

## **Earthshine, Cloudiness and Galactic Cosmic Rays**

Philip R. Goode (PI), Enric Pallé, Pilar Montañés-Rodríguez, Jiong Qiu

New Jersey Institute of Technology  
Center for Solar-Terrestrial Research  
Big Bear Solar Observatory  
and  
Instituto de Astrofísica de Canarias  
Tenerife, Spain  
and  
Montana State University  
Department of Physics

## Proposal Summary

The Earth's albedo has been measured from space for a quarter century using carefully calibrated data from weather satellites (International Satellite Cloud Climate Project - ISCCP), from the ground for more than a decade (Project Earthshine) and over more recent years from satellites like CERES. Changing cloudiness is the dominant factor in terrestrial reflectance variability - a critical climate parameter. New generation cloud data products, such as the ISCCP-FD, open the opportunity to fundamentally advance inter-comparisons among cloud data, so that at last we can determine the true role of galactic cosmic rays (GCRs) in the evolution of cloud cover, and their effect on the Earth's reflectance and climate. At the same time, the inter/comparison of multiple datasets may solve the inconsistencies among the albedo data, such as those between ISCCP-FD and CERES measures of global albedo changes.

We propose to examine and model earthshine data from our two station robotic network (Big Bear, CA and Tenerife and Canary Islands) to compare and calibrate with cloud cover data from satellites to determine the evolution in cloud cover as a function of altitude through an entire solar cycle of GCRs. It is essential to know the relative roles of such changes in the terrestrial energy balance compared to other natural and anthropogenic influences.

The Earth's reflectance is the least well-known of the fundamental climate parameters. Long-term, precise cloud/albedo data verified from a multiplicity of sources are essential in understanding the role of solar-cycle length variations in GCRs in terrestrial cloud properties. Our principal scientific objectives in contributing the team effort to understand the possible role of GCRs in cloudiness are:

1. We propose to continue our decade-long, photometric observations of the earthshine from Big Bear Solar Observatory (BBSO), which led to the first modern reporting of the Earth's albedo (Goode et al. 2001) in the literature. We further have expanded these observations to a two station robotic global network, which is funded from non-NASA sources. Photometric earthshine data are critical in our efforts to determine the relationship between a varying terrestrial albedo and a variable Sun. For this we need

a precise determination of the reflection of the Earth in all directions, the Bond albedo. From a single site, we can reliably determine the Bond albedo for large parts of the Earth as an annual average. The second robot in the Canary Islands gives us the ability to cover all regions of the Earth, except the poles. For this project, annual albedo averages from earthshine are/will be appropriate for comparison with the solar cycle dependent GCRs, as well as disentangling the irradiance from the net sunlight reaching Earth.

2. We propose to sharpen and exploit the empirical connection of the earthshine observations to cloud cover data from the International Satellite Cloud Climatology Project (ISCCP), which will significantly improve our understanding of cloudiness, and aid our efforts to determine the connection between the solar output, GCRs and the net sunlight reaching us on Earth (solar irradiance plus any indirect solar effects on the Earth's reflectance). Parallel to this effort, we will improve our simulations to include more sophisticated models of the terrestrial scenes, while incorporating more cloud parameters, and their altitude dependence, from ISCCP. The improved models will be valuable accounting for uneven sampling, as though earthshine observations were continuous. An ultimate goal is to learn the origin of the terrestrial signature of the solar cycle, and the usefulness of the various solar wind parameters, and their indirect effects like modulated GCRs, as proxies for the net sunlight reaching Earth.
3. We propose to facilitate a determination of the true role of GCRs in cloudiness, with an in-depth temporal/geographical comparison of the earthshine measurements with several datasets related to albedo retrieved from satellite platforms, such as ISCCP-FD, CERES, ERBE, TOMS and GOME. These comparisons will shed more light on the true nature of albedo variations, and associated cloudiness changes.

## A. Results from NASA Support

### A.1 Overview of the Earthshine Project

Earth’s global albedo, or reflectance, is a critical component of the global climate as this parameter, together with the solar constant, determines the amount of energy coming to Earth. Probably because of the lack of reliable data, traditionally, the Earth’s albedo has been considered to be roughly constant, or studied theoretically as a feedback mechanism in response to a change in climate. However, over the past decade several studies have shown large decadal variability in the Earth’s reflectance, which derives largely from changes in “cloudiness” (e.g., cloud amount, cloud thickness and location, etc.). To know the role of Earth-impacting galactic cosmic rays (GCRs) in changing the terrestrial albedo, it is absolutely essential to have reliable measurements of the evolution of the reflectance. The flux of GCRs is anti-correlated with the solar cycle. More broadly, **disentangling the Sun’s output from terrestrial reflectance is essential to meet the LWS TR&T goal “to deliver the understanding of how and to what degree variations in the solar radiative and particulate output contribute to changes in global and regional climate over a wide range of time scales”**.

Variations in the solar irradiance have been precisely measured for more than a quarter century combining observations from various satellites, and it appears that the Sun’s irradiance has climatologically insignificant variations over the solar cycle. So, why are there terrestrial signatures of the solar cycle in climate records? If the recent irradiance variations are typical, the logical effect to search for is corresponding, or even amplified, solar-driven changes in the much less well-studied reflectance of the Earth, which is the “other” component of the net sunlight reaching us. And here is where GCRs come into play. *Under NASA support, we have been almost continuously observing the earthshine from Big Bear since 1998 (with data covering 1994-5, as well) to determine the Earth’s reflectance and its variations. We propose here to continue, and have expanded our more than a decade of earthshine observations from Big Bear Solar Observatory (BBSO) to a two-station global network (a second robotic telescope on Tenerife in the Canaries, which was built and deployed from separate funding and is operated by the Insti-*

*tuto Astrofisica de Canarias). Corroborating observations of the Earth’s reflectance from several independent approaches have great value here. We propose to use earthshine measurements and improve models of terrestrial reflectance to address the LWS/TRT Focused Science Topic concerning the **Robust examination of the observations to quantify the relative influence of GCR precipitation on cloud cover.** Our results provide an essential complement to satellite derived reflectance, as from CERES (Clouds and Earth’s Radiant Energy System) and ISCCP-FD (the International Satellite Cloud Climatology Project recently released its “FD” product, which estimates the top of the atmosphere reflectance). As part of the comparison, we further propose to sharpen our simulations (with more sophisticated treatments of cloud properties, especially including their altitude dependence, and terrestrial scenes using satellite data) of the earthshine to uniquely determine the Earth’s reflectance, and its variability. We plan to observe for an entire solar cycle with our global network of earthshine telescopes. The earthshine, or “ashen light” is sunlight reflected from the Earth and retro-reflected from the Moon to the nighttime Earth. See the schematic in Figure 1.*

In “Astrophysics in 2001” by Trimble and Aschwanden (2002), they remarked about our earthshine observations saying that this “type of lunar-geo-solar observations is one of the rare interdisciplinary examples that naturally fulfills all requirements for NASA funding, for originality of astronomical research to direct benefits for humankind”.

