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The Earthshine Project: update on photometric and spectroscopic measurements

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Abstract

The Earthshine Project is a collaborative effort between Big Bear Solar Observatory (New Jersey Institute of Technology) and the California Institute of Technology. Our primary goal is the precise determination of a global and absolutely calibrated albedo of the Earth and the characterization of its synoptic, seasonal and inter-annual variability. Photometric observations of the Earth's reflectance have been regularly carried out during the past 4 years. The up-to-date synoptic, seasonal and long-term variation in the Earth's albedo are reported in this paper, together with a comparison to model albedos using modern cloud satellite data and Earth Radiation Budget Experiment scene models. The Earth's albedo has a major role in determining the Earth's climate. The possibility of a response of this parameter to solar activity is also discussed. Simultaneously, spectrometric observations of the earthshine have been carried out at Palomar Observatory. The main goals and first results of those observations are also presented.

Keywords: Albedo; Clouds; Earthshine; Photometric measurements; Spectrometric measurements

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1. The earthshine

Terrestrial measurements of the short-wavelength (visible and near-infrared light) albedo of a planet in our solar system is relatively straightforward except for the Earth. However, in principle we can determine the albedo from the ground by measuring the earthshine. The earthshine is the sunlight reflected from the bright side of the Earth to the Moon and finally back to an observer on the dark side of the Earth. At any moment, the earthshine can provide an instantaneous differential cross-section of the sunlight reflected from part of the Earth, see Fig. 1. Three fully-detailed papers on the earthshine data acquisition and analysis, albedo modeling and synoptic and long-term analysis have recently been published (Goode et al., 2001; Qiu et al., 2003; Pallé et al., 2003). In this manuscript our aims are to provide the reader with an overview of the Earthshine Project, along with its main results to date, and our plans for future development.

2. Photometric measurements

The earthshine and moonshine intensities are measured by integrating the brightness of a pair of fiducial patches – one from the bright side ("moonshine") and the other from the dark side ("earthshine") of the lunar disk. In our study, 10 physically fixed fiducial patches have been used with five in the earthshine and five in the moonshine, as seen in Fig. 2. A detailed description of the albedo measurement method is to be found in Qiu et al. (2003).

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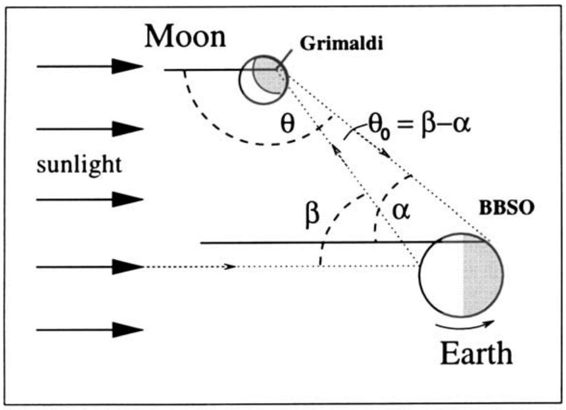

Fig. 1. A not-to-scale cartoon of the Sun–Earth–Moon system defining the Earth's topocentric phase angle, α, with respect to the observer. The plot also shows the Moon's selenographic phase angle, θ, with respect to one of the fiducial points (Grimaldi) used in the observations made from BBSO (also indicated). β is the angle between the sunlight that is incident somewhere on the Earth and reflected, as earthshine, to Grimaldi (the effective phase angle of the Earth as seen from the Moon). $\theta_0 (= \beta - \alpha)$ is the angle between the earthshine that is incident, and reflected from the Moon. The path of the earthshine is indicated by the arrows. θ_0 is of order 1°, or less.

