Earthshine and the Earth's Albedo

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ABSTRACT

Subject headings: Earth : albedo, global climate — Moon: reflection

DON'T TRUST CORRESPONDENCE BETWEEN FIGURE NUMBERS/EQUATIONS AS THEY APPEAR AND AS THEY ARE DISCUSSED IN THE TEXT

For the last year (WE NEED TO KNOW IF WE CAN USE THE OLD DATA BECAUSE IT GIVES US A FIVE YEAR SPAN), earthshine observations have been made in California from Big Bear Solar Observatory. We have re-invigorated and modernized a nearly forgotten way of measuring the earth's albedo, and hence its energy balance. For about a quarter-century, early in this century, Danjon and his followers observed the earthshine from France.

From California, we see the moon reflecting sunlight from Asia in our evening – before midnight – which is during the moon's rising phase, and from Europe in our morning – after midnight – which is during the moon's declining phase. We have precisely measured the scattering from the moon, as a function of lunar phase, which enables us to measure the earth's albedo to an accuracy of 0.5% (equivalent to measuring the earth's emission temperature to ~ 0.2 K). The albedo is due to the interplay of cloud cover and the different landscapes. In the observations, we see large variations in the earthshine from night to night, $\sim 5\%$, due to weather changes on the other side of the world. Averaging the data, we also see seasonal changes with the earth being brightest in the spring.

We also find a favorable comparison of our results to models of the earth's reflectance which use as input cloud cover from satellites – with the trends from the model being weaker than those from the earthshine data. Thus, our earthshine results imply that the models show variations which are too small, as though terrestrial features are overly smoothed in the models. Using satellite cloud cover data to extend our model results back over a solar cycle, we find variations in the power going into

the earth's climate system are about five times more sensitive to the changes in the earth's albedo than to changes in the solar irradiance.

1. Introduction

It is important to know whether there is an on-going global change in the earth's climate. To answer this, one needs precise, global/integrated measures of relavent quantities. The earth's climate depends on the net sunlight deposited in the terrestrial atmosphere, and so, is critically sensitive to the solar irradiance and the earth's albedo. Precise measurements of the solar irradiance have been made by various satellites (REFERENCES) and using ground-based proxies (REFERENCES). The spectrum of efforts to determine the earth's global albedo is not so rich. There have been efforts using systems of satellites (REFERENCES), but virtually no efforts from the ground. Nonetheless, the earth's energy balance is determined in large part by its global albedo – the fraction of the incident sunlight that is directly reflected back into space without altering the internal energy budget of the atmosphere. The earth's surface, aerosols in the atmosphere, and clouds all reflect some of the incoming solar short-wavelength radiation, preventing that energy from warming the planet. Short-wavelength radiation, usually defined as having wavelengths between 0.15 and 4.0 μm, includes about 99% of the sun's radiation; of this energy, 46% is infrared (> 0.74 μm), 9% is ultraviolet (< 0.4 μm) and the remaining 45% is visible, with wavelengths between 0.4 and 0.74 μm. A significant portion of the solar energy is absorbed by the earth, where it drives terrestrial phenomena before being radiated back into space. This long-wavelength radiation peaks at about 15 μm (corresponding to a black-body temperature of about $T_E = 255$ K).

The power going into the earth's climate system is

$$P_{in} = C\pi R_e^2(1 - A), \tag{1}$$

where C is the solar constant, R_e is the earth's radius and A is the short-wavelength Bond albedo (reflectivity). Similarly, the long-wavelength power that the earth radiates into space is

$$P_{out} = 4\pi R_e^2 \sigma \epsilon T_e^4, \tag{2}$$

where σ is the Stefan-Boltzmann constant and ϵ is the emissivity of the atmosphere (about 5.5 km high, where the long-wavelength radiation is emitted).

If the planet is in radiative equilibrium, $P_{in} = P_{out}$, and we have

$$T_e^4 = \frac{C}{4\sigma\epsilon}(1 - A). \tag{3}$$

This means that the Bond albedo directly controls the earth's temperature. If there were global warming, ϵ would decrease and T_e would increase; in such an event one might expect the earth's Bond albedo to increase in response.

It has been known for some time that the so-called solar constant varies. In particular, data from the Active Cavity Radiometer (ACRIM I) on board the Solar Maximum Mission has shown for one cycle that the solar irradiance is about 0.1% greater at activity maximum than activity minimum (Willson and Hudson 1988, 1991). The precise origin of the changing irradiance is generally attributed to a competition between two components of the sun's magnetic field – dark sunspots and bright faculae. It is conventional wisdom that this is about five times too small to be climatologically significant over a solar cycle (REFERENCE). It has been argued that there may have been two to three times larger, sustained excursions (Lean 1997) in the past, like during the little ice age (REFERENCE Baliunas?) when a sunspot was rare. Still, there is strong evidence of a solar cycle going back more than 100,000 years (Ram and Stoltz 1999). If the 0.1% increase in the mean solar irradiance between the mid-1980s and 1990 were typical, it leads one to ask if it is the direct effect of varying solar magnetism on the irradiance that causes the dominant terrestrial signature of the solar cycle. Svensmark and Friis-Christensen (1997) have argued that indirect effect of the sun's magnetic field has a much greater terrestrial significance than the irradiance variations.

Svensmark and Friis-Christensen (1997) have studied satellite cloud cover data and measured a 3-4% greater cloud cover at solar activity minimum. They argue that this implies solar cycle climatological variations an order of magnitude larger than those implied by observed solar irradiance variations over the cycle. They further argue that the source of the excess cloud cover is the relatively greater cosmic radiation at activity minimum which arises from the sun's magnetic field being weaker at activity minimum and, thereby, being less effective in shielding the earth from cosmic radiation. According to their argument, the relatively greater cosmic radiation creates relatively more ions which have a correspondingly greater cloud-seeding effect. The details of their interpretation of the cloud data may or may not be correct, but the apparent terrestrial magnification of solar effects emphasizes the importance of looking for long term trends in the albedo as an indicator of global climate change.

Global changes in the earth's climate would be reflected in changes in the earth's albedo. Here, we focus on a terrestrial determination of the earth's global albedo from an old, and largely forgotten method. That is, global albedo can be determined by measuring the amount of sunlight reflected from the earth and in turn, back to the earth from the dark portion of the face of the moon (the "earthshine" or "ashen light"). The most important historical program of earthshine measurements was carried out by Danjon (1928, 1954) from a number of sites in France. He used a "cat's-eye" photometer to produce a double image of the moon, allowing the visual comparison of the intensities of two well-defined patches of the lunar surface−−one in sunlight and the other in the earthshine−−at various lunar phases. Using the "cat's-eye" mechanism, he stopped down the light from the sunlit portion to match the brightness of the ashen portion. This differential measurement removed many of the uncertainties associated with varying atmospheric absorption and the solar constant, allowing Danjon to achieve an estimated uncertainty of roughly 5%. Our measurements are about an order of magnitude more precise, not simply because we have better cameras available, but we have also solved the problem of the uncertainty in the scattering from the moon as a function of the phase of the moon (see §5). At a better than 1% precision, our terrestrial measurements of the earth's albedo have a precision comparable to that from satellites.

From 1926 to 1930, Danjon made 207 measurements of earthshine. Dubois (1947) continued the program through 1960 from the observatory at Bordeaux using a Danjon-type photometer.

Danjon's and Dubois' results show a number of interesting features. The daily mean values of the observations vary more widely than would be expected on the basis of the variation of measurements on a single night. This can be plausibly attributed to daily changes in cloud cover, but extensive cloud-cover data were not available at the time of the observations.

Danjon (1928) also examined his observations to determine whether there was a long-term trend in albedo, but found none. Dubois' observations for some 20 years ending in 1960, showed considerable annual variability, which he speculated was due to solar activity. His published monthly variations from 1940-1944 also show a strong correlation with the 1941-42 El Niño. In the past forty years, there have been observations of earthshine by Huffman et al. (1989) and one-time observations by Franklin (1967) and Kennedy (1969).

IS THIS ARGUMENT CORRECT, IN LIGHT OF FIGURE 21? Danjon used his observations to estimate the mean global albedo. Since the observations are only at visible wavelengths, they must be corrected for the balance of the short-wavelength radiation, most of which is in the near IR. Estimates of this correction were made by Fritz (1949), after taking into account the decrease of the earth's albedo with increasing wavelength (our "blue planet"). Fritz also attempted to correct for the geographical bias in Danjon's observations. The western hemisphere, which was most frequently observed by Danjon, has a greater fraction of land than does the globe as a whole, implying that Danjon's value would be high because the sea is dark compared to land. Combining the decreases from the absence of the IR and geographical bias, Fritz found that Danjon's visual albedo of 0.40 corresponds to a Bond albedo (considering all the wavelengths and directions) of 0.36.

Flatte et al. (1991) noted that a correction must be made for the "opposition effect" present in lunar reflectance properties. Observations of the moon show that the moon's reflectivity has a strong angular dependence. This "lunar phase function" can rise by as much as a factor of two in going from 5° to 0° (exact backscattering). This enhancement was once thought to be due to the porous nature of the lunar surface (Hapke 1971) and was unknown in Danjon's time. More modern work has shown it to be caused by coherent backscatter in the lunar soil. The smallest lunar phase angle measured by Danjon was only 11°. The extent of the small-angle rise varies over different regions of the lunar surface, but can easily be the 20% required to reduce Fritz's value of 0.36 to the aforementioned 0.30 (Buratti et al. (1997)). We shall see in §10 that an incorrect lunar phase function is the primary source of Danjon's overly large visual albedo.

The observations reported here were carried out at Big Bear Solar Observatory (BBSO) beginning December 1998 (UNLESS WE QUOTE EARLIER DATA FROM ACTIVITY MINIMUM) , using our earthshine telescope. The observations are described in detail in §3. We note that our CCD detector has sufficient resolution and dynamic range to observe both the sunlit and earthshine portions of the moon in the same image (although a dark filter is usually interposed on the bright crescent), so the entire disk is measured at once. We report the results of our data including synoptic, seasonal, and annual variability.

We also compare the results from our observations with the first modern modeling of earthshine. These calculations used ERBE scene models from 1987, and a general circulation model (GCM) derived snow/ice covers to simulate both earthshine and input cloud cover data from operating meterological satellites, which are contemporaneous to the observations to which they are compared (see §8).

2. Determining the Earth's Reflectivity from Earthshine

Terrestrial measurements of the short-wavelength (visible light and near infrared) albedo of a planet in our solar system is relatively straightforward – except for the earth. However, we can determine the albedo from the ground by measuring the earthshine. From a terrestrial perspective, 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 the earth, see Figure 1.

The earth's differential cross-section depends on its geometrical albedo and its phase function. At the earth's surface, the differential cross-section of the reflected sunlight for scattering by an angle β (note that β is the supplement of the usual scattering angle) is given by

$$\frac{d\sigma}{d\Omega} \equiv p_e f_e(\beta) R_e^2, \tag{4}$$

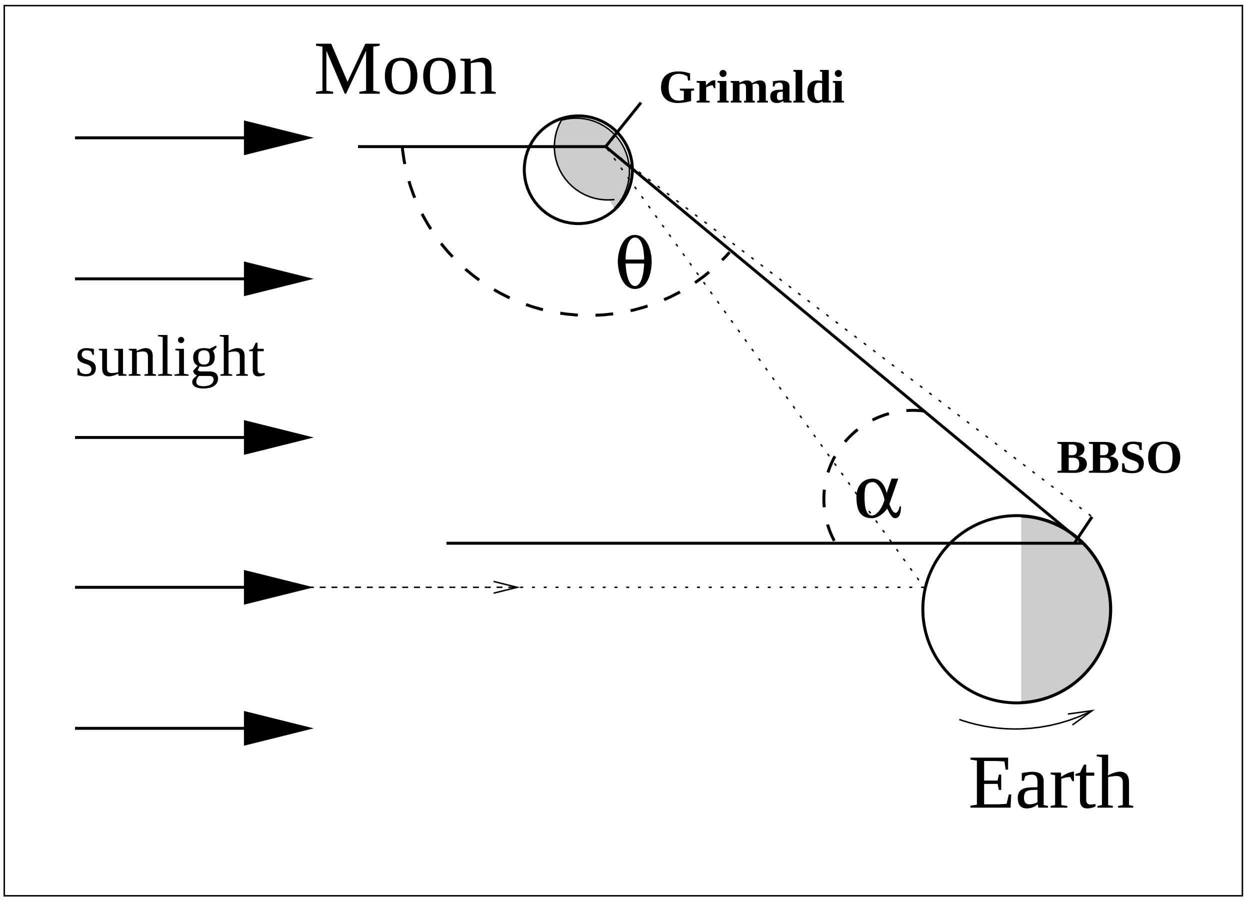

Fig. 1.— A sketch of the sun-earth-moon system defining the earth's phase angle, α, and moon's phase angle, θ. The plot indicates one of the fiducial points (Grimaldi) used in the observations made from BBSO (also indicated). SHOULD CHANGE THIS TO SHOW SUNLIGHT COMING PARALLEL FROM INFINITY.

where R_e is the radius of the earth, p_e is the geometrical albedo of the earth and f_e is the earth's phase function, defined such that $f_e(0) = 1$, as can be seen in the Lambertian limit from equation (7).

The formulation in equation (4) is separable, so that we can write the total scattering cross section as

$$\sigma = \int \frac{d\sigma}{d\Omega} d\Omega = \pi R_e^2 p_e \int_{-\pi}^{\pi} f_e \mid \sin(\beta) \mid d\beta, \tag{5}$$

where p_e and f_e depends on the earth's weather, season and climate, and aspect.

From the total cross-section, we can define the Bond albedo, the fraction of solar energy incident on the planet that is reflected, as

$$A = \frac{\sigma}{\pi R_e^2} = p_e \int_{-\pi}^{\pi} f_e(\beta) \mid \sin(\beta) \mid \beta. \tag{6}$$

Using earthshine data, we integrate over the phases of the moon to determine, say, a seasonally averaged Bond albedo. In that case, β in equations (4)-(6) would equal α in Figure 1. α and β are defined as varying between 0 and $\pm\pi$.