### A.2 The Albedo Problem

A long term global albedo database does not exist even though it is essential to learn the role of GCR flux change in the variation of the Earth’s reflectance. Direct measurements of the Earth’s albedo did not start until the 1980’s. Among them are the earthshine measurements. Pallé et al (2004a) correlated the earthshine data with ISCCP cloud data to construct from the latter a proxy record of the Earth’s reflectance. They showed from that proxy for the Earth’s albedo decreased by about  $6 \text{ W/m}^2$  from 1985 to 2000, while direct earthshine observations from 1999-2003 revealed that the decline had stopped and even reversed to an increasing trend in reflectance. The ISCCP project however, recently released the FD

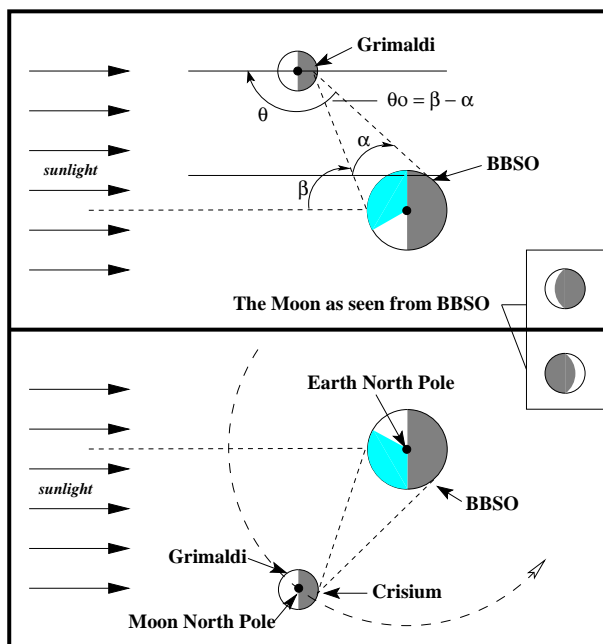


Figure 1: A not-to-scale cartoon of the Sun-Earth-Moon system viewed from the pole of Earth’s orbit. In the top panel, the Earth’s topocentric phase angle,  $\alpha$ , with respect to BBSO is defined. The plot also shows the Moon’s selenographic phase angle,  $\theta$ , with respect to one of the fiducial points (Grimaldi) used in the observations made from BBSO (also indicated).  $\beta$  is the angle between the sunlight that is incident somewhere on the Earth and reflected, as earthshine, to Grimaldi.  $\theta_0 (= \beta - \alpha)$  is the angle between the earthshine that is incident, and reflected from the Moon. The path of the earthshine is indicated by the broken lines.  $\theta_0$  is of order  $1^\circ$ , or less. In the lower panel, the same diagram is drawn for a negative lunar phase angle, and extra features like the Moon’s orbit around the Earth are indicated. In both panels the aspect of the Moon as would be seen from BBSO is also indicated in a box, where the bright crescent is also called “moonshine”. The cyan areas of the Earth indicate the approximate longitudinal range that contributes to the earthshine. Note how for positive lunar phases (top panel) the earthshine contribution comes from longitudes east of BBSO, while for negative phases (lower panel) angles it comes from longitudes west of BBSO. The collection and analysis of earthshine data are detailed in Qiu et al. (2003) and Pallé et al. (2003).

product, which contain estimates of the top of the atmosphere (TOA) albedo. These data are based on ISCCP cloud properties, plus some modeling estimates to derive shortwave and longwave fluxes, and they indicate a much more muted long-term variability from 1983 to 2000. A more apparent difference of opposing trends between albedo estimates was found between the earthshine data and the CERES dataset over the period 2000-2003 (Wielicki et al, 2005). However, when compared to other direct or indirect albedo indicators, a simple answer as to how did the global albedo behaves did not emerge (Pallé et al, 2005b). In the meantime, data collection has continued, and in the past couple of years, all datasets in the aforementioned literature have been re-calibrated and/or re-analyzed, so Pallé, Goode and Montañés-Rodríguez (2008) made a new comparison, which also benefits from a longer time line and found that most of the discrepancies disappear, but what emerges is quite germane for the topic at hand.

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). Continuous earthshine observations from Big Bear Solar Observatory (BBSO) in California, have been performed from November 1998 to October 2005 (7 complete years). Earthshine data collection stopped for a period of eight months, from November 2005 to July 2006, due to the refurbishment of the Big Bear dome for the new solar telescope. When observations were resumed in mid-2006, two telescopes were used simultaneously, the old manual telescope and a new improved, robotic telescope, the first of a global network (see Pallé et al, 2005a). The second robotic telescope was calibrated under the same dome against the first robot for several months in 2007. A identical dome was assembled atop Roque de Muchachos on Tenerife and the robotic clone deployed.

When we compared data from the original earthshine telescope to the first robotic telescope, we found that the new telescope data were superior (an improved design led to cleaner data that is somewhat less noisy within a night and enabled coverage of a slightly broader range of lunar phases) to the same night data of the older telescope. The improved precision plus the temporal length of the data staring motivated us to implement a more systematic way to select “good

nights”. We did this by plotting the nightly albedos as a function of lunar phase, and making fits that were  $\pm 3\sigma$  from the fit to the data. Outliers were cast out and the process repeated until it converged (after about five iterations). This had the consequence of systematically casting out about 10% of the nights, which is only a few percent more than were cast out in our old, night-by-night evaluation. The systematic approach is robust in the sense that it is reasonably insensitive to varying how tight we make the fit in iterative process of casting out relatively poorer nights. Implementing the automated selection process had its most apparent impact on the earthshine annual anomaly trend in reducing the size of the large 2003 albedo anomaly (Pallé et al, 2004a), although the result for each year changed a little. The new annual mean anomalies are compared in Figure 2 to those published in earlier papers. Over the 1999-2007 period, there is an increasing reflectance trend from 1999 to 2003, but after that year the reflectance does not seem to vary. In fact, except for 2003, the Earth’s reflectance as measured by earthshine has not changed since 2001. These data also imply a more modest trend than the old 1999-2003 data analysis suggested (Pallé et al., 2004a). Over the common period of 1999-2004, the new analysis of the earthshine data indicates an increase of about  $2 W/m^2$ , which is about half what the earlier analysis indicated.

The old earthshine analysis shown in black in the top panel of Figure 2 were found to be in strong contradiction to TOA albedo anomalies as measured by the CERES instruments onboard the Terra and Aqua satellite (Wielicki et al, 2005). These data showed a decreasing trend of  $2W/m^2$  over a period of just 4 years. However, since the publication of the earlier results, a calibration error in one of the SW filter was identified and the CERES TOA albedo anomalies have been re-analyzed using an improved six year-long climatology (Takmeng Wong, private communication). As a result, the improved TOA CERES dataset do not show any trend in reflectance over the 2000-2006 period. See the lower panel of Figure 2.

Of course, the reduced disagreement between earthshine and CERES is good news, but a new ISCCP product, ISCCP-FD, sheds additional light on our understanding of albedo evolution. To illustrate, we show the albedo estimates at the top of the atmo-

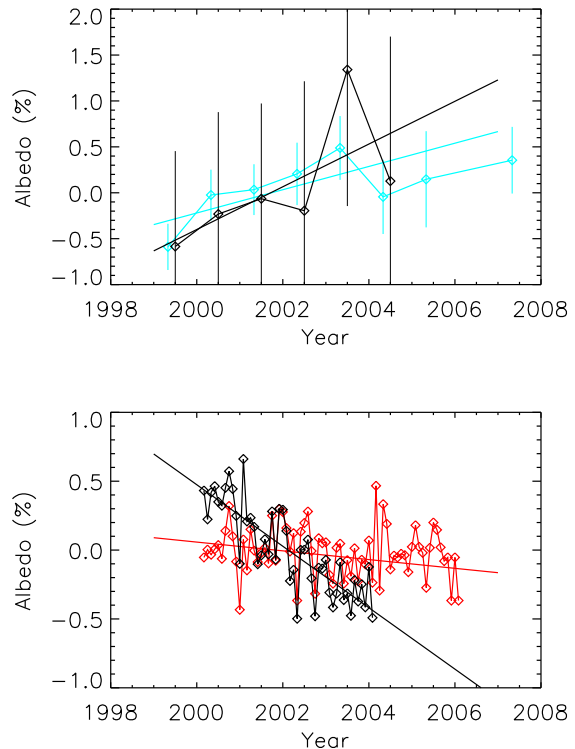


Figure 2: Top: Inter-annual Earth albedo anomalies as measured by earthshine. In black are the albedo anomalies published in 2004, following Pallé et al. (2004), and in blue are the updated albedo anomalies after our improved data analysis, which also included more years of data. Bottom: Inter-annual Earth albedo anomalies as measured by CERES. In black are the albedo anomalies published in 2005, following Wielicki et al. (2005), and in red are the updated albedo anomalies after their improved re-calibration of the on-board sensors (Loeb et al., 2007). To evaluate the recalibration effects, a linear fit is applied to both datasets within each panel using only the data over the common period of 2000-2004. For both, Earthshine and CERES, the linear fit to the full dataset up to 2006 would not differ much.