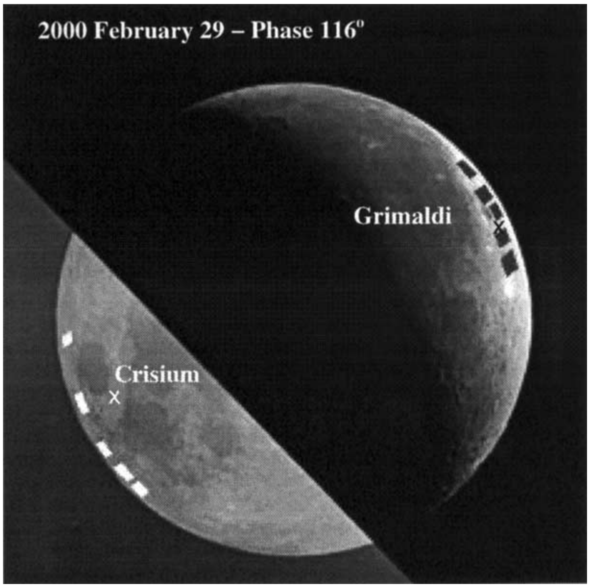

Fig. 2. The Moon showing the bright side and the earthshine. The Grimaldi side is in the moonshine and the Crisium side is in the earthshine. Our 10 fiducial patches used in the observations made from BBSO are indicated. In the image, the lunar phase is 115.9°, near a declining quarter Moon. The earthshine is flat across the disk due to the uniform, incoherent back-scattering (non-Lambertian).

The effective albedo is calculated from the earthshine measurements as:

$$A^*(\theta) = \frac{3}{2 f_{\mathrm{L}}} \frac{p_{\mathrm{b}} f_{\mathrm{b}}(\theta)}{p_{\mathrm{a}} f_{\mathrm{a}}(\theta_0)} \frac{I_{\mathrm{a}}/T_{\mathrm{a}}}{I_{\mathrm{b}}/T_{\mathrm{b}}} \frac{R_{\mathrm{em}}^2}{R_{\mathrm{e}}^2} \frac{R_{\mathrm{es}}^2}{R_{\mathrm{ms}}^2}, \tag{1}$$

where $\frac{I_{\mathrm{a}}/T_{\mathrm{a}}}{I_{\mathrm{b}}/T_{\mathrm{b}}}$ is the ratio of the earthshine intensity to the moonshine intensity in two opposing fiducial patches, after each is extrapolated to zero airmass, f_{L} is the Moon's lambert phase function, and R_{em}, R_{ms} and R_{e} are the distance Earth–Moon, distance Moon–Sun and the Earth's radius respectively. The factor 3/2 accounts for a simple proportionality between the geometrical albedo and the global Bond albedo (Qiu et al., 2003). The ratio between the physical reflectivity of the two opposing fiducial patches, $p_{\mathrm{b}}/p_{\mathrm{a}}$, is determined from the lunar eclipse data taken at Big Bear Solar Observatory (BBSO) on November 29, 1993. The lunar phase function for the bright side, $f_{\mathrm{b}}(\theta)$, is used in the formula to account for the geometrical dependence of the reflectivity of the Moon, while $f_{\mathrm{a}}(\theta_0)$ accounts for the fact that the earthshine is not exactly retroflected from the Moon $\theta_0 \lesssim 1°$. In our analysis, θ_0 is approximated as the angle between the observer's position and the mean of the sub-solar point (position on the Earth's surface of the solar zenith) and the sub-lunar point (position on the Earth's surface of the Moon's zenith) with the apex of the angle being defined with respect to the fiducial patch under consideration, see Fig. 1. We assume that the moonshine and earthshine have the same lunar phase function for each fiducial patch. Thus, we take $f_{\mathrm{a}}(\theta_0)$ from the appropriate moonshine phase function. The earthshine is slightly bluer than the moonshine because of Rayleigh scattering by the Earth's atmosphere. This small effect is subsumed in the lunar geometrical albedos.

To determine the Bond albedo, A, from our earthshine observations we need to integrate $A^*(\theta)$ over all phases of the Moon,

$$A = \frac{2}{3} \int_{-\pi}^{\pi} \mathrm{d}\theta A^*(\theta) f_{\mathrm{L}}(\theta) \sin\theta. \tag{2}$$

To calculate the value of this integration with enough precision, we need several nights of data for almost all phases of the Moon (above $|\pm 50°|$; Qiu et al., 2003), so we can only calculate useful mean albedos at monthly or yearly time scales.

3. The Earth's albedo

Continuous observation and monitoring of the earthshine have been carried out at Big Bear Solar Observatory since November 1998. At the same time we are combining nearly real-time satellite cloud data with Earth Radiation Budget Experiment (ERBE) scene models to simulate the earthshine variability.

