo can be determined by measuring the earthshine's intensity relative to that of the moonshine (sunlight directly reflected from the Moon to Earth, i.e., the bright of the Moon) [27, 21]. Both, earthshine and moonshine, are transmitted through the same airmass just prior to detection and thus suffer the same extinction and imposed absorption features. Their ratio is the averaged reflection coefficient (or albedo) of the global atmosphere, the global atmosphere being defined as the portion of the dayside Earth simultaneously visible from the Sun and the Moon (Fig. 1).

Earth's global albedo, or reflectance, is an critical component of the global climate as this parameter, together with the solar constant, determines the amount of energy entering the Earth. However, a long-term, global albedo database does not exist. Earthshine observations can provide this globally-integrated measurements, to be used as input for global climate models.

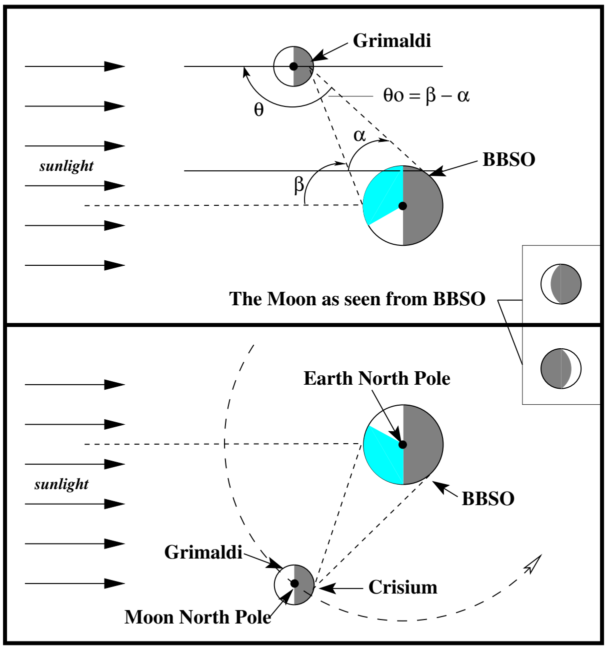

Figure 1: A cartoon describing the Earthshine geometry as viewed from a ground-based observatory (BBSO) when the Moon is waining and waxing. Adapted from [27].

At the same time, the earthshine measurements allow us to obtain a geographically-unresolved view of the Earth, as if the planet was observed from an astronomical distance. This view is useful to measure those properties that make the Earth distinct from other planetary bodies, that signal its major atmospheric constituents, and that signal to the presence of life in its surface.

2 The Earthshine and climate

The increasing global temperatures during the past century are generally assumed to derive primarily from increasing anthropogenic greenhouse gases in the atmosphere. While such gases modulate the earth's long-wave (infrared) emission, the earth's climate also depends on the net absorbed shortwave (SW) solar energy as quantified by the solar constant and the earth's albedo (the fraction of reflected sunlight). The solar constant is known to vary by only about 0.1% over the 11-year solar cycle, a variation widely regarded as insufficient to account for the present warming [17]. However, it is not unreasonable to expect that changes in the earth's climate would induce changes in the earth's albedo, and vice-versa. The earth's surface, atmospheric aerosols, and clouds all reflect some of the incoming solar radiation, preventing that energy from warming the planet. Any changes in these components would likely change the albedo, but would also induce climate feedbacks that complicate efforts to precisely assess causes and effects [5]. The last decades have seen some efforts to measure and monitor the earth's albedo from space with successful missions like ERBE or CERES.