If we assume that the earth is a Lambert sphere, we can do the integral in equation (5) exactly. A Lambert sphere reflects isotropically from its assumed to be fully diffusive surface. Then, f_L, the earth's Lambert phase function, is determined by

$$f_L(\beta) = \frac{(\pi - \mid \beta \mid) \cos\beta + \sin \mid \beta \mid}{\pi}. \tag{7}$$

The earth's phase function is very roughly Lambertian for $\mid \beta \mid \leq \frac{2\pi}{3}$ (REFERENCE). Under this assumption, we determine a simple proportionality between the geometric albedo and the global or Bond albedo, namely,

$$p_{e,L} = \frac{2}{3} A_{B,L}. \tag{8}$$

Again, modeling shows that the earth's phase function is approximately Lambertian for $\beta \leq \frac{2\pi}{3}$. Thus, a convenient, differential measure of the earth's reflectivity is the effective albedo

$$A^* = \frac{3}{2} \frac{p_e f_e}{f_L}. \tag{9}$$

which is the albedo of a Lambert sphere that would give the same instantaneous reflectivity as the true earth.

At that instant, an observer on the moon in the region illuminated by the sun and visible from the earth would see both the direct sunlight and some part of the sunlit earth. The solar intensity seen by that observer would be

$$I_s = \frac{C}{R_{ms}^2}, \tag{10}$$

where C is the solar constant and R_{ms} is the moon-sun distance measured in astronomical units. Similarly, the intensity of the earthlight would be

$$I_e = \frac{C}{R_{es}^2} p_e f_e(\alpha) \frac{R_e^2}{R_{em}^2}, \tag{11}$$

where R_{ms} and R_{es} are the moon-sun and earth-sun distances, respectively. Thus, the earth's reflectivity can be expressed as

$$p_e f_e = \frac{I_e}{I_s} [\frac{R_{em}}{R_e}]^2 [\frac{R_{ms}}{R_{es}}]^2. \tag{12}$$

In the observations, we study two diametrically opposite fiducial patches both near the night-time lunar limb. For our purposes here, we call them "a" and "b" and treat them as unit projected areas. If a is illuminated only by the earthshine, the intensity observed by an observer on the earth at a distance R_{oa} would be

$$I_a = I_e \frac{p_a f_a(\theta_0)}{R_{oa}^2} T_a, \tag{13}$$

where T_a is the transmission of the earthshine through the atmosphere, and $f_a(\theta_0)$ is the *lunar* phase function for the near retroflection from patch a. We note that the expression for the lunar Lambert phase function is the same as given in equation (7) with β replaced by θ. Similar to equation (13), the intensity of the sunlit portion, b, would be

$$I_b = I_s \frac{p_b f_b(\theta)}{R_{ob}^2} T_b, \tag{14}$$

where the lunar phase function, $f_b(\theta)$ embodies the dependence of the fiducial patch on the angle between the sunlight reflected off the moon (so-called "moonshine") to the terrestrial observer, again see Figure 1. Thus,

$$\frac{I_a}{I_b} = \frac{I_e}{I_s}\frac{f_a(\theta_0)}{f_b(\theta)}\frac{R_{ob}^2}{R_{oa}^2}\frac{T_a}{T_b}, \tag{15}$$

and so

$$p_e f_e = \frac{I_a}{I_b} f_b(\theta)[\frac{R_{em}}{R_e}]^2 \frac{T_b}{T_a}\frac{p_b}{p_a}[\frac{R_{oa}}{R_{ob}}]^2[\frac{R_{es}}{R_{ms}}]^2. \tag{16}$$

Since $\frac{R_{em}}{R_{es}} \sim 5 \times 10^{-3}$, we can safely set the the last factor in equation (16) to unity. Similarly, we can set the second to last factor to unity. Further, we can also safely set $\frac{T_a}{T_b}$ to unity because site surveys at BBSO have shown a close correlation between atmospheric turbulence over several tens of meters, and that the seeing arises fairly close to the ground, Goode, et al. (1999). Thus, we determine that

$$p_e f_e = \frac{I_a}{I_b}\frac{f_b(\theta)}{f_a(\theta_0)}[\frac{R_{em}}{R_e}]^2 \frac{p_b}{p_a}. \tag{17}$$

We measure I_a and I_b in our nightly observations. We have measured the lunar phase function quite accurately over the last year. We need a total eclipse to measure the ratio of the geometical cross-sections of the two fiducial patches, $\frac{p_b}{p_a}$. WHAT IS THE VALUE OF THIS RATIO? 1.2? In §6, we combine equations (9) and (17) to define our measure of the earth's reflectivity, A^*, in terms of measured quantities, including the varying earth-moon distance.

SEK NOTES

3. Observations: Earthshine Instrumentation and Data Acquisition

Earthshine observations are currently being carried out at BBSO. The earthshine telescope is aligned with, and mounted atop the 65 cm solar telescope.

3.1. Hardware

The basic optical components of the earthshine telescope consist of an f/15 telescope primary which is a 6-inch diameter air-spaced doublet. The telescope tube is attached and aligned with the 65 cm solar telescope which enables us to use the large telescope's drive software, permitting tracking following the moon's variable rate. The tracking rate is updated, via software, every thirty minutes to match the changing lunar motion in the east-west direction. Minor north-south corrections are done with the telescope control paddle as needed during the course of the night's observations. The moon is initially acquired using a simple two-lens finder scope aligned with the other telescopes on the 65 cm main telescope. The 65 cm telescope is regularly re-balanced for equipment changes so that tracking stability is not a problem even with long exposures. The observatory dome is automated to follow the solar disk during daytime operation. However, the sensors that make this possible do not work for lunar observing, so the dome must be checked every thirty minutes, or so. At the end of the tube is a stray light field stop. The incoming moonlight passes the field stop, and then enters a light tight optical assembly box that holds the filters and camera optics.

In the box, just behind the tube field stop and just before prime focus, is the earthshine neutral density filter switcher. Two filters are placed in the switcher. The first neutral density filter is a Schott NG3 2mm (transmission 0.0117 from 4000-7000 Å) for the Bright Side (BS) measurements. DOES OUR CALIBRIBATION DEPEND ON THE TRANSMISSION? The second filter is a Schott NG10 2mm (transmission is about 2×10^{-5} 4000-6000Å), which is essentially a blocking filter to cut off the bright side of the moon to permit the dark side or earthshine (ES) observations. The BS filter covers the entire field of view and is in place to prevent camera saturation and to provide a reasonable exposure range. The ES filter covers the bright side of the moon to permit long, dark side exposures to get optimal signal to noise for the ES images. The ES filter is carefully placed within the switcher filter holder, by hand, at the beginning of each observing session. Its location, designed to cover the terminator, depends on the phase and libration of the moon. Both filters were scanned to check transmission with wavelength at Gamma Scientific in San Diego using a Radoma spectroradiometer. Both filters were found to be well within the quoted Schott tolerances.

The prime focus is after the switcher, and it is closely followed by a flat field lens. Next in the optical train are two near IR filters that stop any light beyond 7000 Å from reaching the camera.

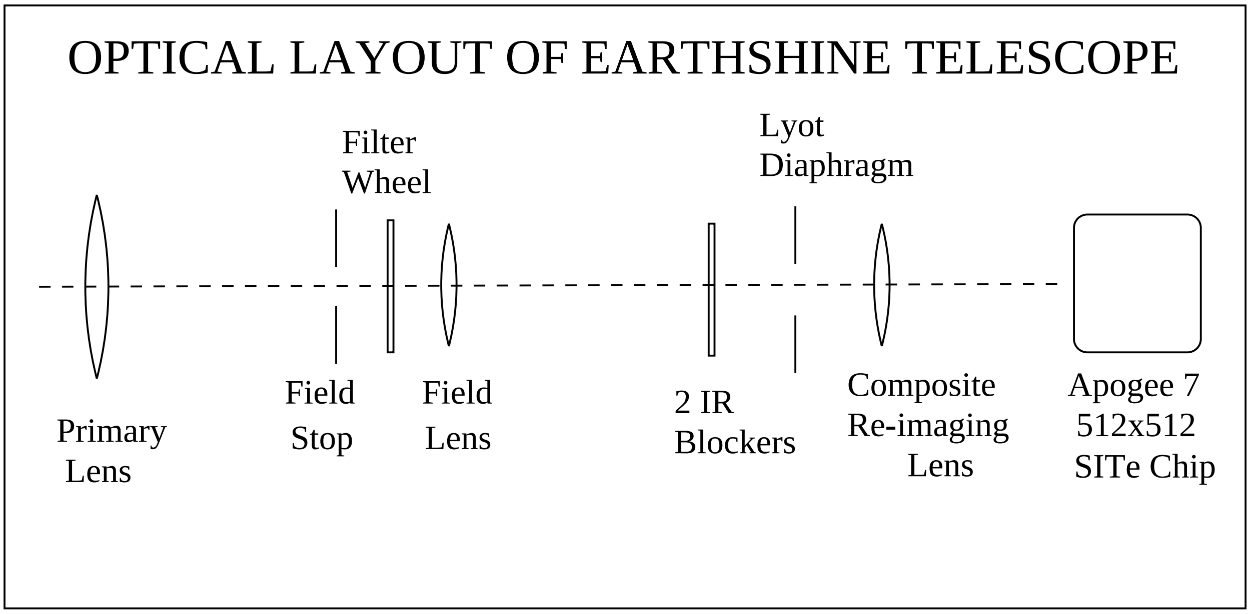

Fig. 2.— The optical set-up of the earthshine telescope.

An iris behind the near IR filters acts as a further stray light stop. Behind the iris is a camera lens that focuses the lunar image on the CCD. Between this lens and the camera is a space for a filter wheel which can be used for narrow band measurements. All elements are rail mounted for linear adjustments, and lens elements are in moveable $y - z$ mountings for fine adjustments. All fine-tuning was done in the Fall of 1998, and nothing has been changed on the system since the start of data acquisition in December 1998. The system was "frozen" to limit possible errors in calibrating the lunar phase function. Flat field images help to point out the location of occasional dust particles that get into the optics. Compressed air removes most particles, and when necessary, elements are removed for cleaning, and then are carefully replaced to preserve optical alignment.

The CCD camera used in our current earthshine observations is an Apogee 7. The camera is a 512 X 512 16-bit scientific system with a SITe back-illuminated, thinned silicon chip. This chip, which is one of SITe's highest grade, is designed for higher quantum efficiency than unthinned front illuminated chips – this advantage is most apparent toward the blue. One drawback of the higher efficiency SITe chip is its sensitivity to "after-images" caused by exposure to UV. Testing the earthshine system to limit this effect resulted in the following observing procedures: The UV from the BS images is blocked by the NG3 filter. The worst after-images show up in the ES images on the unfiltered half of the image – which are of long exposure. It was found that by increasing the number of short BS images, the UV residual image was removed. Careful examination of dark current and flat field images taken during the course of observations is done to confirm this, night by night.

Initial testing demonstrated a linear response over the camera's entire 16-bit range. To check for change in the camera's response with time, a calibrated radiometer was purchased to check the camera's responsivity during each new moon. Dome flats are taken in varying illumination to get pixel count versus intensity. The radiometer is an IL 1700, a NIST traceable Silicon photodiode radiometer. Once a year, the radiometer will be returned to International Light for re-calibration.

3.2. Observations

After initial tests, our current round of earthshine observations began in December 1998. A typical raw image is shown in Figure 3. The camera's graphic user interface C code, supplied by the manufacturer, was modified to efficiently handle the routine earthshine observations. The nightly observations follow a simple set of procedures. Most are almost completely automated. To begin, a few initial images are taken to center the moon. When the image is centered, the ES filter is set by hand, and the observer moves downstairs to the control room. Then, more images are taken to determine the ES and BS exposures which optimize the signal to noise ratio. Finally, data are taken and stored. During the course of observations BS, ES, dark current, and flat field images are taken regularly.

The first 8 months of observations covered lunar phases between 0° and $\pm 140^\circ$, which is about 21 days a month. The initial observation over this wide range of phases was necessary to determine the lunar phase function and prove its' repeatability. During the first 8 months, for the phases near the full moon (-40° through 0° to $+40^\circ$), ES images were not taken because both fiducial patches were in, or so near to sunlight that ES measurements were unreliable. On these nights only

BS, dark current, and flat fields, were taken to determine the scattering of light from the fiducial patches as a function of the phase of the moon. The lunar phase function was determined by July 1999, so that the BS-only nights were dropped – except for observations of the full moon. Full moon observations are still taken to determine the role of the opposition effect (REFERENCE) in the lunar phase function (phases -15° to +15°). Current earthshine observations cover about 14 days per month, and cover lunar phases between ±40° to ±150° centered on the first and last quarters of the moon when we have optimal conditions for measuring the earthshine – close to full-earth with a few hours of observations being possible. Data rates vary depending on phase. An average night will give about 1 image per minute. This means that the number of raw images saved for data reduction, varies between 100 to 600 per night.

4. Data Reduction

4.1. Image Analysis

The earthshine and moonshine intensities are measured by integrating the brightness of a pair of fiducial patches – one from the bright side and the other from the dark side of the lunar disk. In our study, ten physically fixed fiducial patches have been used with five in the earthshine and five in the moonshine, see Figure 3. In selenographic (lunar) coordinates, the center latitudes and longitudes of the five patches on the Crisium side are (-17.5, -70.), (-11.2, -71.5), (-5., -76.), (0., -75.), and (7.5, -76.5), and those of the five pathces on the Grimaldi side are (28.5, 72.5), (12.5, 75), (0., 77.), (-7.5, 75.), and (-13., 75.). Each patch covers a longitudinal range of about 10 degrees and latitudinal range of 3 to 5 degrees, the surface area being about 0.1% of the lunar surface. These patches are located in the "highlands" of the lunar surface, and the physical reflectivity of each is supposed to be roughly comparable. One of the patches on the Grimaldi side is very close to Danjon's choice, while the patches on the Crisium side are closer to the limb than Danjon's patch (Figure 3).