We have calculated the average global albedo for the three complete years of data 1999, 2000 and 2001. More sporadic data are available during the years 1994 and 1995, for which a mean annual albedo has also been calculated, and allow us to take a longer-term look at our data. Albedo values are tabulated in Table 1 and represented in Fig. 3.

Table 1
Mean annual albedos for each of the years available in the earthshine record

Year	Mean albedo	SEM	% Error	Nights	GCR	Temperature	R_z
1994	0.316	0.005	1.6	44	4071	29.9	0.257
1995	0.319	0.007	2.2	29	4160	17.5	0.378
1999	0.297	0.003	1.0	117	4010	93.3	0.338
2000	0.310	0.003	1.1	105	3673	119.6	0.289
2001	0.306	0.003	1.1	89	3747	111.0	0.436
1994/1995	0.316	0.004	1.4	73			
1999/2001	0.301	0.002	0.6	311			

Also given are the standard deviation of the mean, the percentage deviation and the number of nights involved in each albedo determination. Mean values for the period 1994/1995 and 1999/2001 are also given. Note that a value of 0.006 has been added to all albedo in order to account for polar regions, Pallé et al. (2003). Mean annual values for the flux of galactic cosmic rays at Climax neutron monitor (in arbitrary units; ftp.ngdc.noaa.gov), the Zurich sunspot number and the global surface temperature anomalies from the Climatic Research Unit (www.cru.uea.ac.uk) are also tabulated.

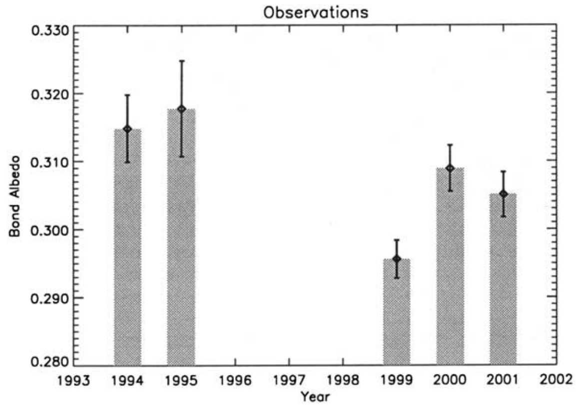

Fig. 3. The Earth's mean annual Bond albedo for each year in our observational earthshine record. The number of nights included in each year are tabulated in Table 1. Error bars represent ±1σ error from the mean.

The major change in albedo occurred between the early measurements and those that are the most recent. For the 1994/1995 period, we obtain a mean albedo of 0.310 ± 0.004, while for the more recent period, 1999/2001, the albedo is 0.295 ± 0.002. The combined difference in the mean A between the former and latter periods is of -0.015 ± 0.005, assuming the 1994/1995 and 1999/2001 uncertainties are independent. This corresponds to a $2 \pm 2\%$ decrease in the albedo between the two periods.

A second way to probe the changes in the Earth's albedo is by calculating the anomalies, see Pallé et al. (2003) for details of the anomaly calculations. In this procedure, 340 nights of observational data are averaged in time in bins containing 10 nights each to get a running average for this period. With this method, we cannot derive an absolute measurement of the Bond albedo, but rather we obtain a measurement of its variability. The anomaly plot for December 1998 through March 2002 is given in Fig. 4. From January 1999 onward, there are 268 nights for which we have both observations and contemporaneous satellite cloud cover data, which have also been averaged in 24 bins with 10 nights in each. The ×'s show the mean of the observations and the diamonds indicate the corresponding simulation results, with the vertical bars being the standard deviation of the mean. The size of the latter stems from the large night-to-night variations in the cloud cover, rather than from uncertainties in the observations. The horizontal bars indicate the temporal span of each average.

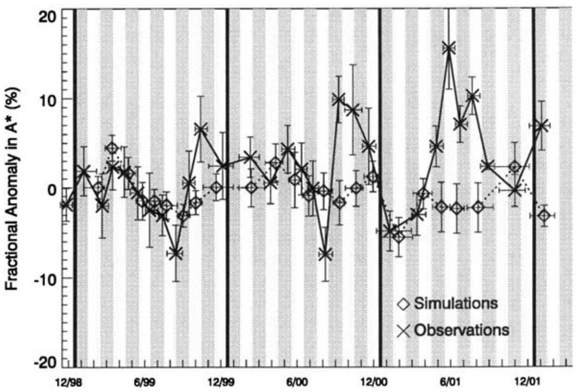

Fig. 4. Seasonal anomalies in the effective albedo, A^* with respect to the mean for 1999. See text for figure description.