sphere (TOA) from the ISCCP FD dataset<sup>1</sup> (Zhang et al, 2004). These data have recently been extended and cover the period from July 1983 to December 2006. In the following discussion, we make use of these improved datasets shown in Figure 2, together with TOA albedo estimates from ISCCP FD data (the longest available albedo dataset) to compare results from the different observing methodologies. (???) SAME PARTS OF THE EARTH COVERED???)

The inter-annual changes in the Earth's albedo from the three datasets is plotted in Figure 3. The top panel in the Figures shows the 25-year period from 1983 to 2007, for which ISCCP FD data are available. Earthshine data are also plotted showing a strong agreement with ISCCP FD estimates. In the lower panel, the temporal scale is truncated to the more recent period 1999-2007, for which earthshine and CERES observations (starting March 2000) are available. Here the agreement between datasets is closer between the earthshine and CERES data than with FD. It is apparent that the agreement between CERES and earthshine data show a dramatic improvement after both datasets have been re-calibrated, and essentially agree within the error bars for 2000-2006. Now, over the common period of data 2000-2007, both datasets show no overall significant changes in Earth's reflectance. While the de-seasonalized CERES data has a small year to year variability (Figure 3), the earthshine data seem to present overly large inter-annual anomalies, along with relatively large error bars being associated with the yearly means. This is mostly due to sampling issues, as earthshine measurements were taken from a single station. However the accuracy of the earthshine data will be improved by the deployment of second earthshine station in the Canaries (Pallé et al, 2005a).

It seems clear from Figure 3 that there is an overall agreement between the earthshine measurements and the FD TOA albedos, which begins to breakdown from 2005 onwards. During 2005 and 2006, FD data indicate an increase in albedo that is not seen either in Earthshine or CERES data. Some authors (Campbell, 2004) have questioned the stability of the long-term calibration in the ISCCP data, so that deviation at the end of the time string might be a calibration bias. Interestingly, over the two-year period 1999-2000, both earthshine and FD data show an increase in reflectance, with very consistent magnitudes. The

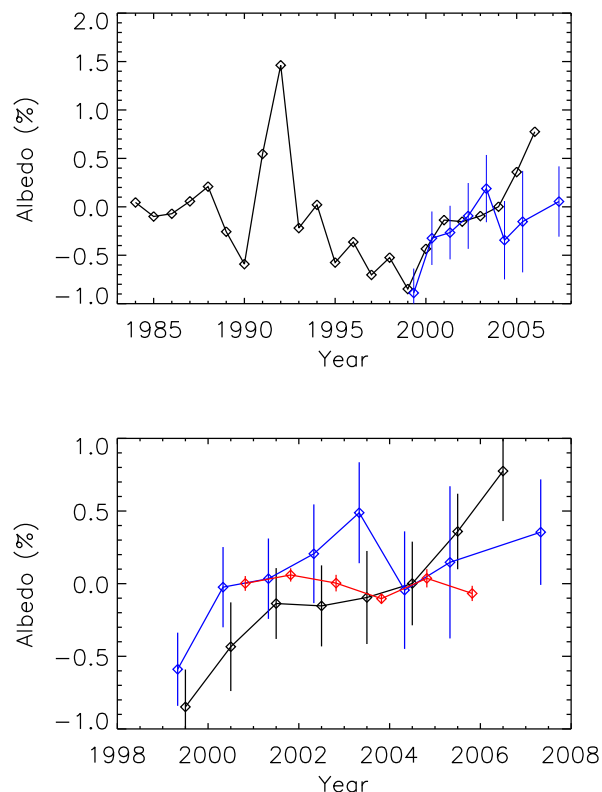


Figure 3: Top panel: Annual mean Earth albedo anomalies, as derived from ISCCP FD data, over the period 1984-2006 are plotted in black (the big bump in the early 1990's is a result of the Mt. Pinatubo eruption). Also plotted in blue are the annual mean anomalies measured by earthshine (note that annual means are only plotted for the years with complete data coverage). Bottom panel: Annual mean albedo anomalies, as derived from ISCCP FD (black), earthshine observations (blue) and CERES data (red). For the earthshine data, annual means are calculated from November to October to take advantage of the full database (see main text). For the CERES data, deseasonalized anomalies are used, which reduces the size of the error bars. However, it is worth noting that the scatter of the CERES points in the lower panel of Figure 2 is comparable to the error bars of the ISCCP FD and earthshine points in the lower panel of this figure.

<sup>1</sup><http://isccp.giss.nasa.gov>

agreements between the two datasets suggests that the change is real, but there were no CERES data to confirm the measurements. The rise in reflectance is climatologically significant, since the increased albedo seems to persist for several years.

*Both the agreements and disagreements motivate continuing all measurements of albedo. Before CERES, ISCCP-FD and earthshine indicate a climatologically significant rise in terrestrial reflectance. However, during the time of CERES all three show a basically flat albedo until ISCCP-FD shows a second growth spurt. Thus, each set of measurements taken in isolation would lead one to different conclusions about what the albedo, and hence the clouds are doing.*

### A.3 Clouds and Earth’s Albedo

Pallé et al. (2006) used recently released ISCCP global cloud data covering 2001-2005 clarify the evolution of the albedo. These data show that the cloud amount (CA) increased by 2-3% from 2000-2004. Curiously, the ISCCP CA shows a solar cycle-like sinusoidal behavior (although it doesn’t seem to correlate with any standard solar activity index, but it bears further study) over the last twenty years (see the upper panel in Figure 4), with a decline in all cloud types from the late 1980’s through the late 1990’s; the total then begins increasing in about 2000. However, low clouds continued to decrease post-2000, while mid and high clouds increased. In the lower panel of Figure 4 (from Pallé et al. 2006), the globally averaged CA was divided into low ( $p > 680mb$ ) and mid combined with high ( $p < 680mb$ ) cloud types and averaged in five-year bins. The difference in CA between mid plus high lying clouds and low lying clouds remains around 7-8% from 1985 to 1999, but almost doubles (13%) over the most recent five year bin (see lower panel of Figure 4). Under current NASA/LWS support, Pallé et al. (2006) pointed out that this shift toward high cloud types decreases the negative cloud forcing. In this way, the turn of the century increase in albedo, consistent with the increase in cloud amount, is not necessarily inconsistent with the observed global temperatures. After all, clouds have two opposing effects on the Earth’s radiation budget: they reflect shortwave radiation (a negative forcing that cools the planet), and they trap infrared/heat radiation (a positive forcing). The net cloud radia-