To locate these patches in each lunar disk image taken every night, it is essential to establish

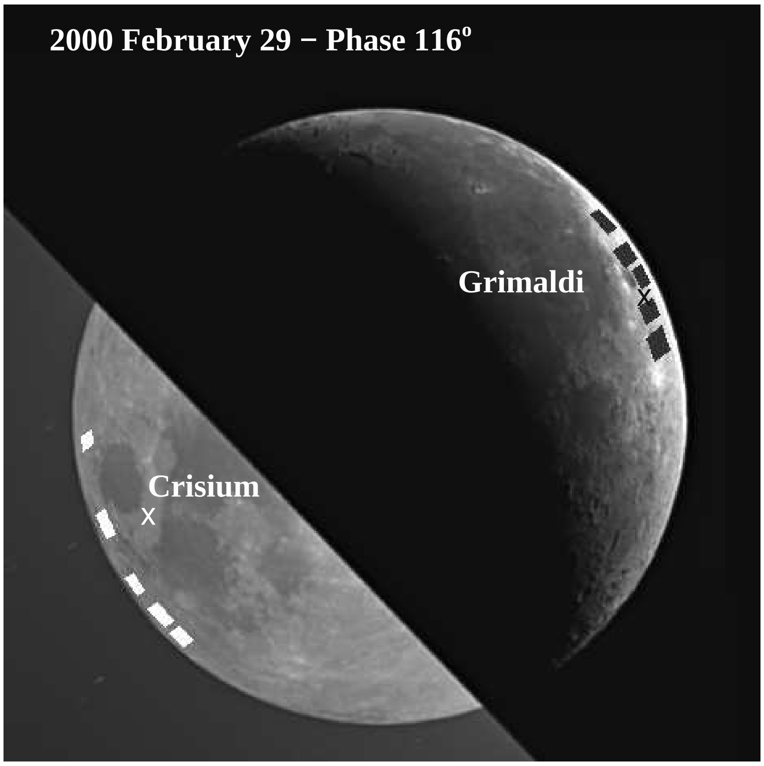

Fig. 3.— The moon showing the bright side and the earthshine. Grimaldi is in the moonshine and Crisium in the earthshine. Our ten fiducial patches used in the observations made from BBSO are indicated. The crosses give the approximate positions of Danjon's fiducial patches. The lunar phase is $115^\circ.9$, near a quarter moon. The ES is flat across the disk.

the transformation between the CCD image coordinate system and the selenographic coordinate system. For this purpose, we first define the limb and center of the lunar disk for each image. Each of the raw lunar images is contrast-enhanced, and the limb points are defined by looking for suitable positions of large intensity gradient. Empirically, a minimum of 40 rim points should be obtained, and are then used to make a Maximum Likelihood fitting to decide the lunar center in the image plane. Once the lunar center and limb are determined, the radius of the lunar disk is calculated in the CCD's coordinate frame. The next step is to define the position of the lunar pole in the image plane. To this end, some outstanding lunar features, whose precise selenographic coordinates are known, are used to co-register the two coordinate systems. The topocentric location of the lunar pole at any given moment can be precisely calculated using parameters from an astronomical almanac, from which one can determine the projected positions of these lunar features in the image plane, which is perpendicular to the vector pointing from the local observer to the lunar center. By comparing these projected positions with the positions of these features in the CCD coordinates, the angle between the projected N-S axis of the moon and the Y-axis of the CCD coordinate system is derived. [SOON I SHOUL DO ANOTHER THING TO DETERMINE THIS ONCE AND FOR ALL SO THAT WE DO NOT NEED THIS STEP ANY MORE AND THE ANALYSIS WILL BE FULLY AUTOMATIC @QJ]

Once the transformation between the image plane and the selenographic system is established, the five pairs of fiducial patches can be precisely located on the lunar disk image. The apparent areas of these patches change from night to night because of lunar libration. The intensity is read out as an average of the whole area, and the difference due to the geometric effect of the reflectivity arising from libration, is accounted for in our next step of data reduction (§4.2).

To ensure accurate photometry, flatfielding and dark current subtraction are performed on each image. For earthshine images, we also need to subtract the background scattering from the bright side of the moon. The background scattering should be a function of both the inclination of the vector connecting the lunar center and the background point with respect to the lunar equator, and the distance from the background point to the crescent. After experimentation, we find that we can safely assume that on the earthshine side, where the background points are not too close to the crescent, at a fixed inclination with respect to the lunar equator, the background intensity falls off linearly with the distance of the background point to the lunar center. Such a linear relation holds for the points which are not too far from the lunar equator. So, for each fiducial patch, centered on the vector connecting the lunar center and the patch, we open a small cone with an angular range of 5 degrees, and fit the intensities of the background points which are away from the lunar limb but inside the cone as a function of their distance to the lunar center. In this way, we can extrapolate the scattering intensity at the position of the fiducial patch using the parameters obtained from the least-square fit, and subtract the extrapolated value from the

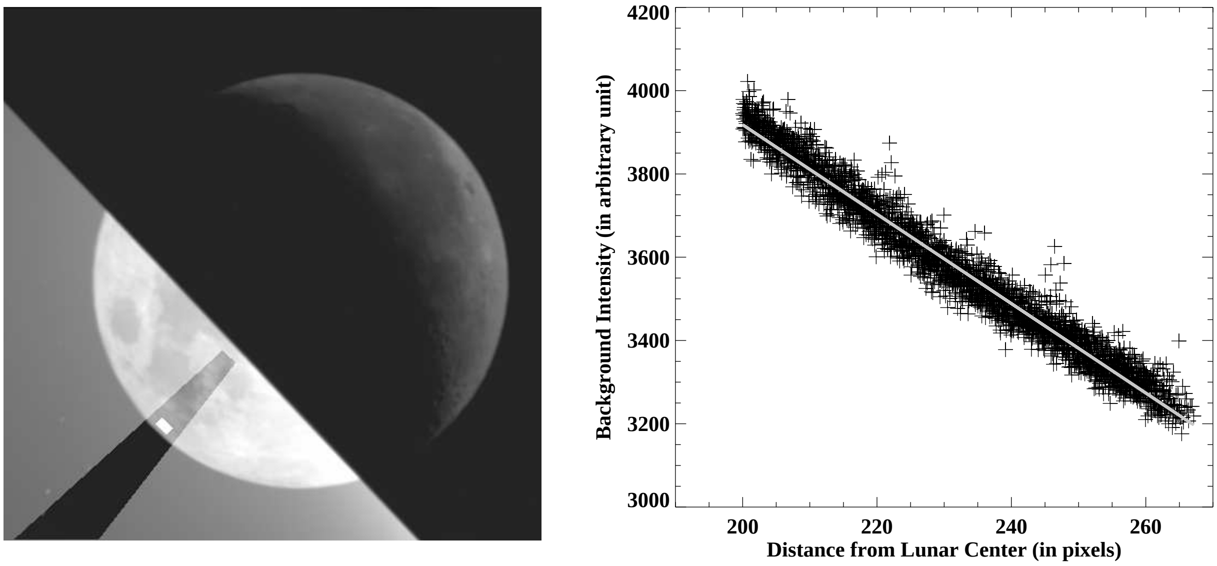

Fig. 4.— Illustration of the background subtraction for earthshine images. The image in the left shows the background cone around the fiducial patch, within which the intensity of the background points are read out to make a fit as a linear function of the distance from the lunar center. For the image shown the intensity inside the cone has the background subtracted already. The plot in the right shows the intensity falling off with the distance of the background point to the lunar center, and the overplottd thick grey line indicates the least-square linear fit.

intensity of the fiducial patch. Such a procedure is illustrated in Figure 4.

In accordance with Equation 16, the intensity obtained from above is also corrected by scaling to a set of standard distances between the sun, moon and earth, before the successive steps of calibration described in the subsequent subsections. These distance parameters are obtained precisely from ephemeris.

4.2. Atmospheric Extinction

To eliminate the effect of the atmospheric extinction, observations are carried out for as long as possible during the night so that a measurement of the intensity at varying airmass can be

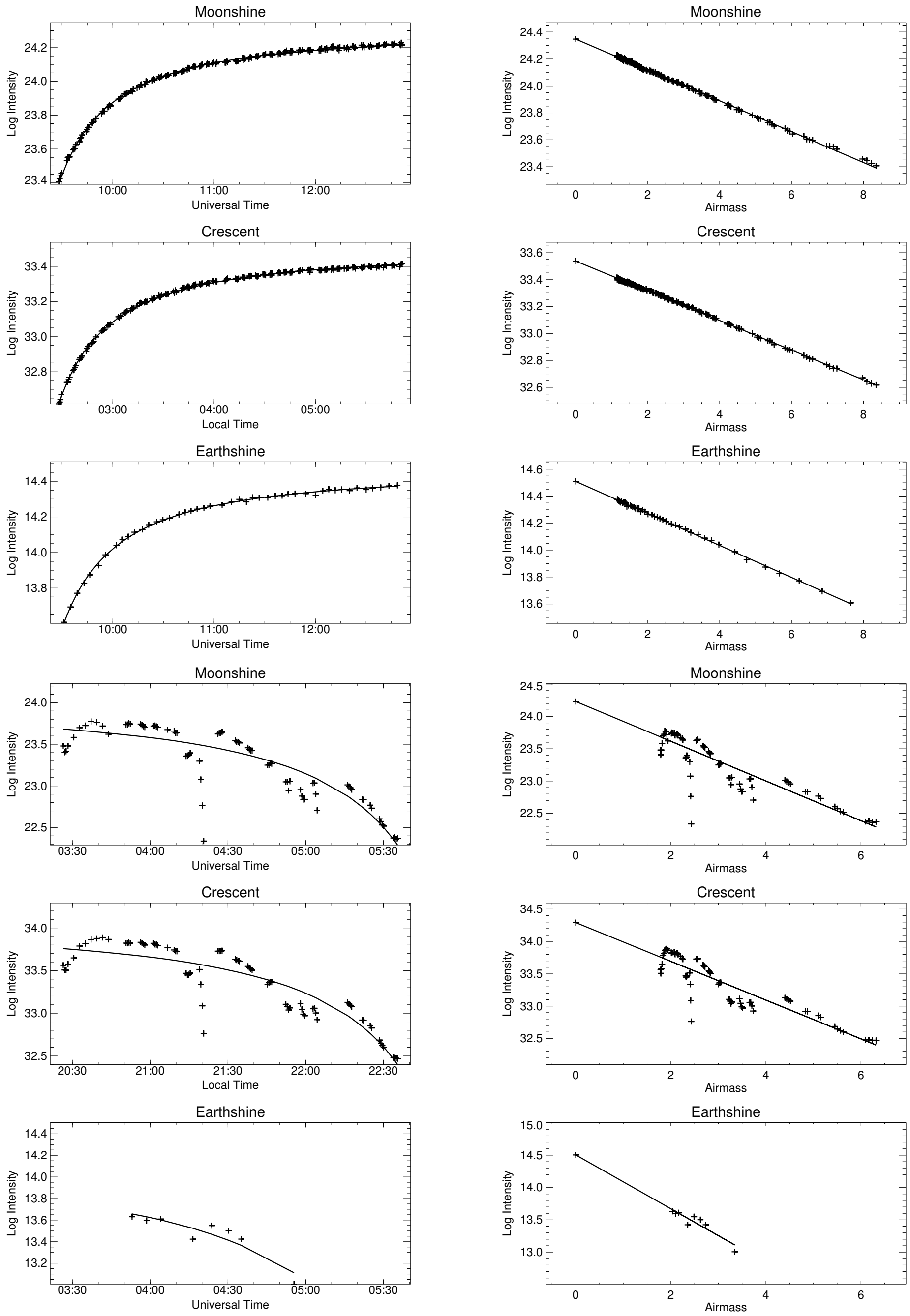

Fig. 5.— In each sub-frame, the moonshine (top panel), crescent (middle panel) and earthshine (bottom panel) intensity is plotted against time and airmass. The "+" indicates observed data points and the solid lines are Beer's law fitting curves. Upper: data from the night on September 5, 1999, demonstrating typical good night, and the standard deviation of the fitting is 0.007, 0.005, 0.007 (from top to bottom). Lower: data from the night on September 17, 1999, demonstrating a typical cloudy night, and the standard deviation of the fitting is 0.219, 0.183, 0.077 (from top to bottom).

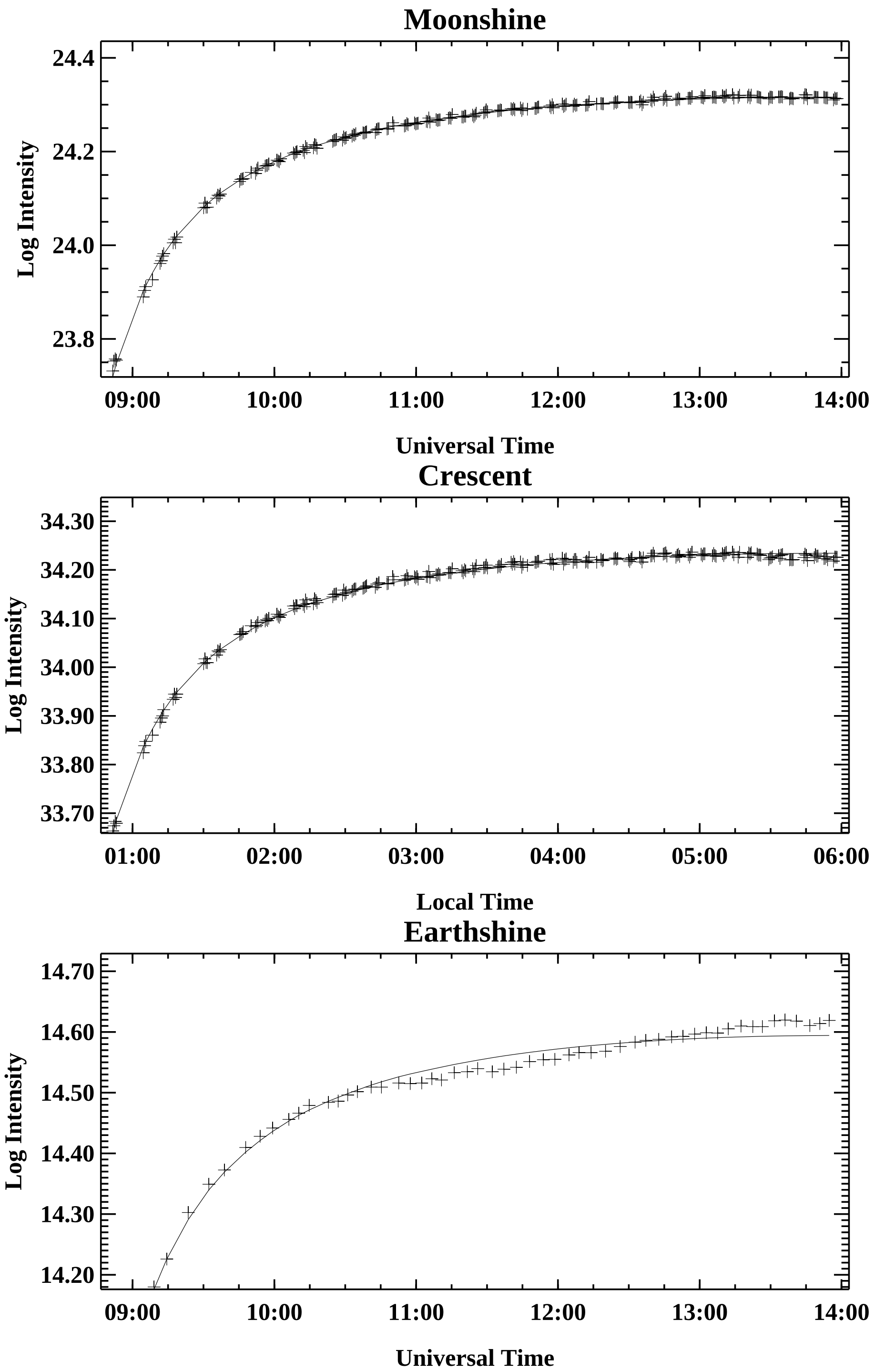

Fig. 6.— The moonshine, crescent and earthshine intensities and their Beer's law fit for the night of 2000 January 28, showing that while the moonshine and crescent intensity follows Beer's law very well, the earthshine intensity evolution deviates from Beer's law. The standard deviations of the fit is 0.004, 0.005, 0.014, respectively.