In general, observations and simulations do not show a very good agreement, although the models have a much more muted seasonal variability due to the few scenes available for our model (Pallé et al., 2003). On average, the Earth is brighter in spring and winter – 2001 being an anomalous year in the observations.

4. Solar activity and Earth's albedo

Propositions have been made recently in the literature about a modulation of the Earth's albedo through solar activity and cosmic rays (Svensmark and Friis-Christensen, 1997; Pallé and Butler, 2002). At the present time, there is not a long enough sequence of earthshine data to confidently affirm or deny a physical connection between solar activity and the Earth's albedo. However the Earth's albedo seems to have been decreasing from 1994/1995 (a time of minimal solar activity) to 1999/2001 (a time of maximal solar activity). We note that this result implies a positive climate forcing, thus going in the same direction as the picture in which the Earth's albedo is lower when the cosmic ray flux is lower, i.e., times of high solar magnetic activity.

But is this result significant or correlated with the flux of galactic cosmic rays, the Zurich sunspot number (R_z) or the global mean temperature of the Earth? Although we have only five annual temporal points, a linear correlation analysis between the observed Bond albedo gives correlation coefficients of 0.34, −0.7 and −0.2, respectively. Thus, none reaches a 95% confidence level. Data is shown in Table 1.

We cannot confidently conclude whether the $5 \pm 2\%$ excess in the Bond albedo is a change tied to the systematic variation in solar activity, a spike in our record due to a relatively short-lived climate phenomenon like El Niño, an unaccounted calibration problem (the earlier observing scheme was different), or most probably some combination of the three. Nonetheless, suppose the difference in reflectance were tied to the cycle. The net sunlight reaching the Earth depends on the Sun's irradiance and the Earth's reflectance. It is generally agreed that a 0.1% variation in the solar irradiance over the activity cycle is too small to be climatologically significant, see Lean (1997) for a review. What about the Earth's reflectance? Taking the aforementioned albedo changes to be real, how significant would they be? To see the relative roles of varying solar irradiance and the varying reflectivity of the Earth in the change in the net input of sunlight to the climate system between a time of high solar activity (1999–2001) and one of low activity (1994–1995), we use:

$$P_{\mathrm{in}} = C\pi R_{\mathrm{e}}^2(1 - A), \tag{3}$$

where P_{in} is the power going into the climate system and C is the solar constant (1.37 kW/m^2) and, under the assumption that the A's scale with the A^*s, we find that

$$\frac{\delta P_{\mathrm{in}}}{P_{\mathrm{in}}} = \frac{\delta C}{C} - \frac{\delta A^*}{1 - A}, \tag{4}$$

where $\frac{\delta C}{C} \sim 0.001$. Our observations of the earthshine take the ratio of the earthshine to moonshine, so they are insensitive variations of the solar irradiance. The $5 \pm 2\%$ change in our observed reflectance translates to $\frac{-\delta A^*}{1-A^*} \sim 0.021 \pm 0.007$. Solar and terrestrial changes are in phase and contribute to a greater power going into the climate system at activity maximum. However, the effect of the albedo is more than an order of magnitude greater. Our simulations suggest a surface average forcing at the top of the atmosphere, coming only from changes in the albedo from 1994/1995 to 1999/2001, of 2.7 ± 1.4 W/m^2 (Pallé et al., 2003), while observations give 7.5 ± 2.4 W/m^2. The Intergovernmental Panel on Climate Change (IPCC, 1995) argues for a comparably sized 2.4 W/m^2 increase in forcing, which is attributed to greenhouse gas forcing since 1850.

Still,whether the Earth's reflectance varies with the solar cycle is a matter of controversy, but regardless of its origin, if it were real, such a change in the net sunlight reaching the Earth would be very significant for the climate system.

5. Spectral campaigns

Since September 1999, regular spectroscopic observations of the earthshine and the moonshine in the visible range, have been taken with the 60″ echelle spectrograph at Palomar Observatory.