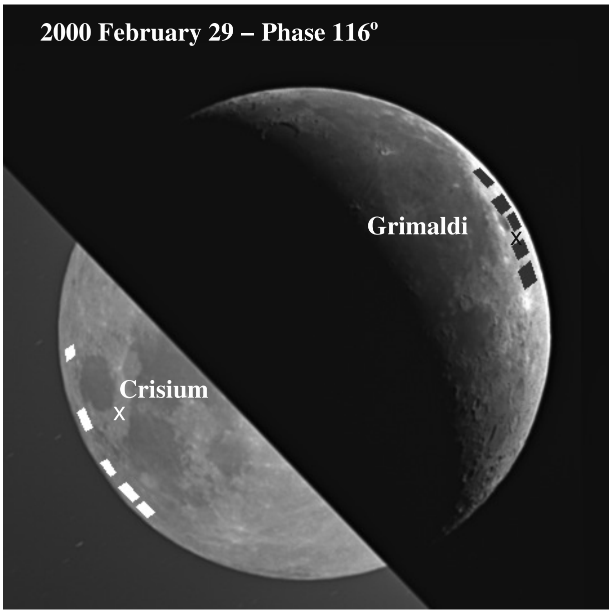

Figure 2: The moon showing the bright side and the earthshine. The Grimaldi side is in the moonshine and the Crisium side is in the earthshine. Our ten fiducial patches used in the observations made from BBSO are indicated. Unlike the moonshine, the earthshine is flat across the disk. The flatness is due to the uniform, incoherent back-scattering (non-Lambertian) in contrast to the forward scattering of sunlight occurring in the sunlit lunar crescent surface. Adapted from [27].

However, a continuous long-term record of the earth's albedo is difficult to obtain due to the complex inter-calibration of the various satellite data and the long temporal gaps in the series.

The earthshine provides information of the global variations in the Earth's albedo. Those variations can be explained by changes in the extent of cloud cover or the region of the Earth that is being illuminated during the observations. Continuous observations of this parameter by the earthshine technique makes possible to characterize the yearly and decadal change in albedo [27, 21]. To this end earthshine observations from Big Bear Solar Observatory (BBSO) in California, have been performed since November 1998 and continue to present, while slowly being extended to a global network [23].

From the brightness of the earthlit moon relative to the sunlit moon (approximately 10^{-4}), one can precisely determine the large-scale reflectance of the earth [13, 27, 21]. From each night of ES observations, we deduce a value of the earth's apparent albedo, p^*, with roughly 1% precision. This quantity depends upon the sun-earth-moon geometry (lunar phase angle), the geographical regions contributing to the ES (i.e., those portions of the earth simultaneously visible from the sun and moon), and upon the weather in those regions on that day (clouds, snow/ice, etc.). The apparent albedo can be understood as the earth's reflectance in one direction, while its average over all directions is the Bond albedo (roughly

0.3; [27]). Although we cannot determine a precise value of the Bond albedo on daily time scales [27], we can study its longer-term variation by averaging the daily anomalies, Δp^*, with respect to their mean (also roughly 0.3) at each lunar phase [21]. The variation in time of the p^* values during two nights caused by the Earth's rotation is shown in Fig. 2.

In [22], the earthshine measurements were correlated with satellite (ISCCP) observations of global cloud properties to construct from the latter a proxy measure of the earth's global shortwave reflectance. This proxy shows a steady decrease in the earth's reflectance from 1984 to 2000, with a strong drop during the 1990's. The subsequent two years of ES data ($2001 - 2002$) indicate a clear reversal of the decline. The net radiative forcing implied by these decadal changes in reflectance is climatologically significant. Since 2002 the Earth's albedo has remained mostly constant. Understanding how these changes are apportioned between natural variability, direct forcing, and feedbacks, is fundamental to confidently assessing and predicting climate change. Regular data collection of earthshine photometry continues at present from three stations, which are: BBSO, Izaña Observatory and Crimea National Observatory.

3 The Earthshine and astrobiology

In the last decades, more than 700 exoplanets have been detected outside the Solar System, while thousands of potential planet candidates from the Kepler mission are waiting to be confirmed. Even though most of these discovered exoplanets are gas giants, as larger planets are easier to detect than smaller rocky ones, evolving observational capabilities have already allowed us to discover tens of planets in the super-Earth mass range (e.g. [34, 7, 26, 3]), some of them probably lying within the habitable zone of their stars [3]. Moreover, some Earth-sized, and even smaller, exoplanets have already been reported in the literature [9, 20]. Indeed, the first statistics indicate that about 62% of the Milky Way stars may host a super-Earth [4]. Thus, one can confidently expect that true Earth analogues will be discovered in large numbers in the near future.

However, detection of such small rocky planets is only the first step; the characterization of their atmospheres and even the possibility of detecting the fingerprints of life will be next. Being able to answer all the questions that such complicated observations will raises requires experience in the study and interpretation of planet spectra. To be prepared for such future detections, the exploration of our own solar system and its planets is essential. This will allow us to test our theories and models, enabling more accurate determinations, and characterization of the exoplanets atmosphere and surface. In particular, observation of the solar system rocky planets, including Earth, will be key for the search for life elsewhere.