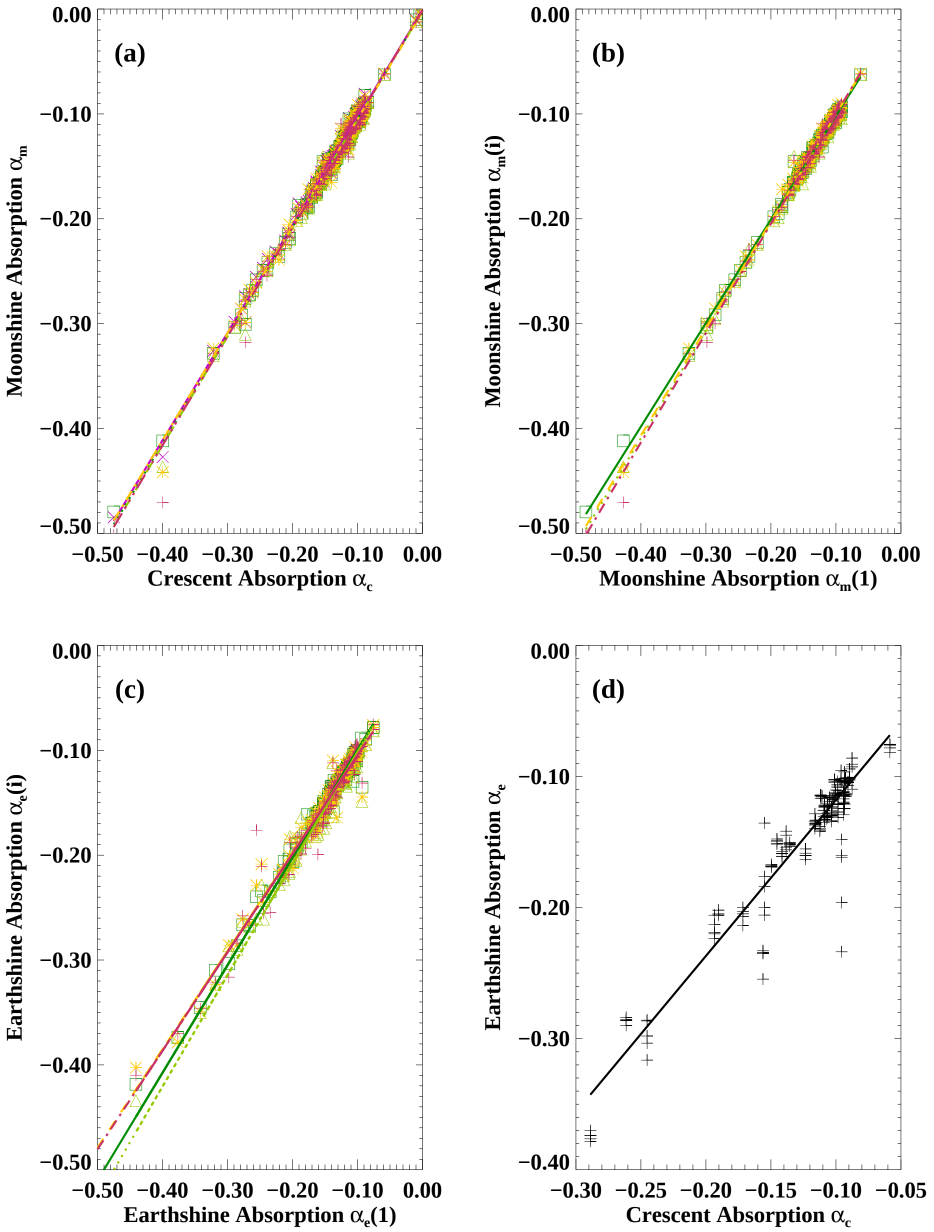

Fig. 7.— The variation of the atmospheric extinction coefficients for the crescent, (α_c), moonshine (α_m) and earthshine (α_e). Panel (a) illustrates α_m (for five fiducial patches as indicated by different symbols) against α_c; (b) shows α_m of four out of five fiducial patches (as indicated by different symbols) scaled to the fifth fiducial patch, illustrating that α_m is virtually the same for different patches; (c) shows α_e for four out of five fiducial patches (as indicated by different symbols) scaled against the other fiducial patch, showing that α_e is also the same for different fiducial patches in the earthshine; and (d) shows α_e (of all fiducial patches in earthshine) against α_c. The solid line in each panel indicates a least-square linear fit.

obtained. For the bright side of the moon, the variation of the intensity should follow Beer's law:

$$I = I_0 e^{(-\alpha z)}, \tag{18}$$

where I is the observed intensity, α is the atmospheric extinction coefficient, z is the local airmass and I_0 is the intensity at zero airmass – the intensity that would be received if the earth had no atmosphere.

The airmass, z , is determined from the angular altitude of the moon in the sky at different times in such a way that when the coaltitude θ_c - the inclination of the observer's line of sight with respect to the local zenith, which is the complement of the moon's angular altitude - is smaller than 60^o, $z = 1./\cos(\theta_c)$, otherwise z is interpolated from a standard airmass table (Table 1):

The above calculation refers to the airmass at sea level with the pressure $p_0 = 760$ mmHg and temperature $t_0 = 10^oC$, and the real airmass at the observer's location should be corrected by a multiplicative factor of $p/p_0/(0.962 + 0.0038t)$ (REFERENCE: C. W. Allen, 1973, Astrophysical Quantities, p.125). The altitude of BBSO is 2067m above sea level, and the pressure scale height at this altitude is 8200m, which yields $p = p_0 exp(-2067./8200.)$. We then incorporate the calculated z into the Beer's law fitting to get the parameters α and I_0. We reckon that throughout a night, the evolving lunar phase function can also contribute to the changing intensity. The maximum phase change in a long night is less than two degrees, within which the intensity change is negligible compared to the change due to the airmass. Nevertheless, we employ a quasi-iterative way to correct this minor effect, in that we use an initial fit of the phase function (see the following

Table 1: Standard Airmass Table (θ_c in degrees)

θ_c	60.	62.	64.	66.	68.	70.	72.	74.	76.	78.	80.
z	2.00	2.12	2.27	2.45	2.65	2.90	3.21	3.59	4.07	4.72	5.60
θ_c	81.	82.	83.	84.	85.	86.	87.	88.	89.	90.	-
z	6.18	6.88	7.77	8.90	10.39	12.44	15.36	19.79	26.96	40.00	-

section on how to obtain the phase function) to correct the data, and after the airmass correction, we make the phase function fit again. After a few iterations, the data converge to a stable result. The observed intensity at each moment, I_i, is corrected, using the airmass, to the intensity at zero airmass, $I_i^0 = I_i \exp(\alpha z)$. I_0 from the fitting is further used as intensity for that night's lunar phase function.

The goodness of the fit to Beer's law offers a ready criterion by which each night's local sky can be judged – the "good" night's data can be separated from that of the "bad" (noisy) nights (Figure 5). In practice, unless it is cloudy the data from almost all observable nights are preserved, and the standard error in the fitting for each night is further used as the input error for the lunar phase function fit. Figure 5 shows an example of a typical good night and a bad night, as judged by the Beer's law fitting. Experience from the observations shows that the data usually follow Beer's law quite well, and the accuracy of the moonshine fitting is often better than 1%. Among all the datasets collected for 320 nights from December 3, 1998 to November 30, 2000, for 147 nights, the accuracy of the fitting is better than 1%, and for 115 nights, the accuracy is between 1% and 2%.

In the case of earthshine intensity, apart from the atmospheric transmission, the evolution of the earthshine is also influenced by changing of the earth during a given night; e.g., the sun rising over China. Indeed, almost every month, on a few nights, we observe that the evolution pattern of the earthshine intensity does not track Beer's law very well, while the moonshine intensity closely follows Beer's law. An example of such a case is shown in Figure 6 In general, the fitting of the earthshine yields a standard deviation which is larger than the moonshine fitting by one-half to one percent. This latter difference contains the signal of the earth's albedo. Furthermore, when the earthshine evolution pattern is significantly controlled by real changes in the earth's reflectance, apart from the atmospheric extinction, as is shown in Figure 6 , the atmospheric absorption coefficient α obtained from the Beer's law fitting of the earthshine observations may deviate from the true value, so that the correction of atmospheric attenuation cannot be properly done.

We study this problem by investigating the relationship between the earthshine coefficient

α_e and the moonshine coefficient α_m. As a reference, we have also examined α_m for different fiducial patches and α_c which is the fitting parameter for the integral intensity of the whole crescent. Figure 7 (a) and (b) show the relation between α_c and $\alpha_m^i (i = 1, 2, 3, 4, 5)$ for all five fiducial patches. A least-square fit yields that α_m^i $(i = 1, 2, 3, 4, 5)$ can be regarded as identical to one another and to α_c. This is not a surprise even though the atmospheric attenuation is also a function of the wavelength (REFERENCE), because the light from a moonshine fiducial patch should have the same spectrum as the light from the whole bright side. Similarly, the absorptivity of earthshine α_e shows a linear correlation to α_c (Figure 7 (d)), but the absolute value of α_e is systemetically larger than that of α_c, indicating a stronger atmospheric attenuation in earthshine than in moonshine. This is because the earthshine and the moonshine have different spectra; specifically, the earthshine is bluer than the moonshine (the earth's atmosphere scatters blue light more effectively), and atmospheric absorption is stronger toward shorter wavelengths.

From the linear scaling law that we find between α_e and α_c, we therefore can make a better determination of α_e from α_c for the nights when earthshine variation shows a mixture of the local airmass change and global change hence does not follow exactly Beer's law. This can be expressed in the following way:

$$\alpha_e = a \times \alpha_c + b, \tag{19}$$

where the scaling parameters a and b are obtained by a linear least-square fit of the above relation using α_e and α_c from the nights which do not show apparent global change. We reckon that for the nights of significant global change, the standard deviation of the Beer's law fitting of the earthshine (σ_e) must be a lot larger than that of the crescent (σ_c), given that the atmosphere is reasonably stable throughout a single night. For this reason, we make a further assumption that when σ_e is less than a cutoff value q times σ_c, i.e., $\sigma_e < q\sigma_c$, we regard the global change as not being significant for this night, and α_e from the Beer's fitting for this night is reliable. Only then do we use these nights to make the fit in order to decide a and b.

In Table 2, we list the fitting results, a, b, σ (the standard deviation of the fit), σ_a and σ_b (the fitting errors of a and b respectively) at various cutoff values, $q = 1.0, 1.2, 1.5, 2.0, 2.5$.

We can see from Table 2 that for $q < 2.0$, the fitting results are consistent. In general, the absolute value of α_e is larger than that of α_c by more than 0.01, or about 10%. Note that we do not distinguish α_e from different fiducial patches, because there is no reason for us to believe that α_e^i should be different from one to another (also see Figure 7 (c)). As a matter of fact, we have tried to scale α_e^i to α_c separately, and the resultant fitting parameters a and b do not differ for different patches. In the subsequent analysis, we employ the scaling parameters at $q = 1.2$ in Equation 19 to obtain α_e for nights when $\sigma_e > 1.2\sigma_c$, and correct earthshine intensity with this α_e. After applying this correction, a direct result is that while the average of [A*] is not altered, for some nights their appreciable, original deviations from the [A*] curve are greatly reduced. At any rate, it is clear that there is no apparent tendency for the earthshine signal to be subsumed in α_m. HOW DOES IT SHOW THIS? MAYBE A COMPARISION OF GOOD AND BAD NIGHTS IN THE SAME TYPE OF PLOT? — GOT TO THINK ABOUT THIS QUESTION @QJ

5. Lunar Phase Function

The lunar phase function, defined in §2 as the change of moonshine intensity as a function of the phase of the moon, is measured from the readout intensity from each of the fixed fiducial patches used throughout the observations, after carrying out step-by-step each of the corrections described above. When the observed intensity readout is plotted against the lunar phase for all nights, the data are quite scattered around the average curve (Figure 8a). Most of the scatter is not due to unknown or random sources of noise, but rather known physical effects which can be systematically removed. Several steps of calibration are necessary before we have an accurate measurement of the true lunar phase function. The results of the successive steps in the correction are shown in the four panels of Figure 8.

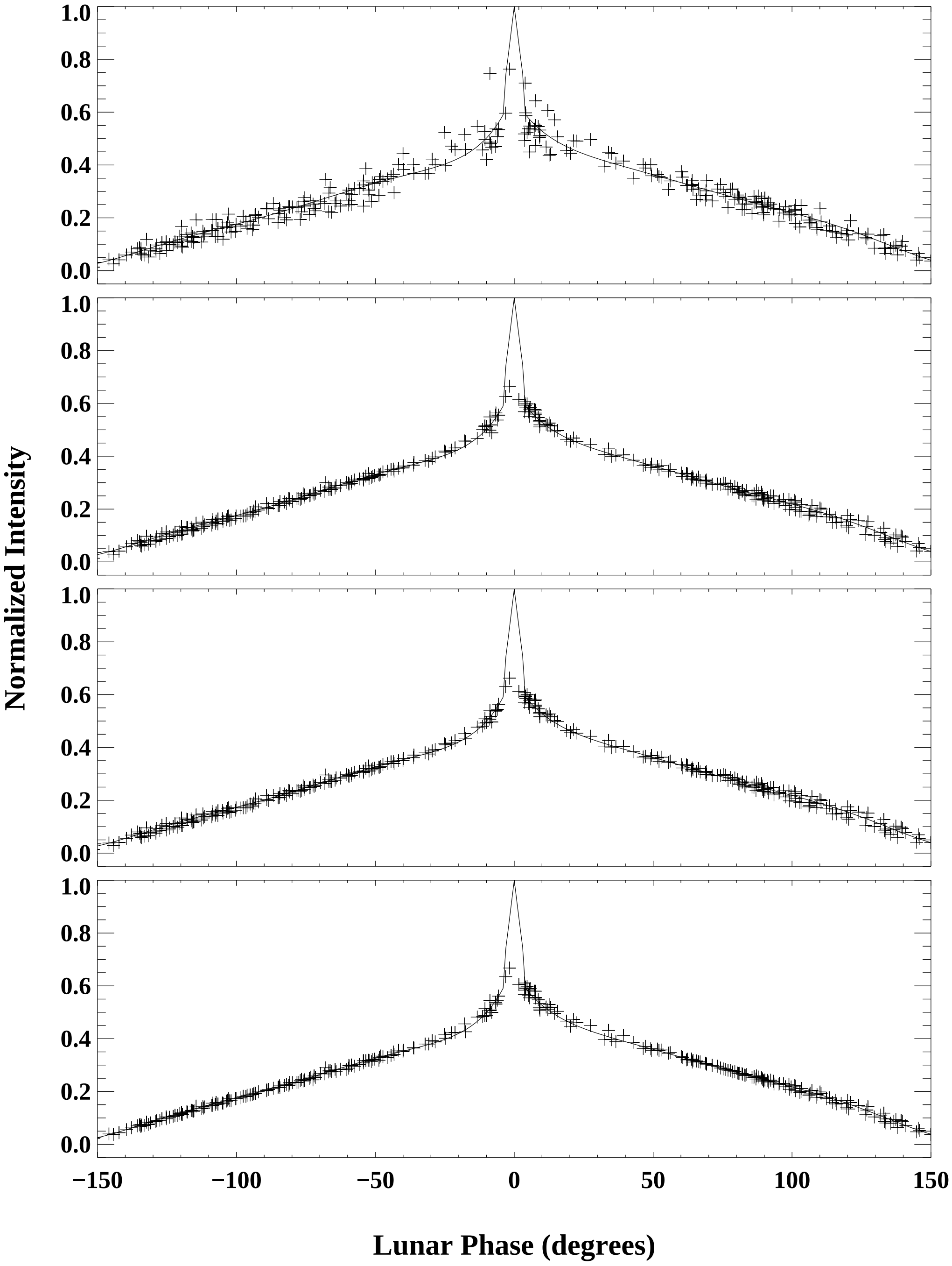

Fig. 8.— Lunar phase function plots from the raw data and from data after each step of correction.

5.1. Atmospheric Correction

The measurement of the moonshine intensity on different nights, even after extrapolation to zero airmass, is subject to changes in the local atmospheric conditions. After all, the local atmosphere is not a uniform plane, parallel gas. Because of this, there is a deviation in the intensity measured from the same fiducial patch at the same lunar phase, but on different nights (that is, successive lunar cycles). The common practice in nighttime observations is to use standard stars to calibrate the night. We have found that the crescent of the moon is our best standard "star". That is, we correct from night-to-night using the correlation between the change of the moonshine intensity and the crescent intensity.