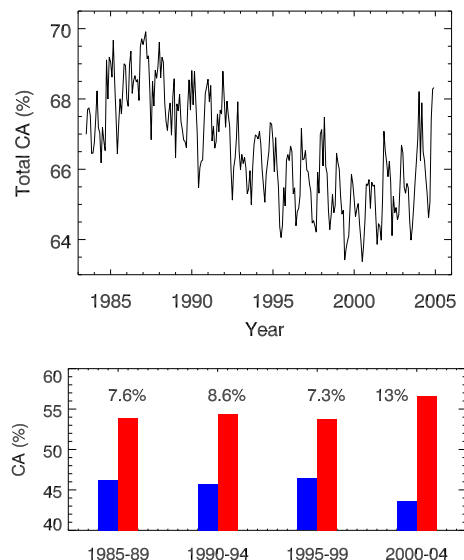


Figure 4: Upper Panel: Globally-averaged monthly mean total cloud amount from the ISCCP data. The overall decrease in cloud amount from 1985 to 2000 is about 4-5% with a recovery of about 2-3% from 2000 to 2004. Lower Panel: Globally-averaged 5-year mean low (blue) and mid+high (red) cloud amounts. The difference in percent between low and mid+high cloud amounts is also given on top of each of the four 5-year intervals. Note the near doubling of this difference over the 2000-2004 period with respect to the previous means.

tive forcing is about  $-13 W/m^2$  (Ramanathan et al., 1989), but various cloud types contribute differently: optically thick low-lying clouds have a strong cooling effect, while high thin cirrus clouds warm. Thus, it seems that under the right circumstances either an increase or decrease in albedo can lead to higher temperatures. This explanation might present the most consistent picture for all of the datasets, but it remains a mystery as to why the distribution of clouds changed. Further, it gives caution to inferring changes in net radiative forcing from shortwave data alone (e.g., the global dimming and subsequent global brightening seen in ground-based data). This motivates adding clouds as a function of altitude into the scene models we have been using, rather than only including total cloud amount to connect clouds to albedo.

Finally, beyond our simple models, accounting for such variations in global climate models is essential to understanding and predicting climate change, including the role of GCRs..

#### A.4 Publications Under NASA/LWS Support

Our principal papers supported by NASA/LWS over the last three years, up to Summer 2008, are listed below. As well, already in 2006-8, members of the group have given invited reviews at the AGU and COSPAR General Assemblies.

Earthshine and inter-annual trends in earth's reflectance 1999-2004, E. Pallé, P. Montañés-Rodríguez, P.R. Goode, *Journal of Geophysical Research*, 2007, submitted.

Measurements of the surface brightness of the earthshine with applications to calibrate lunar flashes, E. Pallé, P. Montañés-Rodríguez, P.R. Goode, *Astron.J*, 2007, 134, 1145, 2007.

Shortwave forcing of the Earth's climate: modern and historical variations in the Sun's irradiance and the Earth's reflectance, P.R. Goode, E. Pallé, P. Montañés-Rodríguez, *J. Atm. and Sol.-Terr. Phys.*, 69,1556, 2007.

Vegetation signature in the observed globally-integrated spectrum of Earth: Modeling the red edge strength using simultaneous cloud data and applications for extrasolar planets, P. Montañés-Rodríguez, E. Pallé, P.R. Goode, *ApJ*, 651, 544,2006.

Can the Earth's albedo and surface temperatures increase together?, E. Pallé, P.R. Goode, P. Montañés-Rodríguez, S.E. Koonin, *EOS*, Vol. 87, No. 4, 24 January, 2006.

Sources of oscillation frequency increase with rising solar activity, W.A. Dziembowski and P.R. Goode, 2005, *ApJ*, 625, 548.

A multi-data comparison of shortwave climate forcing changes, E. Pallé, P. Montañés-Rodríguez, P.R. Goode, S.E. Koonin, M. Wild, S. Casadio, *Geophysical Research Letters*, Vol. 32, No. 21, L21702, 2005.

Toward a global earthshine network: first results from two stations, E. Pallé, P.R. Goode, P. Montañés-Rodríguez, S.E. Koonin, *Geophysical Research Letters*, 32, L11803, 2005.

Globally integrated measurements of the Earth's visible spectral albedos, P. Montañés-Rodríguez, E. Pallé, P.R. Goode, J. Hickey, S.E. Koonin, *ApJ*, 629, 1175-1182, 2005.

Possible satellite perspective effects on the reported correlations between solar activity and clouds, E. Pallé, *Geophysical Research Letters*, 32, L03802, 2005.

Changes in the Earth's reflectance over the past two decades, E. Pallé, P.R. Goode, P. Montañés-Rodríguez and S.E. Koonin, *Science*, 304, 1299-1301, 2004.

The earthshine project: Update on photometric and spectroscopic measurements, E. Pallé, P. Montañés-Rodríguez, P.R. Goode, J. Qiu, V. Yurchyshyn, J. Hickey, M-C Chu, E. Kolbe, C.T. Brown, S.E. Koonin, *Advances in Space Research*, 34 (2), pp. 288-292, 2004.

The Earthshine Spectrum, P. Montañés-Rodríguez, E. Pallé, P.R. Goode, J. Hickey, J. Qiu, V. Yurchyshyn, M-C Chu, E. Kolbe, C.T. Brown, S.E. Koonin, *Advances in Space Research*, 34 (2), pp. 293-296, 2004.

Inter-annual trends in earth's reflectance 1997-2007, E. Pallé, P.R. Goode, P. Montañés-Rodríguez, *JGR*, 2008, submitted.

Pallé et al. 2007, reference

## B. Proposed Research

The Earth's reflectance is the least well-known of the fundamental climate parameters. Saying this is equivalent to saying clouds are the least well-understood fundamental climate parameter. Further, how changes in reflectance/clouds may be driven by a variable Sun remains a mystery. Long-term, precise cloud/albedo data verified from a multiplicity of sources are essential in understanding the role of solar-cycle length variations in GCRs in terrestrial cloud properties. Our principal scientific objectives in contributing the team effort to understand the possible role of GCRs in cloudiness are:

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## B.1 The Earth's Reflectance and Anomalies in Cloudiness

Ideally, to determine the Earth's reflectance, it would be necessary to observe reflected radiances from the Earth, from all points on the Earth and at all angles. Therefore, all measurements from which albedo can be inferred require assumptions and/or modeling to derive a good measurement. The availability of different albedo databases and their inter-comparisons is essential to constrain the assumptions necessary to derive estimates. To determine the Bond albedo from earthshine, one must integrate phase angles of the Earth (or Moon depending on one's perspective). A pictorial representation of the integrand (using Equation 1) for the Bond albedo is given in Figure 5 to illustrate the sensitivity of various instruments. In earthshine measurements, one obtains large-scale values of the reflectance covering the dominant phase angles over a month, but having less temporal coverage than a satellite in LEO, like CERES. A LEO satellite is downward looking and, as such, is ideal for detecting small-scales, but insensitive to large-angle scattering, which must be modeled with their "bi-directional" reflectances. Modeling of bi-directional radiative transfer through the atmosphere, as well as the various terrestrial scenes on Earth, have their own difficulties (see Rasche et al 2006 and references therein), which make the interpretation of the data more complicated, but very useful. A long-term data series of the Earth's albedo from satellites is also difficult to obtain due to the complicated inter-calibration of the different satellite data and the long gaps in the series. Thus, the now mature, two-station ground-based earthshine observations are an excellent complement to LEO satellite determinations of the reflectance, bearing in mind the necessity of collecting and comparing as many truly diverse measures of reflectance as possible. The value of the earthshine is further enhanced by the ISCCP-FD product, which combines data and models to produce a an albedo that is directly comparable to the earthshine.