Over the last years a variety of studies, both observational and theoretical, to determine how the Earth would look like to an extrasolar observer have been carried out. One of the observational approaches has been to observe the Earthshine. It is, however, unlikely that, even if we were to find an Earth-twin, that planet will be at an evolutionary stage similar to the Earth today. On the contrary, extrasolar planets are expected to exhibit a wide range of ages and evolutionary stages. Because of this, it is of interest not only to use our own planet, as it is today, as an exemplar case, but also at different epochs [15], [28].

3.1 Photometry

In the future, large space observatories could directly detect the light scattered from rocky planets, but they would not be able to spatially resolve a planet's surface. Among other important physical properties, the identification of the rotation rate of an exoplanet with relatively high accuracy will be important for several reasons [16]. First, measuring the rotation rate can help to understand the formation mechanisms and dynamical evolution of extrasolar planetary systems [1], [6], [11]. For example, are planetary rotation periods smoothly varying as a function of the planet mass and semi-major axis, as would be expected if the planet's angular momentum is dominated by the gradual accretion of small planetesimals? Or are planet's rotation periods essentially uncorrelated with their mass and orbital properties, as would be the case if the planet's angular momentum is dominated by the late accretion of a few large impactors? The rotation periods of a sample of planets could be also directly compared to numerical simulations of planetary formation that track the spin evolution of planets, to probe the late stages of planetary accretion [29].

Using reflectance models and real cloud data from satellite observations, [24] showed that, despite Earth's dynamic weather patterns, the light scattered by the Earth to a hypothetical distant observer as a function of time contains sufficient information to accurately measure Earth's rotation period. This is because ocean currents and continents result in relatively stable averaged global cloud patterns. The accuracy of these measurements will vary with the viewing geometry and other observational constraints. If the rotation period can be measured with accuracy, data spanning several months could be coherently combined to obtain spectroscopic information about individual regions of the planetary surface. Moreover, deviations from a periodic signal can be used to infer the presence of relatively short-live structures in its atmosphere (i.e., clouds). This could provide a useful technique for recognizing exoplanets that have active weather systems, changing on a timescale comparable to their rotation. Such variability is likely to be related to the atmospheric temperature and pressure being near a phase transition and could support the possibility of liquid water on the planet's surface.

A precise determination of the rotation rate can also help improve our analysis of future direct detections of exoplanets, including photometric, spectroscopic, and potentially polarimetric observations [10, 32, 18, 35]. For practical viewing geometries, most of the light scattered by an Earth-like planet comes from a small portion of the planet, and contains information about weather patterns, surface features, i.e. lands and oceans. While even the most ambitious space telescopes will not be able to spatially resolve the surface of an extrasolar planet, the temporal variability contains information about regional surface and/or atmospheric features, possibly including localized biomarkers [8, 30, 19].

The changes in the earth's reflectance along historical geological eras of the Earth, as a function of continental distribution, cloud cover and surface type changes were analysed by [28]. We found that the changes from desert ground to microbial mats and to land plants, produce detectable changes in the globally-averaged Earth's reflectance that vary substantially