We use a fifth degree weighted polynomial fit for both the fiducial patch intensity and the average crescent intensity over the area of the bright portion as a way to determine the average of the intensity at each lunar phase. Because of the pronounced opposition effect which gives a sharp increase in the moonshine intensity when lunar phase approaches zero degrees, in the polynomial fitting, double weight is given to data points of lunar phase of less than $\pm 5°$. The deviation of the measured intensity at each data point from the fitting curve, see Figure 8, for the lunar phase function, in both the moonshine case and the crescent case are obtained, and the cross correlation between these errors is calculated. For the morning observations, for which the lunar phase is positive, we get a cross correlation of 0.73, and for the evening when the lunar phase is negative, 0.77 (Figure 9). A simple least-square linear fit is made between the moonshine deviation and crescent deviation (equation 20), and the correlated part of the error is subtracted from the moonshine data as a correction for the nightly variation (equation 21).

$$\frac{I_i - \bar{I}_i}{\bar{I}_i} = a_0 \times \frac{C_i - \bar{C}_i}{\bar{C}_i} + b_0 + S_i \tag{20}$$

$$I_i' = I_i - a_0 \times \bar{I}_i \times \frac{C_i - \bar{C}_i}{\bar{C}_i} \tag{21}$$

Here, I_i is the observed fiducial patch intensity, C_i is the crescent intensity, $\bar{I}_i$ and $\bar{C}_i$ are the average fiducial patch intensity and crescent intensity, respectively, at the same lunar phase. The coefficients a_0 and b_0 are derived from the least square fitting of equation (20). The scattering

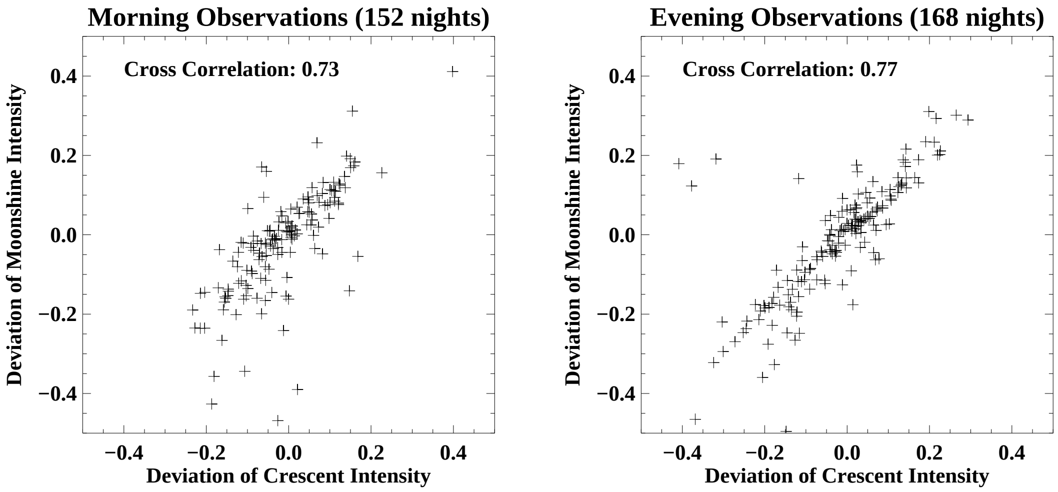

Fig. 9.— The deviation of the moonshine fiducial patch intensity from average against the deviation of the overall intensity of the crescent. Left: data points from morning observations; right: data points from evening observations.

among the datapoints is much reduced after this correction (Figure 8 (b)). This correction is more significant for the evening data (lunar phase < 0), because in the evenings we are mostly observing the moon in the western sky over Los Angeles and the Pacific Ocean, which are more subject to local atmospheric changes.

5.2. Declination Correction

The second step in correcting the lunar phase function is made by taking into consideration the relative position of the moon and the sun with respect to the earth. The difference in right ascension between the sun and the moon (hereafter, the "relative right ascension") changes from 180 to -180°, which essentially determines the lunar phase, defined as the angle from between the moon-earth line and the sun-moon line, see Figure 1. The difference in the declination between the sun and the moon (hereafter "relative declination") changes as well, since the orbital plane of the moon around earth is inclined to that of the earth around the sun. Toward the full moon, the relative declination also becomes important in determining the lunar phase. As a result, at the same lunar phase, but on different nights (that is, different months), the position of the moon may be different, and this difference alters the readout intensity of the fiducial patches. To correct for this effect, for a given lunar phase around the full moon, we choose a standard position of the moon and normalize the readout intensity of different positions to this standard position. The standard position is the one for which the relative declination is zero and the lunar phase is equal to the relative right ascension. The normalization is made as follows:

$$I_i - \bar{I}_i = a_1 P_i + b_1 D_i + c_1 + S_i, \tag{22}$$

where I_i is the observed intensity, $\bar{I}_i$ is the average intensity at the same lunar phase as I_i, obtained from a fifth degree polynomial fitting, P_i is the absolute value of the difference between the lunar phase and the relative right ascension, D_i is the relative declination, and a_1, b_1, and c_1 are fitting parameters which are determined from the least square fitting using all the observed intensities. The normalized intensity, I_i', is derived by taking P_i and D_i as zero:

$$I_i' = I_i - (a_1 P_i + b_1 D_i). \tag{23}$$

This correction is only made for lunar phase between -15 and +15 degree since the effect of the relative position of the moon is only important around the full moon. After this correction, the data points which were originally quite noisy around the full moon get tighter (Figure 8c).

5.3. Libration Correction

The third step correction accounts for the lunar libration. Since the orbit of the moon around the earth is not in the equatorial plane of the moon, the north pole and south pole of the moon are seen alternatively during each orbit. This is latitudinal libration. Since the orbit of the moon is not a circle, but is slightly elliptical, the moon moves faster at apogee than at perigee, and therefore is seen wobbling around its axis of rotation. This is longitudinal libration. As a result of both kinds of libration, for different cycles of the lunar orbit, even at the same lunar phase,

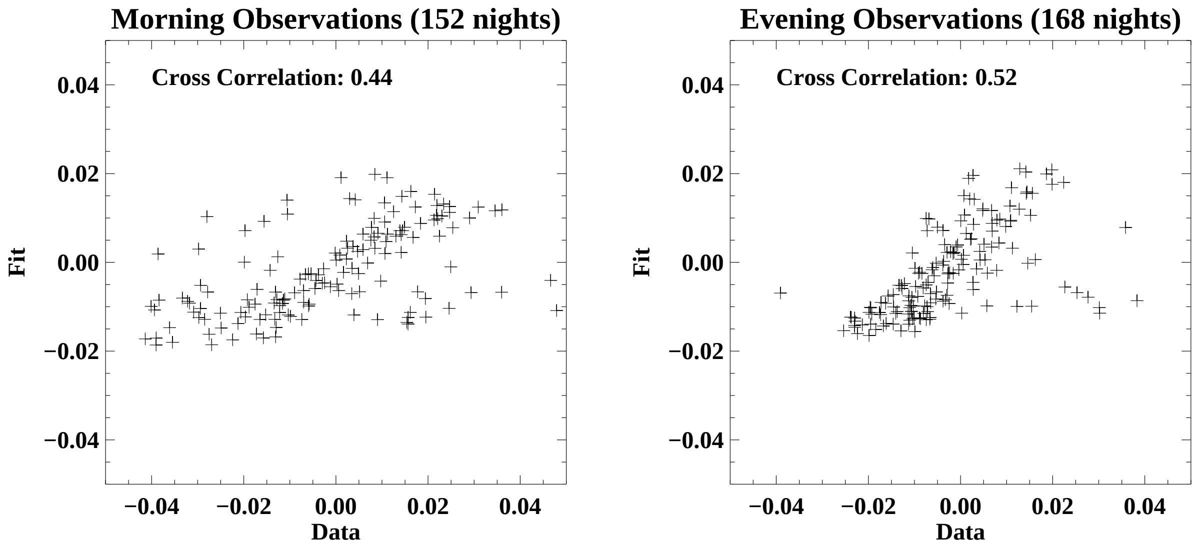

Fig. 10.— The deviation of the moonshine fiducial patch intensity (after the first and second step corrections) from average against the deviation as a fitting result from Equation (23). Left: data points from morning observations; right: data points from evening observations.

we would expect a change in the positions of the fiducial patches on the lunar disk. The readout intensity thus changes as a function of the geometric position of the fiducial patch on the lunar disk. Specifically, the longitudinal and latitudinal librations have the consequence that, at the same lunar phase there are multiple values of moonshine intensities for a given lunar phase. To first order accuracy, we derived a description of the deviation of the observed intensity to the averaged intensity as a linear function of the longitudinal and latitudinal librations, which goes as: THERE IS ALSO A DYNAMICAL LIBRATION BECAUSE THE MOON IS PROLATE AND THE POINTING WANDERS–DOES THIS MATTER? IS IT TOO SMALL TO MATTER? — I THINK THIS IS TAKEN INTO ACCOUNT BELOW; BECAUSE WHATEVER REASON PRODUCES THE LIBRATION, IT HAS TWO COMPONENTS, WITH WHICH WE MAKE THE CORRECTION BELOW. QJ

$$I_i - \bar{I}_i = a_2 L_i^{\alpha} + b_2 L_i^{\beta} + c_2 + S_i, \tag{24}$$

where L_i^α is the longitudinal libration and L_i^β is the latitudinal libration. The coefficients a_2, b_2 and c_2 are obtained from the least-square fit of the above equation. Figure 10 shows that the fit well describes the data, in that the observed scattering at this step is mainly accounted for by the libration. (For the lunar phase function fit, we use 152 mornings and 168 evenings, and the correlation between the fit and the data is 0.44/0.52 respectively. DONOT THINK WE NEED TO WRITE THIS; IT IS HARD TO UNDERSTAND FOR A READER AND LESS MEANINGFUL TO MENTION EITHER; BUT I KEEP FOR OUR RECORD. QJ) Using the parameters from the fit, we then normalize the intensities at all lunar phases to the case of zero libration with the equation:

$$I_i' = I_i - (a_2 L_i^\alpha + b_2 L_i^\beta) \tag{25}$$

EQUATION ABOVE IS WRONG.

The lunar phase function for both fiducial patches are produced from a fifth degree weighted polynomial fit to the corrected data. The same algorithm is used for all the steps above as the means of deriving the average of the intensities through the lunar phase. After each step of correction, the standard deviation of the fit is deduced from orginally 0.07/0.04 (evening/morning) to 0.04/0.03, 0.02/0.02, and eventually 0.01/0.01, with the phase function normalized to unity. A restricted regularized fitting is performed as well, which parameterizes the intensities at 181 bins (corresponding to lunar phase 0° to 180°). These 181 parameters from the fitting describe the lunar phase function, in that the intensity of any lunar phase is the linear interpolation between the values at the two grids into which the lunar phase falls. Note that since there are no data points beyond 150° degrees, the phase function fit beyond this range is not reliable. Similarly, there are not enough data points within ±5°, and so, in the next section we will replace this part based utilizing a fit of the opposition effect at small phase angles (near the full moon). From the third-step fit, the estimated error of the mean is at the level of 0.5%???, thus, we have measured the lunar phase to 0.5% (NOT 1% ? USE 0.5% FOR SUBSEQUENT DISCUSSION) I GOT TO REMEMBER HOW TO EVALUATE THE ERRORS AGAIN. @QJ

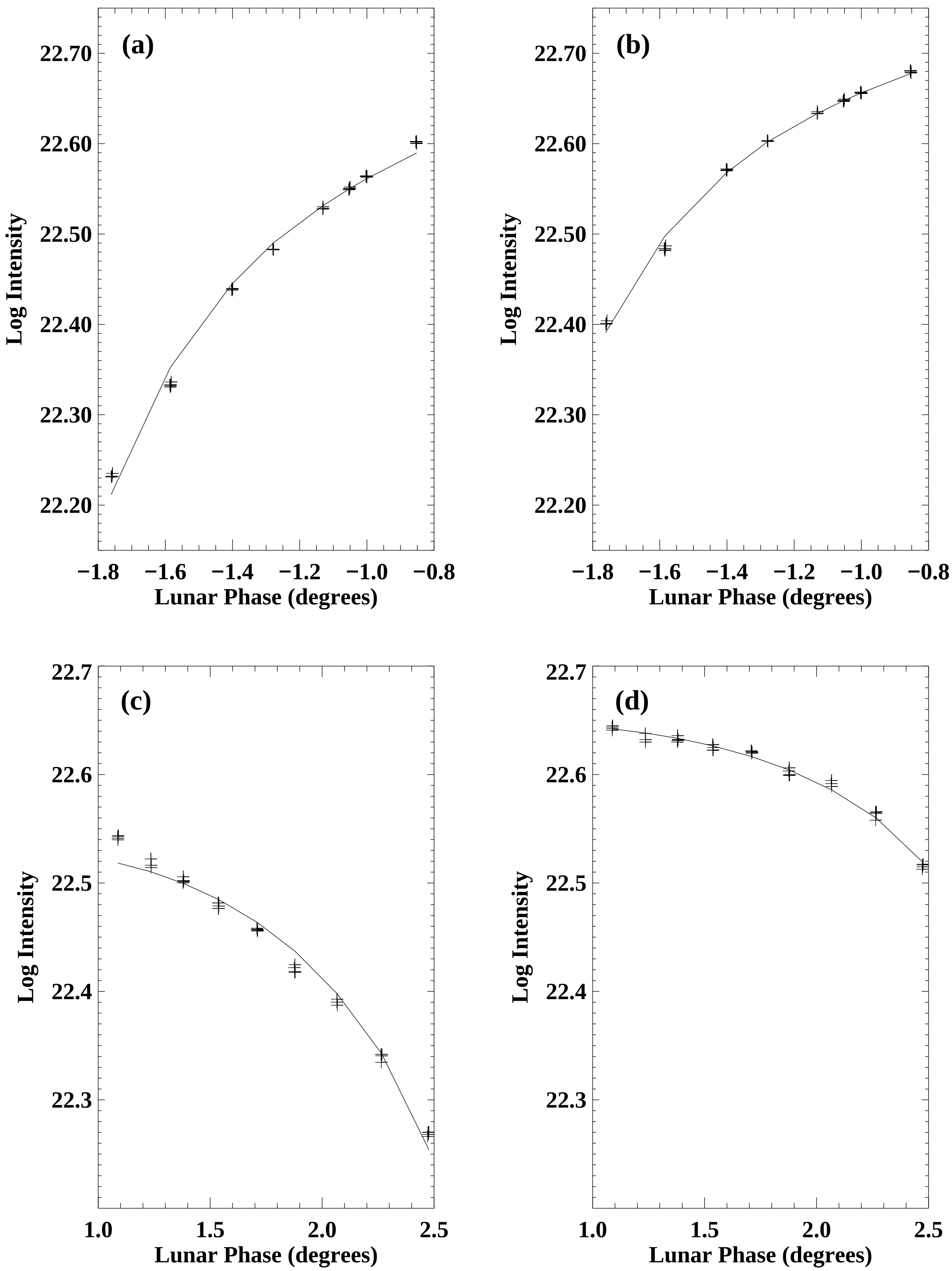

Fig. 11.— Fit of lunar eclipse data obtained on November 29, 1993. (a) Beer's law fit of the Crisium side (Equation 18); (b) Composite Beer's law plus opposition effect fit on the Crisium side (Equation 26); (c) same as (a) on the Grimaldi side; (d) same as (b) on the Grimaldi side.

5.4. Opposition Effect

The final lunar phase function for each fiducial patch needs to be normalized to the full moon opposition peak. In reality, the moon is not observable at zero lunar phase because the shadow of the earth will then occupy about $\pm 0.8°$. So far, the smallest phase we have reached is $\pm 1.0°$ on the night of November 29, 1993, when a total lunar eclipse occurred. On this night, the sky was clear and stable throughout the night, and observations were made both before and after the total eclipse which offers a unique dataset to investigate the opposition surge effect for all fiducial patches on both the Grimaldi side and the Crisium side.

The images taken on the eclipse night were processed and the intensities of the fiducial patches are read out as described in Section 4.1. The atmospheric attenuation has to be corrected to get the real moonshine intensity. However, throughout the night, evolution of the moonshine intensity is controlled not only by changing airmass, but also by the changing phase angle. This latter effect is appreciable because of the strong opposition effect at small lunar phase angles. As a result, the shape of the intensity evolution deviates strongly from Beer's law (Figure 11a and c), and Equation 18 can no longer produce a reasonable fit.