We note that a GEO satellite could cover all phase angles, as could an observatory on the Moon. It is often naively thought that one can determine the Bond albedo from a satellite at L1, like TRIANA (DSCVR) would have done. However, Figure 5 and Equation 1 make it clear that such a satellite would only see nearly retro-reflected sunlight, which turns

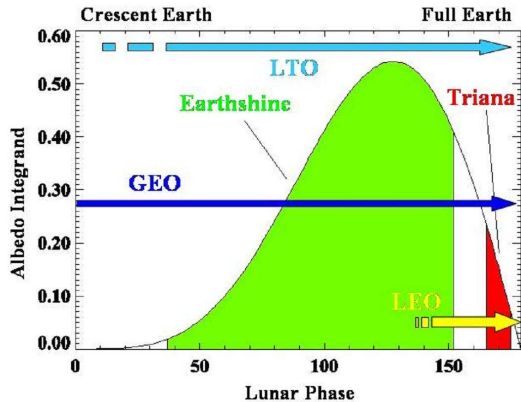


Figure 5: Albedo kernel ( $f_L(\theta) \sin \theta$ ) of Equation 1 vs. lunar phase. Satellites in geo-synchronous (GEO) and low-Earth orbits (LEO) sample vastly different parts of the contributors to Earth’s Bond or global albedo. A satellite orbiting around L1 would detect primarily back scattering, and would fill the essential part of the albedo missed by earthshine. A lunar-based terrestrial observatory (LTO) would cover all phase angles, much as a satellite in GEO.

out to make a relatively small contribution to the Bond albedo, and modeling of the bi-directional radiances becomes a problem of even greater significance.

On any one night of earthshine observations, we determine the reflectance of most of the sunlit Earth for a particular phase of the Moon (the apparent albedo,  $p^*$ ). However, we need to integrate over all phases of the Moon to determine a global or Bond albedo for the Earth,

$$A = \frac{2}{3} \int_{-\pi}^{\pi} d\theta p^*(\theta) f_L(\theta) \sin \theta, \quad (1)$$

where  $p^*$  is the measured apparent albedo associated with a particular night,  $f_L(\theta)$  is the Moon’s Lambert phase function (normalized scattering function for a fully diffuse reflector) and  $A$  is the Bond albedo. The value of  $p^*$  is measured many hundreds of times throughout each observing night. We note that integrating over a lunation would give the monthly averaged Bond albedo. With the goal of averaging many nights to obtain a mean Bond albedo and study longer term changes in it, one needn’t worry about bi-directional reflectances. To obtain a Bond albedo for a single night from earthshine, one needs to incorporate such modelling, as discussed in Sections B.3 and B.4

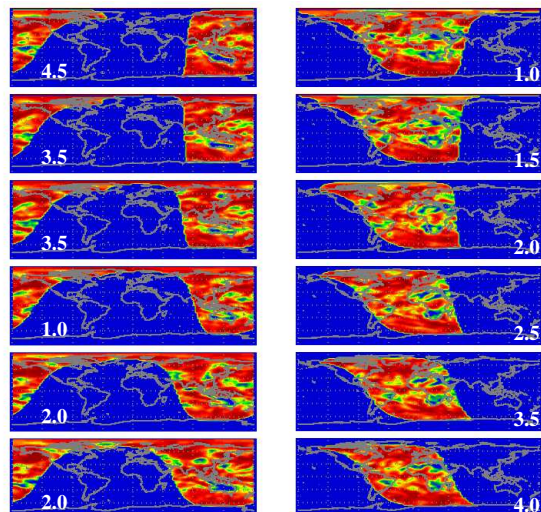


Figure 6: A plot of the total earthshine contributing Earth regions for the observed nights in June 1999 for illustration (with the large reddish regions contributing to the earthshine). The color scale represents the mean cloud amount at each point of the Earth. The numbers over-plotted on the maps indicate the number of hours of observations for the night. Right: The six nights correspond to the observing round of the 5-10 June (positive lunar phases or waning Moon), from bottom to top respectively. The area covered in the Atlantic region. Left: The six nights correspond to the observing round of the 17-22 June (negative lunar phases, or waxing Moon). As the Moon waxes, the Earth as seen from the Moon becomes an ever thinner crescent, but this is compensated by the Moon staying observable for a longer time period in the night sky. The combined effect is that the area of the Earth contributing to the earthshine on any night is roughly constant. The night of 14 June (4th panel from the top of the left column) is the exception, due to local bad weather in Big Bear.

of this proposal.

The method of error analysis in earthshine was developed and described in detail in two lengthy GRL papers (Qiu et al., 2003 and Pallé et al., 2003). Here we sketch some essential points. A fair criticism is that we don’t precisely know the lunar backscattering. This information we get from lunar eclipses, which enables us to do a *post facto* sharpening of our knowledge of the lunar phase function at small phase angles, and consequently the Bond albedo, as we acquire



Figure 7: The Moon showing the bright side and the earthshine. The Grimaldi side is in the moonshine (brightside) and the Crisium side is in the earthshine. Our ten highlands fiducial patches used in the observations made from BBSO are indicated. The crosses give the approximate positions of Danjon’s fiducial patches. Goode et al. (2001) used one fiducial patch on each side, and on the Crisium side it is the one closest to the white cross, while on the Grimaldi side, it is the one immediately above the black cross. In the image, the lunar phase is  $115^\circ.9$ , near a declining quarter Moon. 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.

more eclipse data with the latest total eclipse observations from Big Bear being 28August2007. Thus, our Bond albedo could have a systematic error that would cause an offset, which is our largest source of uncertainty. However, most of our quoted results are for albedo anomalies for which such a systematic error would be exactly cancelled out, as discussed in detail later in this section.

One incorrect criticism levelled against the earthshine data is that the geographic sampling varies each night. To illustrate, as the Moon rises to full, each observing night is longer; however, less of the Earth is covered at each moment. But at the end of the night,

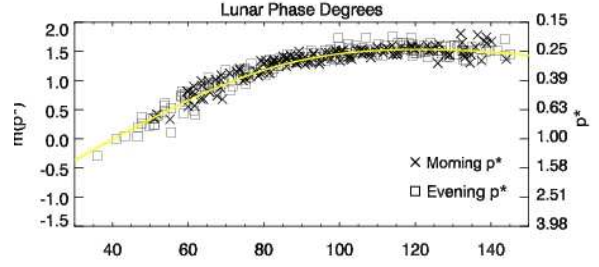


Figure 8: The measured  $p^*$ 's vs. lunar phase from 1999-2004. The  $p^*$ 's are shown in magnitudes for ease of viewing. The yellow line is the fit to all the data and anomalies in  $p^*$  are defined with respect to the mean. Note that there is no apparent difference between the data for positive and negative lunar phases.

almost precisely the same area of the Earth is covered for each night for a waxing (waning) Moon. This is true night-after-night, month-after-month and even year-after-year (Pallé et al., 2006), and illustrated for one month of observations in Figure 6. We have used models to show that longer term wanderings of lunar orbit are not significant, Pallé et al. (2007). The models are described in Section B.3.