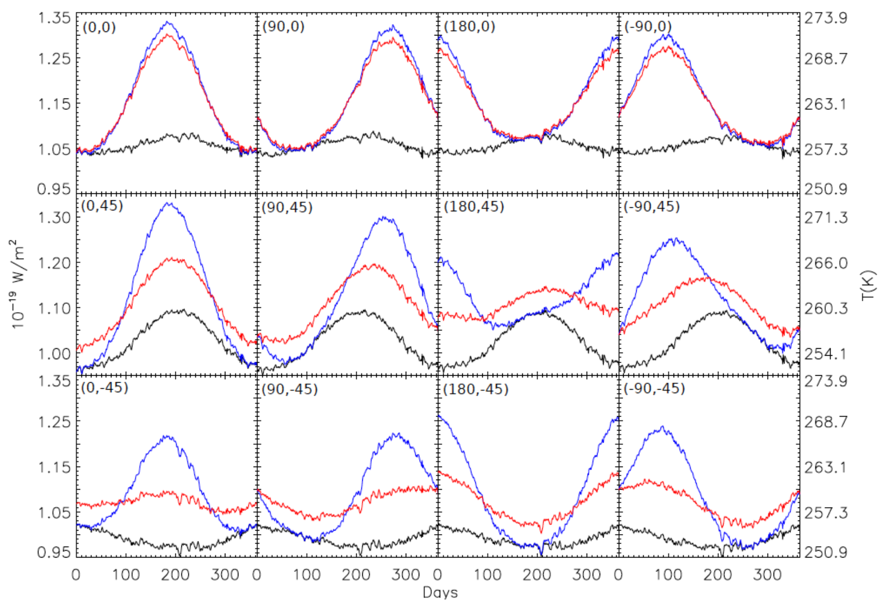

Figure 3: Earth+Moon mid-infrared emission light curves along one planetary orbit. From top to bottom, we place an observer at the Equator (top row), 45 N (second row), 45 S latitudes (bottom row). In column, the observer is located at 0 N, 90 E, 180 N, 90 W longitudes, respectively. The colors correspond to the lowest (red) and highest (blue) inclination angles for the Moon's orbit according to the observer's geometry, (the Moon's possible orbits are comprehended between the two). Adapted from [12].

as the Earth rotates. By binning the data into standard astronomical photometric bands it is readily seen that the variability of each surface type is located in different wavelengths and can induce reflectance changes of up to 40% in periods of hours. We concluded that usign photometric observations of an earth-like planet at selected photometric bands, it would be possible to discriminate between bare continental surfaces, large microbial mats extensions or land populated continents.

The wavelength coverage of the Earth's photometry and presented an analysis of the globally-integrated mid-infrared emission flux of the Earth based on observational data from satellite measurements was extended by [12]. They studied the annual, seasonal and rotational variability to determine which properties can be inferred from the point-like signal. They found that the analysis of the time series and light curves allows to determine the 24-hour rotational period of the planet for certain observer's geometries, although the effects of global-scale meteorology can effectively mask the rotation for several days at a time. They also found that orbital time series exhibit a seasonal modulation, which amplitude depends strongly on the latitude of the observer but weakly on its ecliptic longitude. As no systematic difference of brightness temperature is found between the day- and night-side, phase variations of the Earth in the infrared are insignificant and the phase variation of a spatially-unresolved Earth-Moon system are dominated by the lunar signal (see Fig. 3).

3.2 Spectroscopy

A series of missions will be launched over the next few decades that will be designed to detect and characterize extrasolar planets around nearby stars. These missions will search for habitable environments and signs of life (biosignatures) in planetary spectra. The visible spectrum of the Earthshine has been studied by several authors [36], [18] while more recent studies have extended these observations to the near-infrared [33] and to the near-UV [14]. Low-resolution intensity spectra of Earth's atmosphere obtained from space reveal strong signatures of life (biosignatures), such as molecular oxygen and methane with abundances far from chemical equilibrium.

Several authors have also attempted to measure the characteristics of the reflected spectrum and the enhancement of Earth's reflectance at 700 nm due to the presence of vegetation, known as red-edge directly [2, 19] and also by using simulations [32]. The difference in the intensity in the continuum between 680 and 740 nm is due to the high reflection at the reddest wavelengths caused by the presence of chlorophyll. The vegetation's "red edge" is often suggested as a tool in the search for life in terrestrial-like extrasolar planets. Through ground-based observations of the Earth's spectrum, satellite observations of clouds, and an advanced atmospheric radiative transfer code [19] determined the temporal evolution of the vegetation signature of Earth. They found a strong correlation between the evolution of the spectral intensity of the red edge and changes in the cloud-free vegetated area over the course of the observations.

A special case of earthshine illumination occurs durig a lunar eclipse. Hundred of the exoplanets discovered so far 'transit' the stellar disk, meaning that they can be detected through a periodic decrease in the flux of starlight. The light from the star passes through the atmosphere of the planet, and in a few cases the basic atmospheric composition of the planet can be estimated. As we get closer to finding analogues of Earth, an important consideration for the characterization of extrasolar planetary atmospheres is what the transmission spectrum of our planet looks like. [25] reported the first optical and near-infrared transmission spectrum of the Earth, obtained during a lunar eclipse (Fig. 4). Some biologically relevant atmospheric features that are weak in the reflection spectrum (such as ozone,molecular oxygen, water, carbon dioxide and methane) are much stronger in the transmission spectrum, and indeed stronger than predicted by modelling. They also found the 'fingerprints' of the Earths ionosphere and of the major atmospheric constituent, molecular nitrogen (N_2), which are missing in the reflection spectrum.