Moonshine spectra contain information on the local atmospheric conditions while earthshine images contain information from both the local and global atmosphere. The spectral ratio between the two is given by

$$\frac{P_{\mathrm{e}}(\lambda)}{P_{\mathrm{m}}(\lambda)} = \frac{P_{0\mathrm{e}}A_{\mathrm{e}}\mathrm{e}^{\alpha_{\mathrm{e}}m_{\mathrm{e}}}}{P_{0\mathrm{m}}\mathrm{e}^{\alpha_{\mathrm{m}}m_{\mathrm{m}}}} + A_{\mathrm{e}}(\lambda), \tag{5}$$

where P is the observed, P_0 is the intensity at zero airmass, α is the extinction coefficient and m is the airmass. The subscript e and m indicate earthshine and moonshine, respectively. At each spectral point, $\alpha_{\mathrm{e}} = \alpha_{\mathrm{m}}$ and we take the images close enough in time so that the difference between m_{e} and m_{m} can be ignored. For the normalized (to continuum) spectra, P_0 is 1 at each

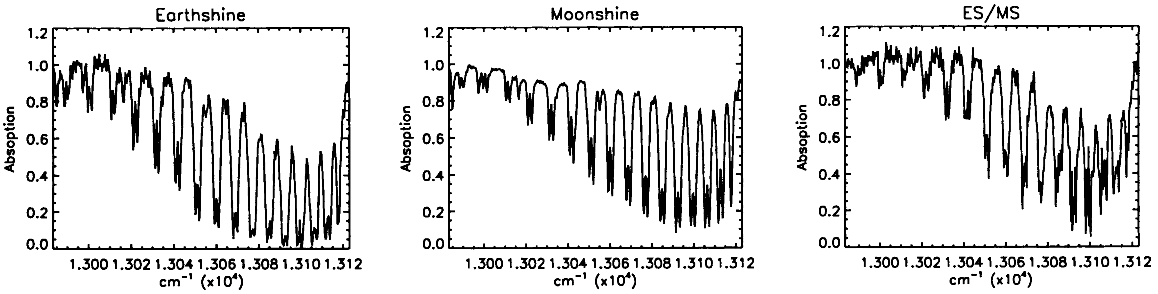

Fig. 5. Figure shows an O_2 molecular band for the earthshine, moonshine and the ratio between the two. The spectra were taken in September 4th 1999. Moonshine and earthshine spectra have been flatfielded, bias and sky subtracted, and normalized to exposure time 1 s. Spectral resolution along the H_2O band is ≈0.2 Å.

spectral point, but for the earthshine light, A_e is dependent of wavelength, and describes the global atmospheric attenuation.

Through our spectroscopic measurements we are hoping to retrieve information on the average column densities of several species like H_2O, O_2, CO_2, and CH_4 among others. In Fig. 5, the earthshine, moonshine and ratio spectra for the O_2 molecule are represented.

A more detailed discussion on the earthshine spectral campaigns and the first results can be found in the paper published in this same volume by Montañés Rodriguez et al. (2003).

6. Earthshine future

Routine monitoring observations, both photometric and spectrometric, of the earthshine will continue in the coming years. We are currently building a web of manual telescopes, to be deployed at regular longitude intervals over the Earth surface, providing continuous global coverage of the earthshine. Our mean annual albedo determination precision is now around 1%, and the uncertainty in the albedo determination strongly depends on the number of nights for which we have data. In this sense, we expect that increasing the number of earthshine stations will significantly reduce this uncertainty. The fact that the morning and evening earthshine measurements are almost identical (Qiu et al., 2003) suggests that data from different stations may be easily combined to derive a 24-h, annual Bond albedo with a precision far better than a percent, and monthly albedos with a precision closer to a percent.

Because of our existing precision, and the prospects of increasing it in the near future, we are hoping to detect and characterize, if it exists, any possible solar influence on the Earth's reflectance by tracking its variability through the coming decreasing phase of the current solar cycle.

7. Overall

Traditionally the Earth's albedo has been considered as a roughly invariant parameter in global circulation models and climate studies. With the earthshine project, we have shown how, on the contrary, the Earth's albedo is quite a variable parameter for which a detailed study of its seasonality, long-term variability and climate implications need to be carefully undertaken, if we are to fully understand the present changes in the Earth's climate.

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