The apparent albedo value for an individual night is calculated from the earthshine measurements for that night using

$$p^*(\beta) = \frac{3}{2f_L} \frac{p_b f_b(\theta)}{p_a f_a(\theta_0)} \frac{I_a/T_a}{I_b/T_b} \frac{R_{em}^2}{R_e^2} \frac{R_{es}^2}{R_{ms}^2}, \quad (2)$$

where  $\beta$  is the Earth’s phase angle (the angle between the sunlight that is incident somewhere on the Earth and reflected to the Moon,  $\beta$  is simply related to  $\theta$  as shown in Figure 1),  $\frac{I_a/T_a}{I_b/T_b}$  is the ratio of the earthshine intensity to the moonshine intensity in two opposing fiducial patches, after each is corrected for airmass, and  $\frac{p_b}{p_a}$  is the ratio between the geometrical reflectivity of the two opposing fiducial patches, which were measured along with the lunar phases function over the first several years of earthshine observations (Qiu et al., 2003).  $R_{em}$ ,  $R_{es}$ ,  $R_{ms}$  and  $R_e$  refer to the Earth-Moon distance, the Earth-Sun distance, the Moon-Sun distance and the Earth’s radius respectively. The earthshine-moonshine ratio is an essential advantage over Earth-looking satellites in calibration in which several uncertain quantities are precisely cancelled, like the solar irradiance. This latter advantage enables a clean comparison of irradiance and earthshine variations. The lunar phase function for the bright side,

$f_b(\theta)$ , is used in the formula to account for the geometrical dependence of the reflectivity of the Moon, while  $f_a(\theta_0)$  accounts for the fact that the earthshine is not exactly retroflected from the Moon ( $\theta_0 \lesssim 1^\circ$ ).

The lunar phase function is defined as the normalized change in the moonshine intensity as a function of lunar phase, which represents the geometric reflectance of the Moon. It is measured from the readout intensity of each of the fixed fiducial patches (see Figure 7), all in the lunar highlands (five on the Crisium side and five on the opposing Grimaldi side), used throughout the observations, after carrying out the series of straightforward corrections to the raw data as described in detail in Qiu et al. (2003). The corrections basically account for the lunar declination, libration and night-to-night changes in the attenuation of the local atmosphere (using the brightside of the Moon as a guide star).

Each night, by observing ten fiducial patches, five on the Crisium side, and five on the Grimaldi side (see Figure 7), we obtain, in principle, twenty-five values of  $p^*$  from the twenty-five combinations of the five pairs of fiducial patches. This gives us a way to evaluate the reliability of our measurement of  $p^*$ , see Pallé et al. (2003) for details. The same pattern of variation appears in all datasets, and we take an average of the 25 measurements of  $p^*$  for each night, where each of the 25 is a mean of several hundred measurements of that pair.

The earthshine measurements for the first six years of the project are shown in Figure 8. The albedo anomalies for that period are defined with respect to the mean (the yellow curve). If future measurements of lunar backscattering were to reveal that the effect is larger than we now believe, then every point on the curve would be accordingly smaller, but the anomalies would be unchanged. Thus, dealing in anomalies eliminates the greatest uncertainty in the albedo determination from earthshine, see Qiu et al. (2003). We remark that there is no apparent difference between the evening (waxing Moon) and morning (waning Moon) observations (see Section B.2. for more details).

Although the methodology of earthshine observations and analysis, including uncertainties, were developed in detail in two lengthy JGR papers (Qiu et al. 2003 and Pallé et al. 2003), a few points merit discussion. First the telescope was designed like a

“coronagraph”, which here means that the measurements is insensitive to any light that is not precisely in the path from the Moon to the telescope aperture (see Section B.2). Further, the aforementioned papers present several years of measurements of the lunar phase function, which is most sensitive backscatter at small phase angles. This offset in the phase function also precisely cancels out in the albedo anomalies that are discussed in this proposal. Finally, earthshine observations from a single site is insensitive to the polar regions, and so is insensitive to seasonal changes. Nonetheless, it is sensitive to the long-term trends in albedo as illustrated in Figures 2 and 3.

Our earthshine observations are further motivated by recent results from *in situ* measurements of ocean temperatures (0-750 m depth), which imply that climate change science still has some essential surprises for us. The added energy of global warming is expected to be stored in the vast heat reservoir that is the oceans (Hansen et al., 2005). And for a decade this was the case. But there has been a flattening over the last three years, Lyman et al. (2006) and Willis et al. (2007). By eliminating the annual averaging and differentiating these data (Willis 2006, private communication) and converting to a global average heat flux sink, there is a good agreement with the earthshine albedo anomalies. (???NEED TO UPDATE THIS???) The physical reasons behind this cessation of oceanic warming remain unexplained, while the apparent agreement between the derivative of the heat content and the earthshine motivate further measurements of the latter, and their expansion to a global network.

## B.2 Robotic Global Earthshine Network

When we observe the earthshine from BBSO, night-after-night we see the same two distinct large regions of the Earth, as shown in the top panel of Figure 9 (also see Figure 6). We see the same large region to the west of BBSO night-after-night when the Moon is waxing, and a comparably sized large region to the east night-after-night when the Moon is waning. When the albedo anomalies for these two large regions of the Earth are calculated, we find that they show the same trends, so that data covering the two regions can be usefully combined to yield a quasi-global reflection anomaly.

To obtain true global coverage of the earthshine, so

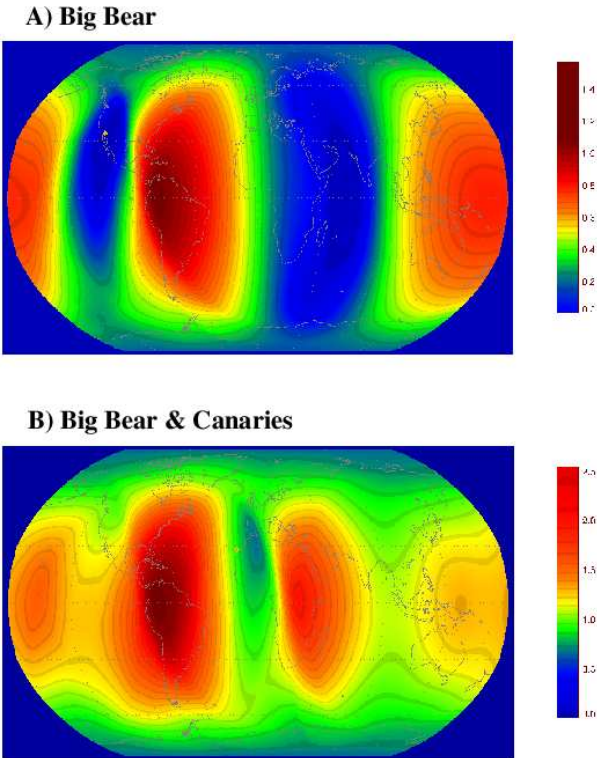


Figure 9: Upper: The parts of the Earth (in Mercator projection) detected in the earthshine signal from BBSO, including geometrical factors appropriate for the Earth-Moon-Sun system. Red means full coverage and blue means no coverage. For instance, BBSO does not see much of the earthshine from North America (brightest red lobe covers South America and the Atlantic). Lower: The parts of the Earth detected in the earthshine signal from BBSO and the Canaries. Two stations cover the Earth.

that we have redundant coverage of the whole Earth, we need a network with stations at the best sites carefully spaced around the world, and this is only feasible with robotic telescopes at the best observing sites. With this in mind, we have designed, built, tested and observed for more than two years with a robotic earthshine telescope that resides under its own dome on the causeway at BBSO. We also built a second robotic telescope and calibrated it, side-by-side for several months, against the first robotic earthshine telescope. The second robot has been deployed to the Canaries, and has begun observations. We also calibrated the original earthshine telescope against the first robot. The original earthshine telescope has been removed

(and put into storage) to make way for the new, 1.6 m clear aperture, off-axis solar telescope that is about to have first light in BBSO. Next, we will begin construction and calibration of a third robotic earthshine telescope for deployment to Australia, although that will probably come only late in the work proposed here.