We developed a simple solution to this problem under the reasonable assumption that the opposition effect is a linear effect within a small range of phase angles, say, from 0 to 5°. After all, the phase angle changes by less than two degrees in the eclipse for either the Crisium branch or the Grimaldi branch. The observed intensity can then be represented by:

$$I_i = I_0 \times (1 - \beta P_i) \times e^{-\alpha z_i}, \tag{26}$$

where I_i is the observed intensity at phase angle P_i and airmass z_i. In contrast to Equation 18, I_0 describes the intensity at both zero airmass and zero phase angle. The third item in the right of the equation describes the term of atmospheric attenuation, i.e., Beer's law. The second item describes the opposition effect in that with the increase of lunar phase, the intensity is reduced linearly by a factor of β per degree.

We input the observed I_i at lunar phase P_i and airmass z_i into the equation above and make a least-square non-linear fit to obtain the atmospheric absorption coefficient α, the moonshine intensity at zero lunar phase and zero airmass I_0, and the opposition effect coefficient β. Note that I_i is also corrected for libration using the relations derived in equation 25. The fit is made for all ten fiducial patches. We collected about 40 data points for the fit on each side of the moon, and the standard deviation of the final fit is at the level of 0.5%. Figure 11 shows the different fitting results for one pair of fiducial patches, using Equation 18 and Equation 26 respectively, from which we can see that Equation 26 accurately describes the composite effect of the opposition surge and Beer's law. The opposition parameter β from the fit is then used to normalize the phase function for each of the fiducial patches. Figure 8 shows an example of the final lunar phase function normalized to the opposition peak.

In Table 3, we list values of the derived opposition coefficients, β, for all ten fiducial patches. The value of β for all fiducial patches is approximately 0.08, indicating that when lunar phase changes from 6 degrees to full moon (zero degree), the intensity almost doubles. This is the well-known opposition surge which has not been quantitatively determined previously.

The parameter I_0 is also used to obtain the ratio of the earthshine patch reflectivity to the moonshine patch reflectivity p_a/p_b. Table 5 gives the determined ratios of the each of the Crisium regions patch reflectivities to the each of the Grimaldi regions patches reflectivities:

In Figure 12, we compare Danjon's fitted phase function to our corrected one. Danjon used slightly different fiducial patches, but that is not the source of differences. Rather, it is the opposition surge which was unknown in Danjon's time. There is a clear offset in the Danjon phase function which would yield uniformly higher albedos than the true phase function. For our phase function, we have eliminated this large source of error introduced by the phase function in earlier incarnations of earthshine studies, like those of Danjon.

Table 2: α_e against α_c

q	a	b	σ	σ_a	σ_b
1.0	1.1886	-0.0073	0.0099	0.0183	0.0023
1.2	1.1830	-0.0061	0.0128	0.0170	0.0023
1.5	1.1813	-0.0051	0.0132	0.0172	0.0023
1.8	1.1881	-0.0050	0.0140	0.0171	0.0023
2.0	1.2281	-0.0095	0.0167	0.0169	0.0023
2.5	1.2222	-0.0124	0.0164	0.0161	0.0022

Table 3: Opposition Effect

Patch	1	2	3	4	5
Grimaldi side	0.084	0.078	0.083	0.079	0.083
Crisium side	0.086	0.079	0.076	0.083	0.083

Table 4: $\frac{p_a}{p_b}$ (Crisium/Grimaldi)

Patch	1	2	3	4	5
	1.12110	1.12977	1.14125	1.08628	1.10858
	1.04154	1.04969	1.06028	1.00926	1.02994
	0.918889	0.926113	0.935420	0.890433	0.908657
	0.983244	0.990883	1.00092	0.952730	0.972273
	0.988684	0.996367	1.00646	0.958002	0.977653

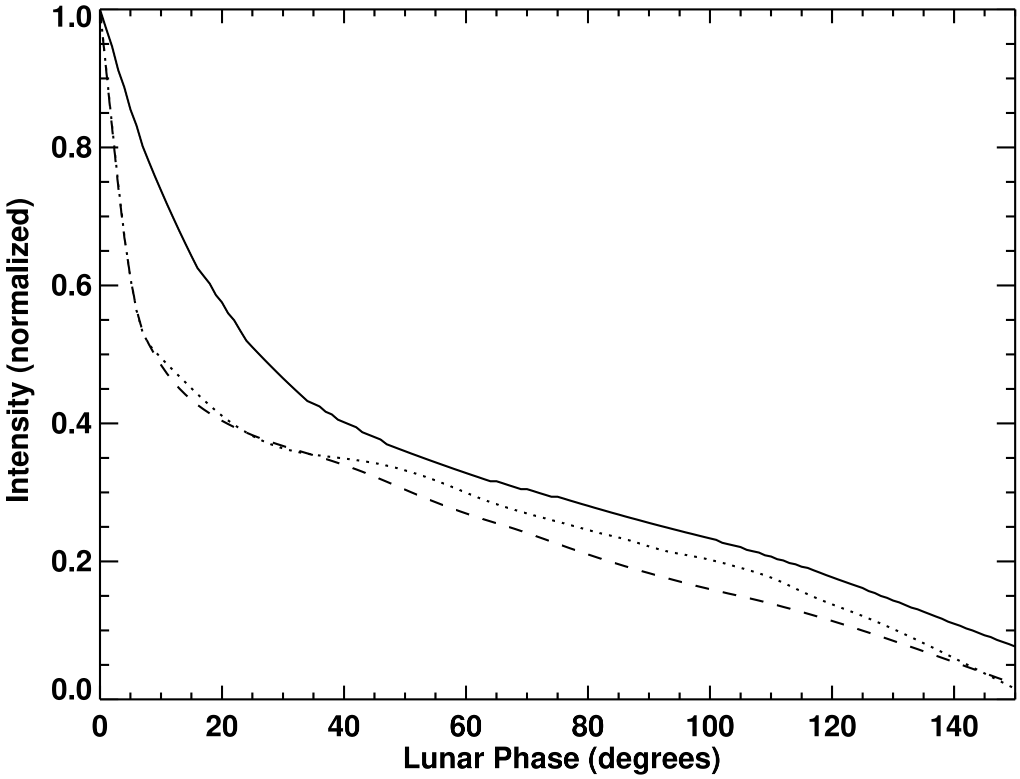

Fig. 12.— Danjon's phase function (solid line) is plotted against lunar phase. Using Figure 8d, the dashed line is our phase function for evening observations and the dotted line for morning.

6. Determination of the Earth's Albedo

The effective albedo is calculated from the earthshine measurement by combining equations (9) and (17):

$$A^* = \frac{3}{2f_L}\frac{f_b(\theta)}{f_a(\gamma)}\frac{I_a}{I_b}\frac{R_{em}^2}{R_e^2}\frac{p_b}{p_a}, \tag{27}$$

where I_a/I_b is the ratio of the earthshine intensity to the moonshine intensity in two opposing fiducial patches. Each is the extrapolated intensity to the zero airmass, with the libration effect corrected. The ratio between the physical reflectivity of the two opposing fiducial patches, $\frac{p_b}{p_a}$, is determined from the lunar eclipse data taken at BBSO on November 29, 1993, as given in Section 5.4. 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, and $f_a(\gamma)$ accounts for the fact that the earthshine is not exactly retroflected from the moon ($\gamma \lesssim 1°$). In our analysis, γ is taken as the angular distance between the observer's position and the center of the sub-solar point and the sub-lunar point on the earth's surface with respect to the lunar center. We also corrected libration effect in the earthshine data, assuming that the libration effect on the earthshine intensity follows the same law as it does on the moonshine intensity, as determined from Equation 24.

For convenience, the measured earth's albedo is often expressed as the magnitude of the effective albedo, A^* (see Equation 11), i.e.,

$$[A^*] = -2.5 \log A^*. \tag{28}$$

This standard astronomical definition implies that the larger $[A^*]$ is, the smaller the albedo. Note that a 1% change in A^* corresponds to a about $0^m.01$ change in $[A^*]$.

Since we observed 10 fiducial patches, 5 on the Crisium side, and 5 on the Grimaldi side, in principle, for each night, we shall obtain 25 values of [A*] from the 25 combinations of the 5 pairs of fiducial patches. This gives us a way to evaluate the reliability of our measurement of [A*]. Figure 13 (a) and (b) shows the [A*] plot (morning and evening respectively) against lunar phase of all 25 datasets. It is clear that the variation pattern appears in all datasets, indicating that this pattern is real and not from measurement noise. We take an average of the 25 measurements

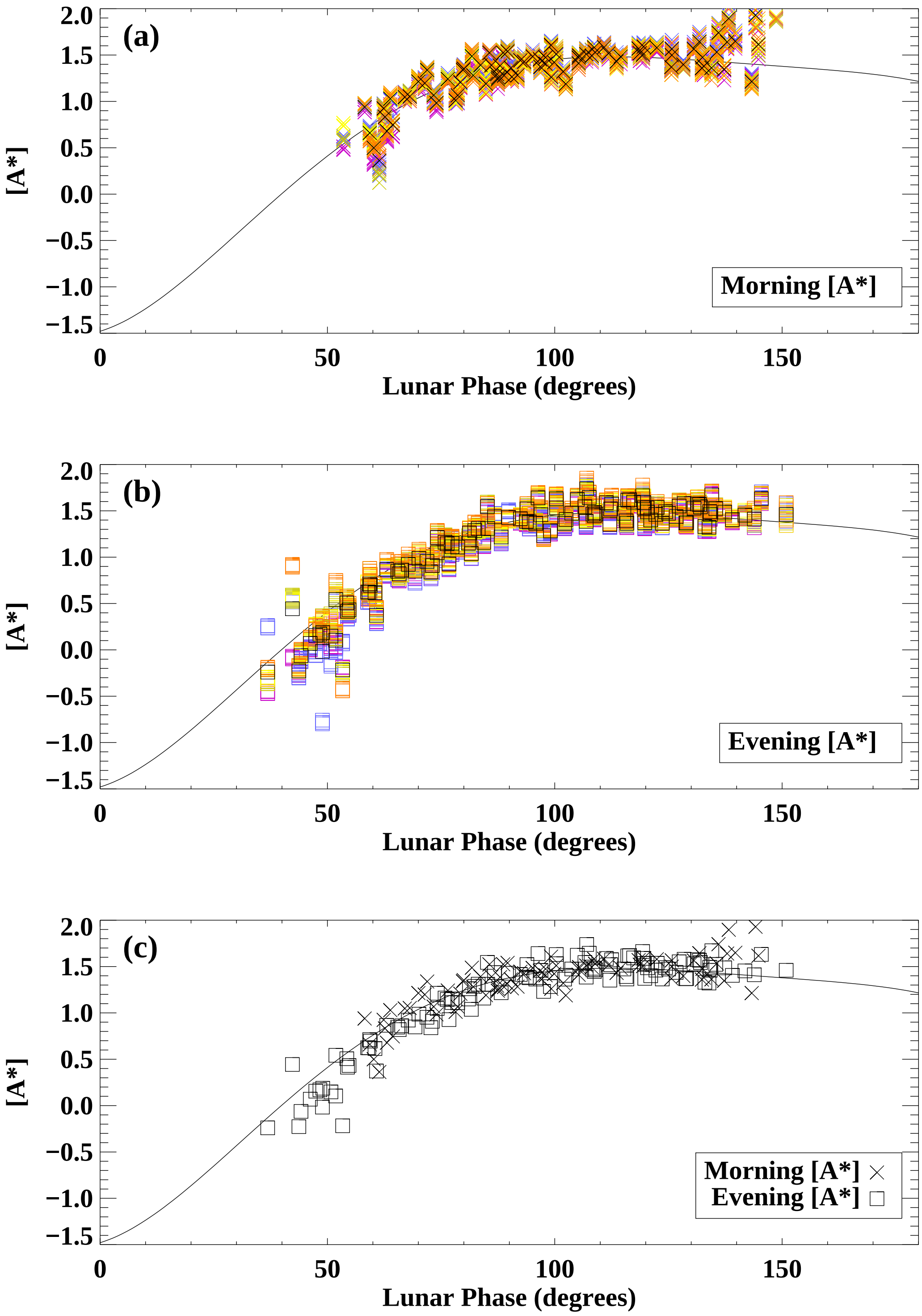

Fig. 13.— Plot of $[A^{*}]$ determined from 25 sets, as indicated by different colors, for (a) morning and (b) evening observations, superposed with the average of the 25 sets in black. Panel (c) gives the average of the 25 sets for each night, and for mornings and evenings, respectively. The dark solid line in all panels indicate the curve from the fit to the simulations for the same nights (see §6.3). NOTE THAT THE CURRENT FIT IS ACTUALLY THAT OF KOONIN, KOLBE AND CHU.

of [A*] for each night as shown in Figure 13 (c), and the standard deviation of the mean in [A*] is calculated as 0.007 and 0.008 for morning and evening respectively, yielding a measurement accuracy of better than 1%.

So far, observational data have been accumulated for 24 months covering the winter of 1998-1999 through the end of 2000 (1998 December 9 - 2000 November 30). We also have 74 nights of data from 1994 January 7 - 1995 August 4 which will be discussed in §6.2. Both the instantaneous [A*] variation during each single night, and the variation of the nightly average [A*] throughout the seasons, have been obtained and compared to the simulated results using a scene model, snow/ice cover data and satellite cloud cover data.

6.1. The Observed $[A^*]$'s during 1999-2000

Figure 14 illustrates the change of $[A^*]$ against lunar phase as determined from the nightly earthshine observations. In the plot, each data point represents a nightly averaged $[A^*]$ value, with which we study the changes in $[A^*]$ for different nights, months and seasons. One may first note that while $[A^*]$ is relatively flat near the quarter moon, it sharply decreases as the full moon approaches. This decrease implies that the earth looks relatively shinier due to enhanced reflectivity at grazing angles (glint). For lunar phase magnitude below about 40°, we presently regard the results as unreliable because of the proximity of the earthshine fiducial patches and the terminator (the transition from the moonshine to the earthshine is not sharp). Further, we do not have reliable earthshine data near the new moon (beyond a lunar phase magnitude of about 140°) because the earthshine is visible for only a brief time near sunset or sunrise, depending on whether the moon is in its waxing or waning phase. Thus, the extrapolation to zero air mass is, therefore, unreliable. For large phase angles, it is also difficult to find a fiducial patch that is confined to the moonshine.