3.3 Polarimetry

While sunlight (and stellar ligh in general) is not polarized, the light passing through the Earth's atmosphere is strongly linearly polarized by scattering (from air molecules, aerosols and cloud particles) and by reflection (from oceans and land). Spectropolarimetric obser-

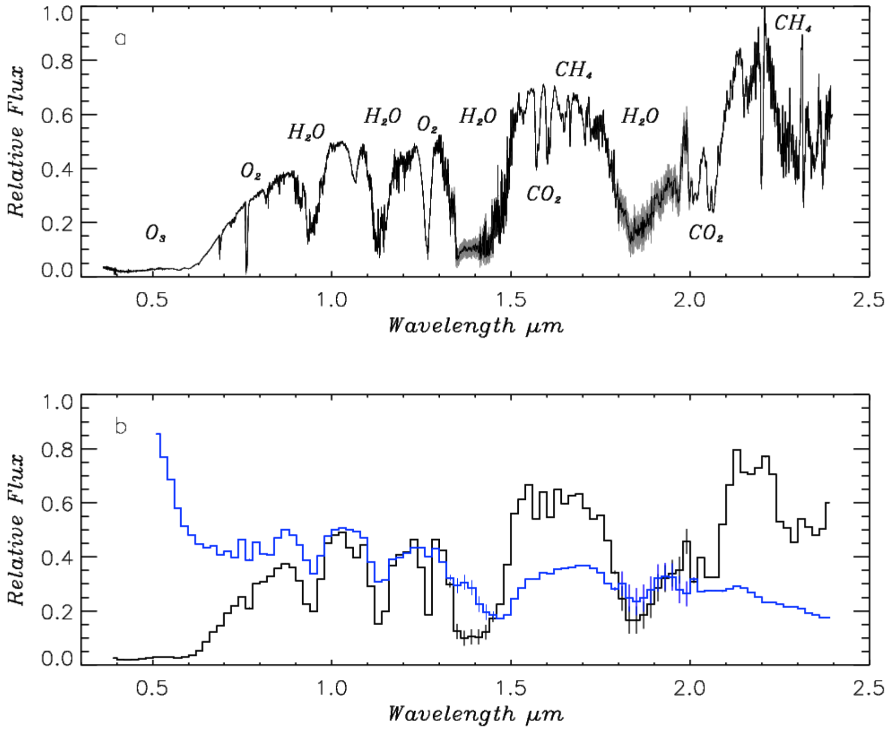

Figure 4: Earth's visible and near-infrared transmission and reflection spectra. The Earth's transmission spectrum is a proxy for Earth observations during a primary transit as seen beyond the Solar System, while the reflection spectrum is a proxy for the observations of Earth as an exoplanet by direct observation after removal of the Sun's spectral features. *Upper panel:* The transmission spectrum, with some of the major atmospheric constituents marked. *Lower panel:* A comparison between the Earth's transmission (black) and reflection (blue) spectra. Both spectra have been degraded to a spectral resolution of 0.02 mm and normalized at the same flux value at around 1.2 mm. It is readily seen from the figure that the reflection spectrum shows increased Rayleigh reflectance in the blue. It is also noticeable how most of the molecular spectral bands are weaker, and some non-existent, in the reflection spectrum. Adapted from [25].

vations of local patches of Earths sky light from the ground contain signatures of oxygen, ozone and water, and are used to characterize the properties of clouds and aerosols. When applied to exoplanets, ground-based spectropolarimetry can better constrain properties of atmospheres and surfaces than can standard intensity spectroscopy.

Very recently [31] measured the earthshine using spectro-polarimetric techniques. They reported the fist disk-integrated linear polarization spectra of Earth as a planet. The observations allow them to determine the fractional contribution of clouds and ocean surface, and were sensitive to visible areas of vegetation as small as 10%. These data represent a benchmark for the diagnostics of the atmospheric composition, mean cloud height and surfaces of earth and of exoplanets in the near future.

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