Building the first robotic telescope required some care because it needs to translate/rotate in and out a blocking filter that blocks the bright side at the first focus during exposures on the earthshine side of the Moon. The second focus is at the camera. In between, the telescope has a Lyot stop at the pupil image to block the stray light. The telescope needs this coronagraphic structure to reduce stray light because it has to take very short exposures ( $\sim 10$  ms of the brightside) and very long exposures ( $\sim 1$  min of the earthshine). The source of the stray light is the bright side of the moon when observing earthshine. The telescope was designed and built with straylight contamination in mind. In fact, we test bright lights inside the dome and they only had a measurable effect if they were directed straight into the telescope along the path of the moonlight. Coupled with Eq. (2), which contains the ratio of the earthshine to moonshine, one sees that the effects of transmission and absorption through the terrestrial atmosphere to the telescope are precisely cancelled out. The dome, telescope and coronagraph-like features are all under the control of a remote computer. One can remotely open the dome, take flat fields, and then point the telescope, and the observations go on their own, but can be closed down from afar if conditions call for it, and if there is sufficient bandwidth over the computer network. Generally, the robots are controlled within the local network in which the bandwidth is limitless for our purposes here. Purchase of much of the hardware for this telescope was funded by a private, family foundation; the private funding will only support hardware and its deployment.

With a station in the Canaries, we will have global coverage that is not quite uniform - see the middle panel of Figure 9. Nonetheless, we will be able to combine earthshine data with our models to do gap-filling in the data (see Section B.4).

Smoothing to obtain global values for the albedo from earthshine requires knowing precisely what region of the Earth we are covering. Determining coverage is just one part of what we do with our modeling efforts. In fact, Figure 9 was constructed from our

models, and such maps are available for each night of observations.

### B.3 The Models

In modeling the reflectance properties of the Earth, we have used scene models developed for the ERBE observations (Suttles et al., 1988). The model reflectances are defined as a mean over the broad short-wave interval from 200 to 4000 *nm*, while our observations cover the spectral range from 400 to 700 *nm*. The reflectance variables are tabulated for twelve model scenes, varying from “desert” (areas for which the annual precipitation is less than 26 cm) to “mixed land-ocean” areas, which are cells bordered by two land and two ocean cells. The simulations of the Earth’s albedo were performed using the ISCCP cloud data, and snow and ice data from the Canadian Center for Climate Change and Analysis.

For the cloud cover, we have used the daily (D1) and monthly (D2) mean fractional cloud cover data from ISCCP. They are the most accurate global cloud data available, but making them so precise precludes their availability in real-time. The presently released ISCCP dataset covers more than twenty years over the period July 1983 through June 2007. ISCCP data make use of visible and infrared radiances; total cloudiness is determined using both of them, whereas the various cloud types are determined using visible and/or infrared radiances. For further details on the ISCCP data see Rossow et al. (1996). All ISCCP data products are archived at the ISCCP Central Archive ([isccp.giss.nasa.gov](http://isccp.giss.nasa.gov)).

The simulated albedo anomalies agree broadly with those from observations. However, to be realistic, we know there are flaws in our simulations, and we propose a more sophisticated parametrization of cloud properties and the terrestrial scenes in our simulations. Here we will directly benefit from the other members of the team exploring this topic. Clouds control the Earth’s albedo, and a change in the global albedo of only 3% (see Figures 2, 3 and 10 for scale) would cause a change in the Earth’s energy balance, warming or cooling, comparable to that generally attributed to greenhouse gasses since the beginning of the industrial revolution. The ISCCP D2 products include a distinction between high-, mid- and low-level cloudiness. We propose to include this distinction in our model parametrization. At present, we use only total cloud

cover in our simulations. We further propose to introduce more sophisticated scene models that have been developed, like those for CERES, in the fifteen years since ERBE. This will give us a way to directly test their model bi-directional reflectances against earthshine results. We also propose to use more cellular or small-scale maps of the scenes that are now available. Our models will be more realistic with these improvements; the trends in the simulated Bond albedo variability will almost certainly change. Note that the earthshine observations circumvent all of these problems by directly measuring the Earth’s albedo without the need for parameterizing cloud quantities, scenes and reflectances. Thus, the improved modeling is an ideal way to connect with distinct measures of cloudiness.

Particularly important for our proposed goals is the comparison of our earthshine measurements to complementary datasets obtained from space (ISCCP, TOMS, CERES, and perhaps, SCARAB, GERB and MODIS, as well). To some extent, the selection will depend on the composition of the team. The strength of our albedo measurements is that they are relative measurements, not prone to instrumental, or long-term calibration problems. Satellite observations almost always rely on absolute radiance measurements, and all absolute measurements are prone to long-term calibration errors because of instrumental degeneration with age. Problems associated with degeneration become worse for satellite instrumentation because of the stress of their launch, the hostile environment in which they operate, and the impossibility of manual repair if a part of the instrument malfunctions.

While far from perfect, the geographical and temporal sampling of the satellite instrumentation is more extensive than the earthshine, although our two station network will reduce this shortcoming. In all cases, diverse measurements from which albedo can be inferred require assumptions and/or modeling to derive a reliable estimate, and the availability of different albedo databases and their inter-comparisons is essential in constraining the assumptions necessary to derive precise terrestrial albedos. Such precision is essential when these data are used to extract the role of GCRs in changing cloudiness.

Thus, we also propose to undertake a day-by-day comparison of our earthshine measurements to those from satellite platforms. These comparisons will be

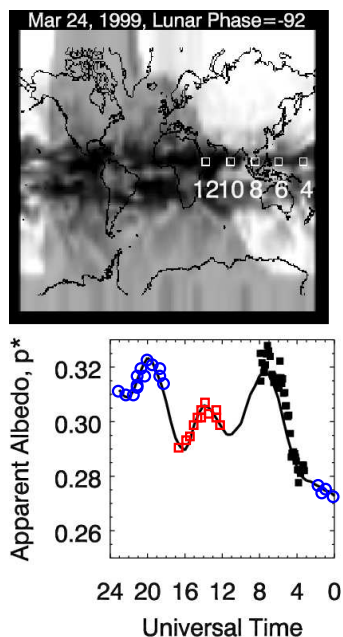


Figure 10: In the upper panel, the extended bright areas highlight the parts of the Earth that are the source of the earthshine during the observations. The satellite-derived cloud cover maps are shown in a secondary gray-scale, with brighter areas indicating greater cloud cover. The empty white boxes in the top panel indicate the longitudes of maximal contribution to the earthshine at the Universal Time (UT) shown. The solid black boxes in the lower panel shows the observed apparent albedo as a function of time (note that the time axis is reversed), while the solid line indicates the simulated  $p^*$  values as the Earth rotates. The blue circles (red boxes) are not real observational data, but are meant to illustrate the point of maximal contribution at each moment of the four hours of observations from a robotic telescope in the Canaries (in Learmonth). The whole of the Earth contributes with three stations totaling only 12 hours of observations. As can be seen from Figure 9, the whole of the Earth would contribute, albeit unevenly, with only two stations.

important, along with improving our models, in any smoothing of coverage we have to do with the earthshine. To this end, it will be necessary to ‘simulate’ the satellite observations by selecting a sub-sample of their observations covering the areas and times of the earthshine observations. This is not an easy task because of the data gaps in both earthshine and satellite data, and because the distinct geometries of the observations from the two methodologies also need to be carefully taken into account. However, our experience with the earthshine-ISCCP comparison make us confident that we know in detail how to perform this task and that reasonably good agreement will result from comparisons of earthshine with satellite data.