A detailed examination of Figure 14 reveals that, with respect to the fitted mean, the $[A^*]$ determined from the local BBSO morning observations (lunar phase > 0) are not distinct from

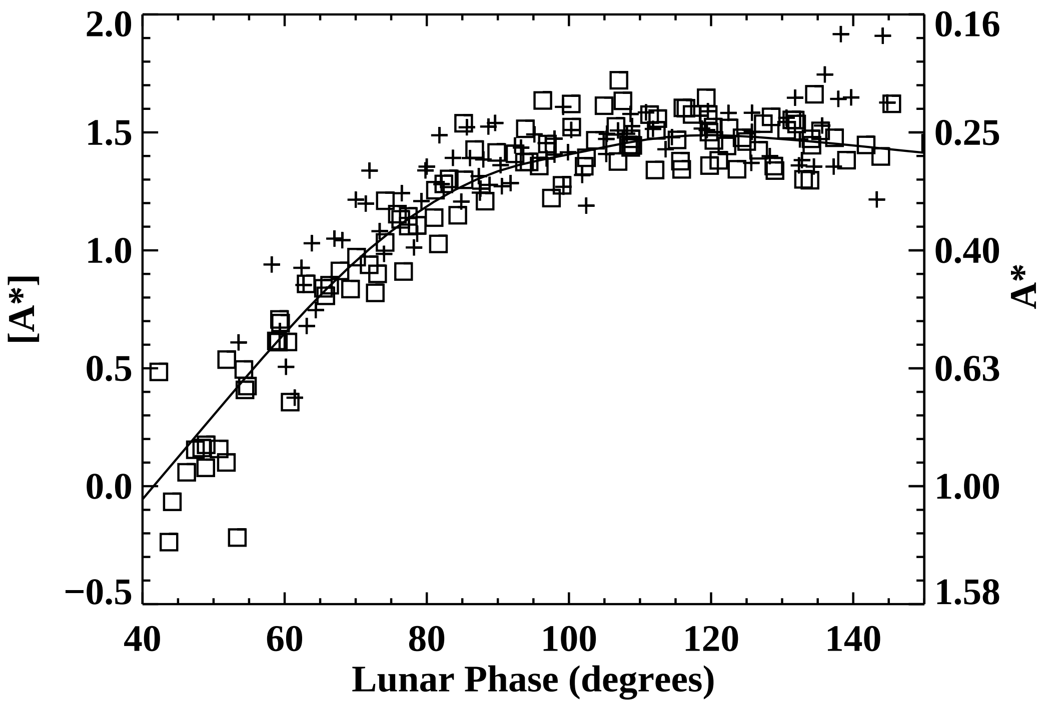

Fig. 14.— Plot of [A*] (see Equation 25) from all observing nights against lunar phase (in absolute value). Each data point represents the averaged [A*] value throughout one night; "+" indicates morning observation (lunar phase > 0) and "square" indicates evening observation (lunar phase < 0). The solid curve is a regularized fit of the data points. Note that the smaller the value of $[A^*]$, the shinier the earth. On the righthand y-axis, we use units of A^*.

those determined from the local evening observations (lunar phase < 0); i.e., the earthshine data from BBSO nights implies that the contemporaneous sunlit parts earth are equally shiny in the evening and in the morning (QUOTE ACTUAL NUMBERS AND/OR % DIFFERENCES). The lack of a difference is somewhat surprising because the earthshine we observe in the mornings and in the evenings comes from the reflection of sunlight from different parts of the earth. In our evening observations, the earthshine is dominated by southeast Asia. In the mornings, the earthshine is dominated by Africa, Europe and the Atlantic.

Bearing in mind that a change in $[A^*]$ of $0^m.01$ corresponds to a 1% change in A^*. There is also a roughly $\pm5\%$ night-to-night variation in the earthshine, A^*, even near the quarter moon where the data are most reliable. This variation is primarily associated with changes in the cloud cover, rather than some error in the data collection/reduction process. In the figure, the spread about the mean is even larger and we shall see that this is primarily associated with seasonal variations (§6.4) in the reflectance.

To better understand the influence of the earth's varying topography and cloud cover on $[A^*]$, we plot the albedo as observed throughout single nights in Figure 15. In Figure 15a and Figure 15b, observations of two nights with almost the same lunar phase, but from different months are compared. Both observations were made in evening at BBSO (as opposed to the early morning). They demonstrate a common tendency of a decreasing $[A^*]$, or a brighter earth, with time. This is because the sun is rising over Asia, increasing the contribution from the relatively bright Asia. This causes a 5-10% change in A^* over the period of observations. Even though the curves in Figure 15a and 15b closely resemble each other, the mean value of A^* in 15a is 2% smaller. This difference reflects a greater Asian cloud cover on March 24 than July 20. In Figure 15c and Figure 15d, the observations are from two mornings at similar phases of the moon, and covering comparable local times. One notices immediately, that A^* in Figure 15c and 15d are about 20% larger that their counterparts in 15a and 15b. As we shall see in §6.4, this appreciable difference is due probably due to seasonal effects. In Figure 15c and 15d, each panel shows an increasing $[A^*]$, or a darker earth, as time goes on. This is because the sunrise over Africa is increasing the

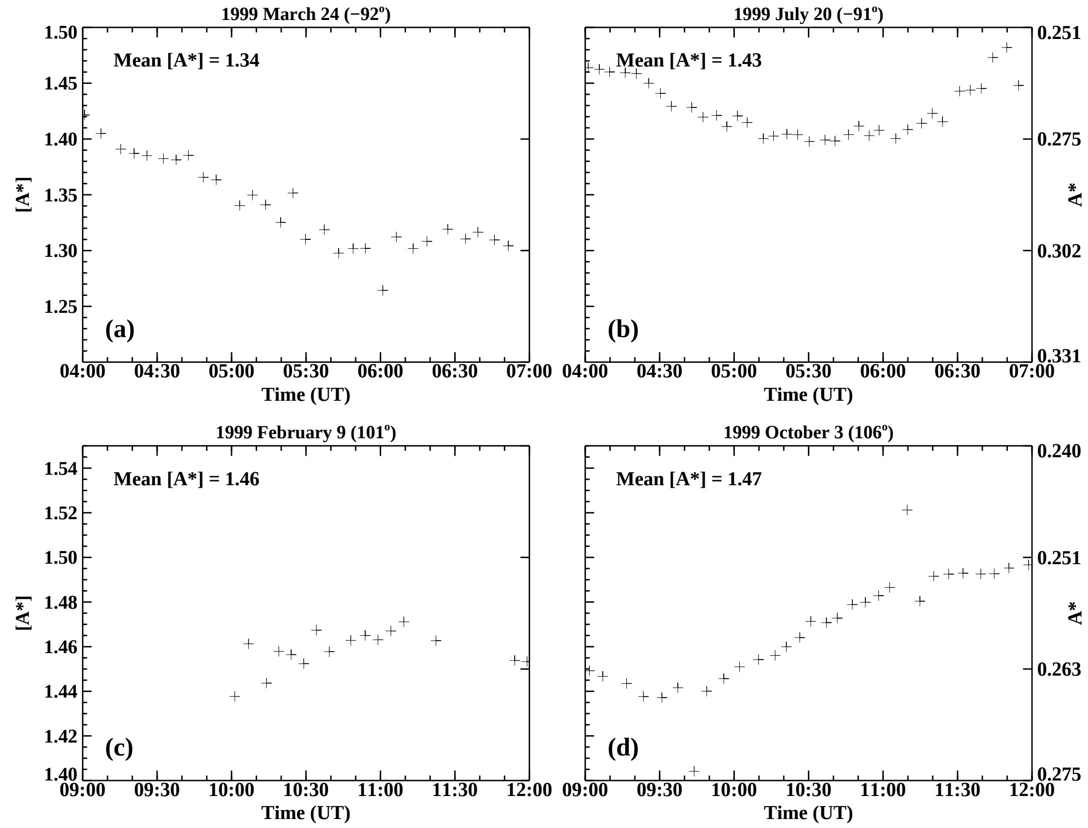

Fig. 15.— Plots of $[A^*]$ observed in the night of (a) 1999 March 24, (b) 1999 July 20, (c) 1999 February 9, and (d) 1999 October 3, against the time of observations. The right y-axis gives the unit in A*.

role of the darker (less cloudy) Africa in the earthshine. Finally, early in the observations shown in Figures 15c and 15d, there is about a 5% difference between the two A^*'s (WHERE DO WE SEE THIS IN FIG 12C 12D?).

From Equation (24), one may surmise that the observational errors in A^* that arise from the uncertainty in the earthshine measurements, come mainly from the errors in the readout intensity from the moonshine and earthshine fiducial patches, and error in the determination of lunar phase function. The ratio $\frac{p_b}{p_a}$ can be regarded as an overall normalization. The standard deviation of the lunar phase function can be determined down to 0.5%. The standard deviation of the Beer's law fitting of the moonshine for each night is taken as the error of the moonshine intensity. This gives a value of 1.1%. For the case of the earthshine, the scattering of the data is due to both the errors and the real physical changes in the terrestrial albedo. The average standard deviation from Beer's law fitting of earthshine intensities is 1.9%. Conservatively speaking, if half the amount of such scattering comes from the real physical change in average, the error in nightly earthshine intensity measurement is about 1.0%. Adding up all the errors and assuming they are independent, we get a nightly measurement error of about 2%. If we combine nights to obtain, say, a seasonal average, then the total error will be smaller, but no smaller than that associated with the lunar phase function. For instance, we have 216 nights of data for which the fit to Beer's Law has a standard deviation of less than 1%. We regard these as our "good" nights. If we calculate the standard deviation of the mean for the 95 (121) mornings (evenings), we find 0.3% (0.4%). Combining this with the uncertainty in the lunar phase, we find an error of less than 1% in the binned A^*'s. (DISCUSS POSSIBLE SYSTEMATIC ERRORS? BEYOND THE RATIO OF p_a to p_b) (UPDATE THIS)

6.2. Solar Cycle Variations in $[A^*]$?

We have more than 200 nights of observations covering the two year period 1999-2000. We also have 72 nights of earthshine data covering 1994-1995. These 72 nights favor no particular season. We show these data in Figure 16 against the fit from Figure 14. The mean A^* from the

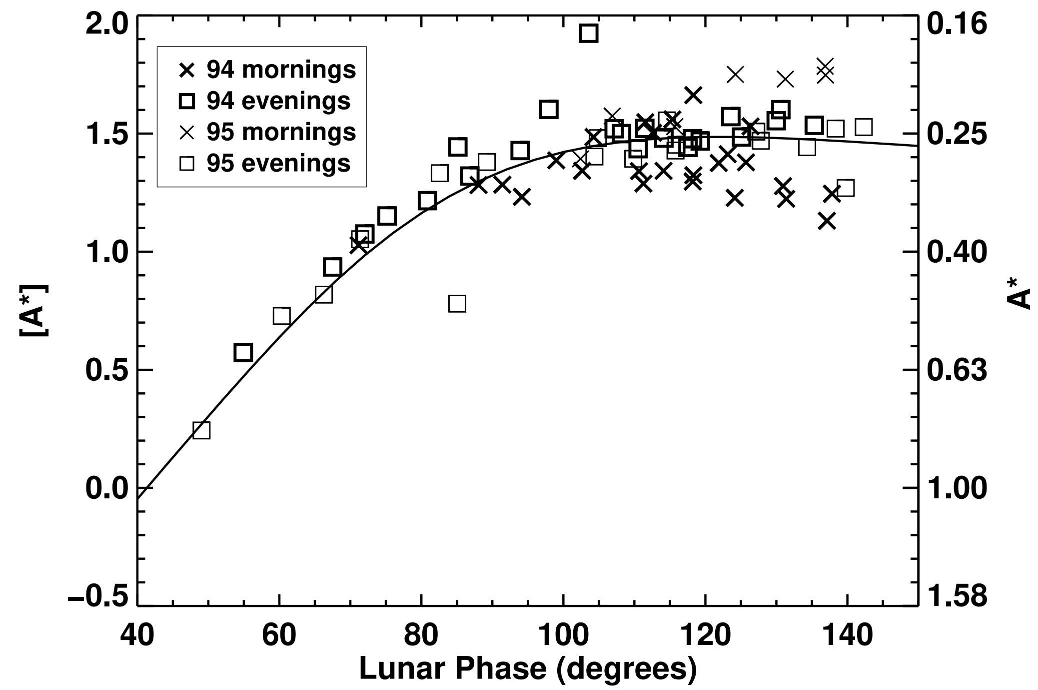

Fig. 16.— Plots of $[A^*]$ observed during 1994 and 1995. They are shown separately as morning and evening observations for each of the two years. The fit shown is that from Figure 14 which is for the 1999-2000 data.

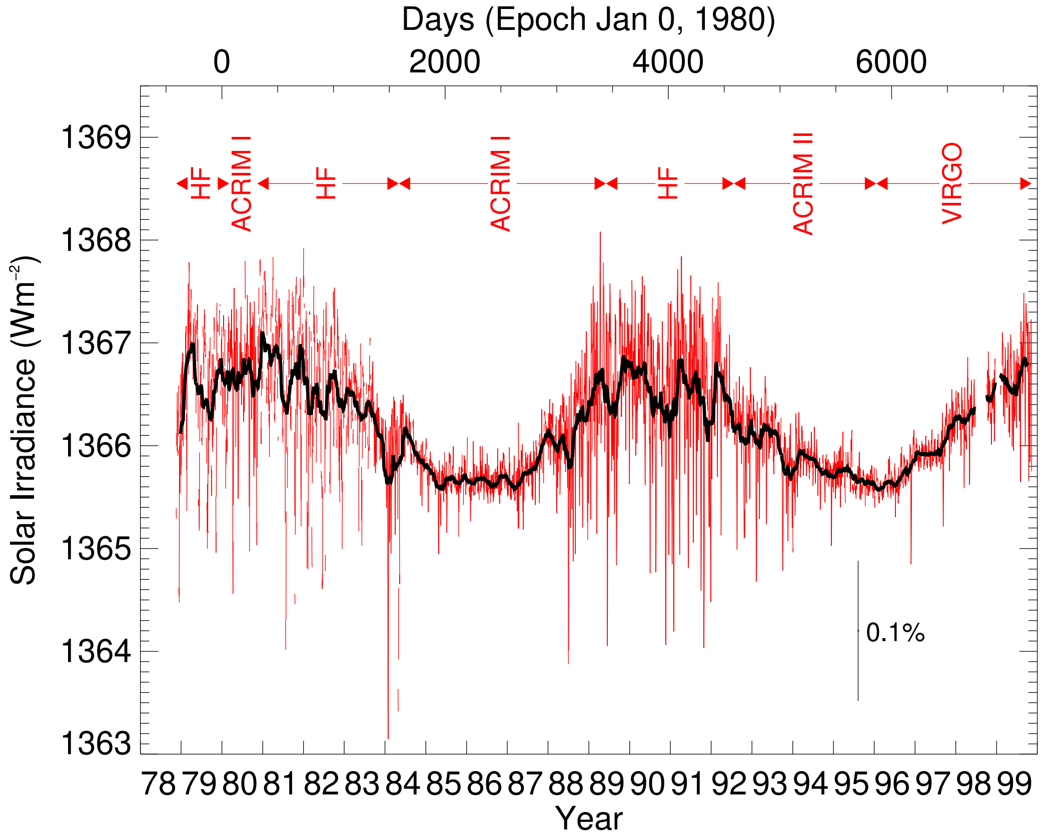

Fig. 17.— Plot of the solar irradiance vs. time

earlier time is 2.5%±1.5% greater. The deviation from the same curve for the 1999-2000 data is 0.0%±0.9% This suggests that the earth was 2.5%±1.8% more reflective in the earlier time which was also a time of lower solar activity.

It has been know for sometime that the solar irradiance is correlated with solar activity, Willson and Hudson (1991) with the irradiance being about 0.1% greater at activity maximum. The latest results covering the twenty years of satellite observations of solar irradiance are shown in Figure 17, Fröhlich (2000). Using the Figure, we see that 1994-1995 was a period of minimal solar activity, whereas 1999-2000 was near peak activity. Whether the earth's reflectance varies with the solar cycle is a matter of controversy, Svensmark and Friis-Christensen (1997) and Goode et al. (2001). 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 (1999-2000) and one of low activity (1994-1995), we use equation (1) under the assumption that the A's scale with the A^*'s to find that

$$\frac{\delta P_{\rm in}}{P_{\rm in}} = \frac{\delta C}{C} - \frac{\delta A^*}{1-A}. \tag{26}$$

Our observations of the earthshine take the ratio of the earthshine to moonshine, so we are insensitive variations of the solar irradiance. Taking the solar irradiance from Fröhlich (2000), we have $\frac{\delta C}{C} \sim 0.001$, while from our data we find $\frac{-\delta A^*}{1-A^*} \sim 0.011 \pm 0.007$. The two effects are in phase and contribute to a greater power going into the climate system at activity maximum. However, the effect of the albedo is about an order of magnitude greater.

The shinier earth in the earlier time could be consistent with the picture of Svensmark and Friis-Christensen (1997). The 2.5% larger albedo is about the same as would result from the 3-4% greater cloud cover at activity minimum for which Svensmark and Friis-Christensen argue using data from the previous solar cycle.

On the other hand, if we examine our data more carefully, we find that the largest part of the discrepancy comes from 1994 morning observations. The morning observations are sensitive to South America and the Pacific just west of it. This place and time was in the midst of an El Niño event, so we cannot conclude that the 2.5%±1.8% excess is a solar cycle effect.