#### B.4 Variability of Daily Observations and Model Results

In Figure 10, the lower panel shows the apparent albedo from one evening’s BBSO earthshine observations (solid black boxes) overlaid on model calculations (solid black line) covering in UT the twenty-four hour period encompassing the observations. The panel shows in red and blue colors the points of maximal contribution of the global coverage from a three station network. These results come from near a waxing quarter Moon, and are compared with the simulations using cloud cover maps from the same day, as shown in the upper panel.

The upper panel reveals that at high geographical latitudes poleward of  $\pm 45^\circ$ , the cloud cover is fairly steady. Thus, the short timescale variations in reflectance in Figure 10 are due primarily to irregularities in the fractional cloud cover at low latitudes, and secondarily to the scene type. In the lower panel of Figure 10, one sees observed and calculated maxima in  $p^*$  at 7:00 UT due to a relative cloud excess over the Far East, while the calculated local minimum in  $p^*$  at 11:00 UT arises from the cloudless area above India and the Arabian Sea.

One of the most important observational result from Figure 10 is that over about two hours there is a more than 10% change in  $p^*$  for all of the sunlit Earth contributing to the earthshine. This sharp increase is due to the increasing contribution of a cloudy Asia to the Earth’s reflectance as the Earth rotates. Further, the model results show a high degree of variability for the same day. These results are not particularly atypical. *They serve to emphasize the need*

*to average as much data as possible, irrespective of the temporal spacing of points (as long as the seasons are uniformly covered), to obtain a precise mean albedo anomaly of the Earth, for say, a year.* Same-day observations from different locations will allow us to ‘fill-out’ that graphic in time, and smooth the intensity bumps so each region contributes uniformly, rather than some being over-represented while others are under-represented, as in Figure 9 to do gap-filling in the observations by means of our modeling. The BBSO data and the idealized (Canaries and Learmonth) earthshine data in Figure 10 is consistent with the large-area, overlapping patches in the lower panel of Figure 9. Smoothing the gaps with simulated albedos would yield a true global albedo without the patchiness of the bottom panel of Figure 9. By true global albedo, we mean the one that would result from continuous 24-hour measurements of the earthshine with as many stations as required to achieve this coverage. We will be able to check our smoothing by using the not-always-available data from the other two (non-robotic) stations. For instance, adding data from the Crimea would close half the gap between Learmonth and the Canaries and overlap with the Canaries observations for about two hours. Thus, we will have several measures of global reflectance, which will broaden and deepen our understanding of the terrestrial albedo and temporal changes in it. All of this development will aid us in comparing the albedo/cloud data various specific measures of solar activity at Earth, especially the open magnetic flux (read CGRs).

## **B.5 Solar Wind and Terrestrial Reflectance**

Variations in the Sun’s photospheric magnetic fields modulate the total and spectral solar irradiance (Solanki & Krivova 2006). The Sun’s open magnetic flux, although only a small fraction of the total flux, is responsible for the modulation of the GCR flux reaching the Earth and, hence the production rate of cosmogenic isotopes (Heber et al. 2006). It remains unclear how these parameters that are apparently correlated (or anti-correlated) on decadal, or solar cycle length time scales effect climate change on Earth. A feasible, though debated driver is one in which GCRs become cloud condensation nuclei (e.g. Dickinson 1975, Marsh and Svensmark 2000) and/or modulate the global thunderstorm electric circuit (e.g. Tinsley

2000). In contrast to direct solar forcing, the cosmic ray forcing operates on all time scales including sub-decadal time scales (Scherer et al. 2006). We propose to conduct a comprehensive comparison between terrestrial cloud properties from ISCCP and solar wind parameters that modulate cosmic rays. This has become timely since vast amounts of significantly more accurate solar and terrestrial measurements of various sorts have been accumulated over the past two decades, and a systematic search needs to be made for correlated, relevant solar and terrestrial signals. This work will build on our unique experience in generating and utilizing solar and cloud data.

The total cloud amount from ISCCP is shown in the upper panel of Figure 4. The data cover two decades and show an apparent systematic behavior that resembles the 22 year sunspot cycle. However, a close comparison shows strong differences. Further the combined earthshine and cloud property data (more than just cloud amount, but also cloud thickness and cloud location) to derive the reflectance results in Figure 3 show a different periodicity also covering about the length of a full solar cycle. The two figures seem to hint at some correlations, but also seem to show that a direct comparison between the gross cloud properties and sunspot numbers is unlikely to bear fruit. More detailed investigations are required to uncover more relevant solar and terrestrial signals. We plan temporal and geographical decompositions, such as by latitudes (e.g. Usoskin et al. 2004), of cloud components (as we did to obtain Figure 3) and look for trends in these components and their distribution with solar wind parameters. Our more sophisticated approach will also employ knowledge of the altitudes and other cloud properties (Yu 2002, Arnold 2006), as discussed in Sections B.3 and B.4 of this proposal.

For the solar input, we will primarily exploit existing results and techniques to derive the solar open magnetic flux, apart from the more conventional sunspot number and solar irradiance. It is found that 75% of cosmic ray flux variations are accounted for by magnetic open flux (Lockwood 2001). Reconstructing the Sun’s open magnetic flux has been performed by a few independent groups, yielding consistent results (Wang and Sheeley 1995, Lockwood et al. 1999, Solanki et al. 2000, 2002). We will examine existing, as well as developing data bases for probing correlation patterns between the Sun’s open flux and geo-



graphically decomposed cloud properties on decadal and sub-decadal time scales, and analyze their significance. If trends are found, we will also work to establish an empirical relationship between anomalies in solar and terrestrial data sets. Apart from published results, for the upcoming observations, we will also compute the Sun's open flux applying the Potential Field Source Surface (PFSS) model (Schatten et al. 1969, Hoeksema 1984, Wang and Sheeley 1992) to synoptic magnetograms. The synoptic magnetic field observations are generated on a regular basis and provided to the research community via an open-data policy. The PFSS code is open to a wide research community at the Community Coordinated Modeling Center as well as the built-in the open source Solar SoftWare (SSW). In our efforts, we will sharpen our skills, while benefiting from the community's effort to accurately model and/or measure the large-scale solar magnetic fields (Riley 2007).

Although our effort cannot directly address the intrinsic connections between variations in cloud properties and cosmic ray particles or particle transport processes in the heliosphere, the proposed comparison in multiple dimensions will provide insight into understanding the solar modulation of cosmic ray flux by magnetic fields and decomposition of the ISCCP data.

### **C. Budget and Responsibilities of Team Members**

The total budget for this three year proposal is close to \$365 K. This proposal provides full support for a postdoctoral associate, who will advance the data reduction and modeling efforts. It also provides partial support for Prof. Jiong Qiu (co-PI, Montana State University professor and earthshine veteran). Significantly, two former BBSO earthshine researchers, Dr. Pilar Montañés-Rodríguez and Dr. Enric Pallé, have returned to Spain and are employed at the IAC in the Canaries. Enric Pallé has a permanent position in the IAC and is an expert in earthshine, cloud modeling utilizing satellite data and climate change. Dr. Pilar Montañés-Rodríguez is in charge of starting up various nighttime observations on Tenerife, which will include the robotic earthshine telescope located near the German Vacuum Tower Telescope. Prof. Phil Goode (PI) and the earthshine team will work the postdoc

to utilize albedo and cloud data and analyze the solar wind data to understand the true GCR-cloud connection. Again private funds supported the construction, deployment, and redundant (backups for most likely to fail) hardware of the network telescopes, but will not provide further support to the project. Phil Goode (PI) will have overall responsibility for the project. The travel budget is primarily to support our team member travel to the full GCR team meetings and also to enable the postdoc to attend scientific meetings.

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