Currently, we are taking data at triple the rate we did in 1994-1995 - I WOULD SAY FIVE TIMES! We are planning a three-station global network which would triple our current data rate. Thus, during the declining phase of the current activity cycle, we should be able to precisely determine the present role of solar activity on the earth's reflectance.

6.3. Modeling the Observations

Here, we compare the observations with simulations using scene models of the earth, and adding cloud cover data from satellites and snow/ice cover from models. To begin the modelling, we consider the ratio of the earthlight to sunlight, Γ, that would be seen by an observer on the moon. There is a systematic variation of Γ throughout the lunar month. When the moon is nearly new (lunar phase $\theta \approx \pm\pi$), the earth is nearly full, and so Γ is relatively large ($\approx 10^{-4}$). Conversely, when the moon is nearly full ($\theta \approx 0$), the earth is a thin crescent and Γ becomes vanishingly small. Fluctuations of Γ about its average behavior are caused by varying terrestrial conditions, including weather, the seasons and climate change. The lunar phase, θ is defined in Figure 1.

The Bond albedo is given in terms of the albedo of each element of the earth's surface by,

$$A = \frac{1}{\pi R_e^2} \int d^2R(\hat{R} \cdot \hat{S})a, \tag{26}$$

where d^2R is an element of the earth's surface, $\hat{R}$ is a unit vector pointing toward the local zenith, and $\hat{S}$ is a unit vector pointing toward the sun. The albedo of each surface element, a, depends on the surface type, cloud and snow/ice cover and solar zenith angle. The integral is over all portions of the globe illuminated by the sun (i.e.,$(\hat{R} \cdot \hat{S}) \geq 0$). After correction for the dependence of the lunar reflectivity on angle, one obtains, Γ, the ratio of earthlight to sunlight that would be seen by an observer on the moon. Γ is given by

$$\Gamma = \frac{1}{\pi R_{em}^2}[\frac{R_{ms}}{R_{es}}]^2 \int_{(\hat{R}\cdot\hat{S},\hat{R}\cdot\hat{M})\geq 0} d^2R(\hat{R} \cdot \hat{S})a(\hat{R} \cdot \hat{M})L, \tag{27}$$

where $\hat{M}$ is the unit vector pointing from the earth toward the moon, and the integral is over all of the earth's surface for which the sun and moon are simultaneously above the horizon (i.e., $\hat{R} \cdot \hat{S}$ and $\hat{R} \cdot \hat{M} \geq 0$). The anisotropy function, L, generally depends on surface type, cloud cover, and the zenith angles and relative azimuth of the sun and moon. L is defined so that it is unity for a Lambert surface(see equation 7).

6.3.1. The Models

In modeling the reflectance properties, a and L, of the earth, we used scene models developed for the Earth Radiation Budget Experiment (ERBE) observations (Suttles, et al. 1988). Twelve scenes are tabulated, 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. For the snow/ice cover, we used simulations from the Canadian Centre for Climate Modelling and Analysis (CCCM II, `http://www.cccma.bc.ec.gc.ca`). The Gaussian grid is roughly $3.8^\circ \times 3.8^\circ$ in longitude and latitude. The model gives the monthly mean snow/ice cover for each grid cell. The simulations of the earth’s albedo were performed using two different cloud cover data sets.

The first dataset is D2 (revised algorithm) monthly mean fractional cloud cover data from International Satellite Cloud Climatology Project (ISCCP). The ISCCP dataset covers 10 years for the period January 1984 through December 1993. We have used calibrated data on a square grid which is $2.5^\circ \times 2.5^\circ$ degrees in latitude and longitude. NEED A DETAILED DISCUSSION OF HOW CLOUD COVER DATA ARE CONVERTED TO FRACTIONAL CLOUD COVER.

ISCCP was established as part of the World Climate Research Program (WCRP) to collect and analyze satellite radiance measurements to infer the global distribution of clouds, their properties and their diurnal, seasonal, and interannual variations. Data are collected from the suite of weather satellites (including NOAA, METEOSAT, GOES-EAST, GOES-WEST, GMS satellites) operated by several nations and processed by several groups. All ISCCP data products are archived at the ISCCP Central Archive (`http://isccp.giss.nasa.gov`).

The second dataset is uncalibrated images of the global cloud cover produced by the Weather Services International (WSI) Corporation. The WSI corporation is the only place we know of which is currently producing real-time, online publication of global cloud cover maps. WSI is publishing maps (`http://www.intellicast.com`) composed of data from both geostationary and polar orbiting satellites, including: GOES7, GOES8, METEOSTAT 5 and POES. Data from multiple orbits are mosaicked together to provide wide-scale global and full earth views in a single image. To allow for continuous night and day viewing of cloud patterns, infrared imagery is used.

We download and calibrate daily WSI images. Each daily image is placed on the “T42” square grid of ISCCP. We have made WSI monthly mean cloud cover maps (values are in arbitrary units), and compared them with the ISCCP monthly mean maps (in units of fractional cloud cover). This yields us a nonlinear calibration curve (HOW? DETAILS?). The first simulated results, revealed that the earth's effective albedo, $[A^*]$, obtained from thus calibrated WSI maps, was smaller than that expected from the GCM model and from the observations. This implies that the fractional cloud cover was overestimated during the calibration of WSI maps. To match the observed values we have subtracted a constant value from the WSI fractional cloud cover maps (IS THERE A BETTER SOLUTION TO THIS?). It is worth noting that the above mentioned corrections in the nonlinear calibration curve only reduce the daily mean value of the earth's albedo, and do not affect its daily variations which occur as the earth rotates.

We emphasize that there is *no* intercalibration between the model reflectances and those determined from our earthshine observations.

6.3.2. Comparing Daily Observations and Model Results

In Figure 18, we show evening and morning earthshine observations overlaid on model calculations covering the entire day. The two lower panels show the earthshine as a function of time (note that the time is plotted in reverse chronological order). The solid curve shows the variation of the calculated effective albedo A^* during the twenty-four hour period, and the solid boxes are the observed effective albedo. These results come from near to a quarter moon and are compared with the earthwide WSI cloud cover from the same day in the top panel.

The top panel shows the cloud cover maps illustrating which parts of the earth contributes to the earthshine. We highlight (the large bright areas) those parts of the earth that are the source of the earthshine (i.e., are simultaneously in the sunshine and are visible from the moon at some time during the observation). The cloud cover is also shown as secondary grayscale, for instance, the east-west dark bands just north and sourth of the equator illustrate cloudless areas. We also indicate with boxes an intersection of the earth's surface with the bisectrix of the spatial angle between the directions from the center of the earth to the moon and the sun or, in other words, the point of equal angles, where the angle of incident is equal to the angle of reflection.

The observations are consistent with the simulations for 24 March 1999 which is one of the

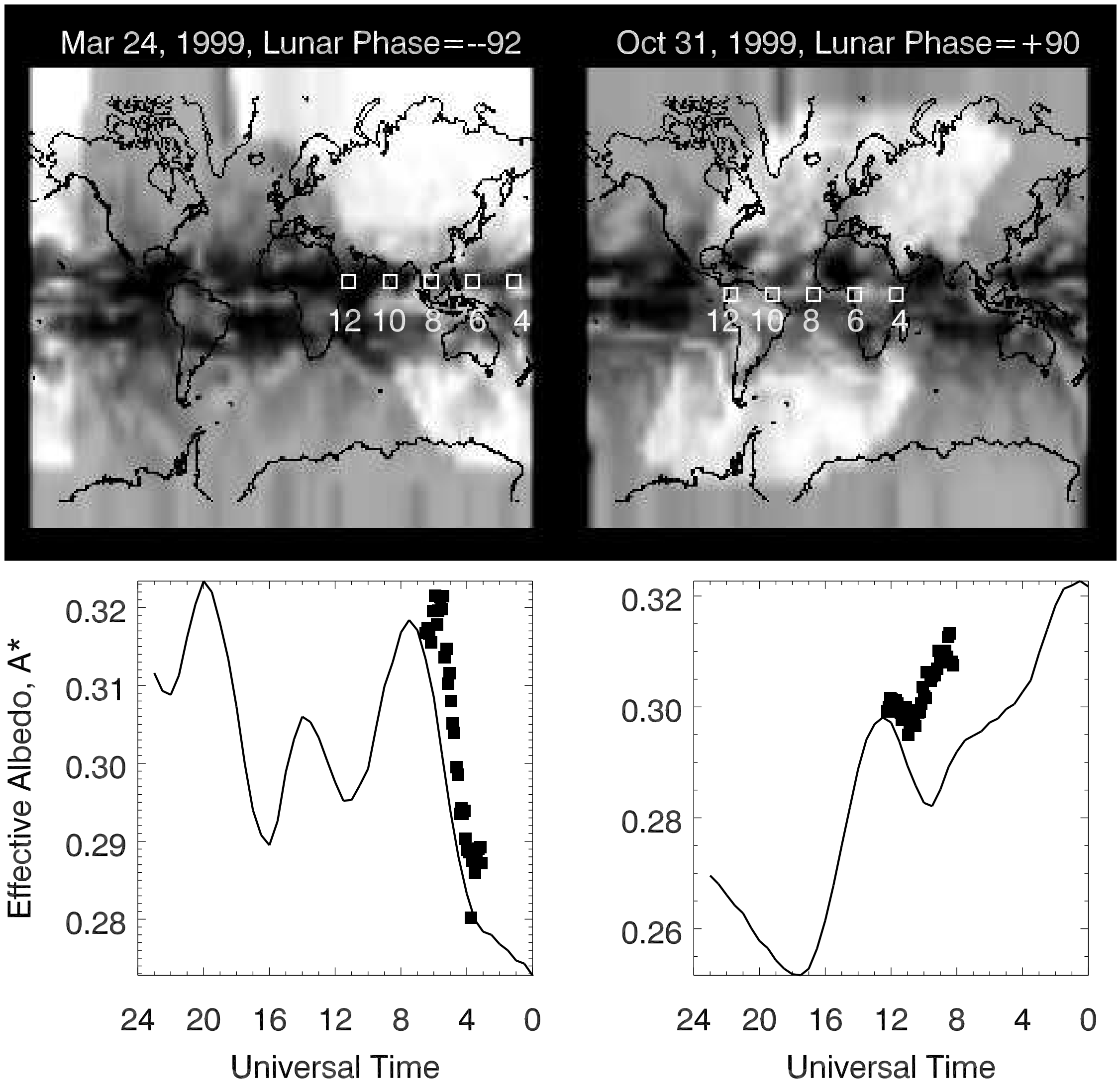

Fig. 18.— In the top panels, the satellite-derived WSI cloud cover maps are shown in gray-scale with brighter areas indicating greater cloud cover. The extended bright areas highlight those parts of the earth that are the source of the earthshine. For 31 October 1999, note that the northernmost regions are not sunlit and the southernmost regions do not contribute to earthshine because the moon is fairly far north in the sky. Simulations of 506 nights show that not detecting the pole in this way reduces A by about 0.005 because of the nearly invariant, relative brightness of the polar regions (SHOULD THIS GO ELSEWHERE?). The boxes in the top panels indicate the longitudes of maximal contribution to the earthshine at the Universal Time (UT) shown. The solid boxes in the lower panels show the observed effective albedo as a function of time (note that the time axis is reversed), while the solid line indicates the simulated A^*.

nights for which the agreement is quite good. On 31 October 1999, a more typical night, there is a discrepancy of about 5% relative (or 0.015 absolute) in the effective albedo. One may notice slight, and opposite, temporal offsets between the simulations and observations in the lower panels. One must bear in mind that the cloud cover data are a composite of many observations which are taken over about six hours. Thus, a precise timing between the observations and simulations is not possible. We simply assume that the cloud cover is invariant from one posting to the next. We make no effort to smooth the transition. Under circumstances of rapid cloud movement could result in observational and simulated results which don't have the same form. (LOOK FOR EXAMPLES)

As the cloud cover is fairly steady and high at geographical latitudes above 45°, the short timescale variations in reflectance in Figure 18 are due to primarily to irregularities in the fractional cloud cover at low latitudes and secondarily to the scene type. In the lower left panel of Figure 18, one sees that the observed and calculated maxima in A^* at 7:00 UT are due to a relative cloud excess over the Far East, while the calculated local minimum in A^* at 11:00 UT arises from the cloudless area above India and the Arabian Sea. In the lower left panel, there is a nearly 10% change in A^* over about two hours. This sharp increase is due to the increasing contribution of a cloudy Asia to the earth's reflectance as the earth rotates. An offset between the observed and calculated effective albedos is evident in the lower right panel; this turns out to typify the general result that the observed night-to-night variations are greater than those of the simulations. In §6.4, we show that the larger variation in the observed results is a consequence of muted seasonal variations in the models.

6.3.3. Model Results Covering 1999 -2000

In Figure 19, we show daily mean global albedos from a simulation of the whole earth covering 1999-2000. Roughly, the figure shows peaks in the earth's reflectivity in the fall and spring, while showing minima in the winter and summer (see §6.4).

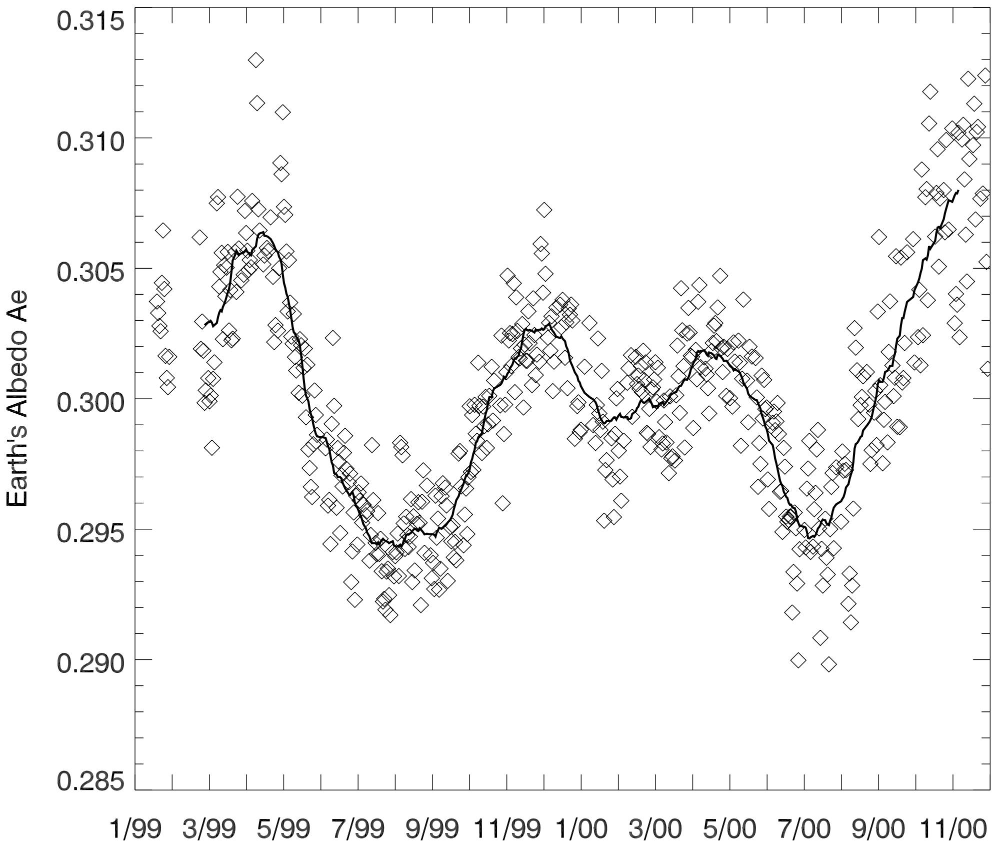

Fig. 19.— Daily mean global albedos (diamonds) during the two year simulation beginning January 1999. The bold solid line shows the 30 day running mean. The amplitude of the simulated seasonal variation of the whole earth albedo is 4-5%.

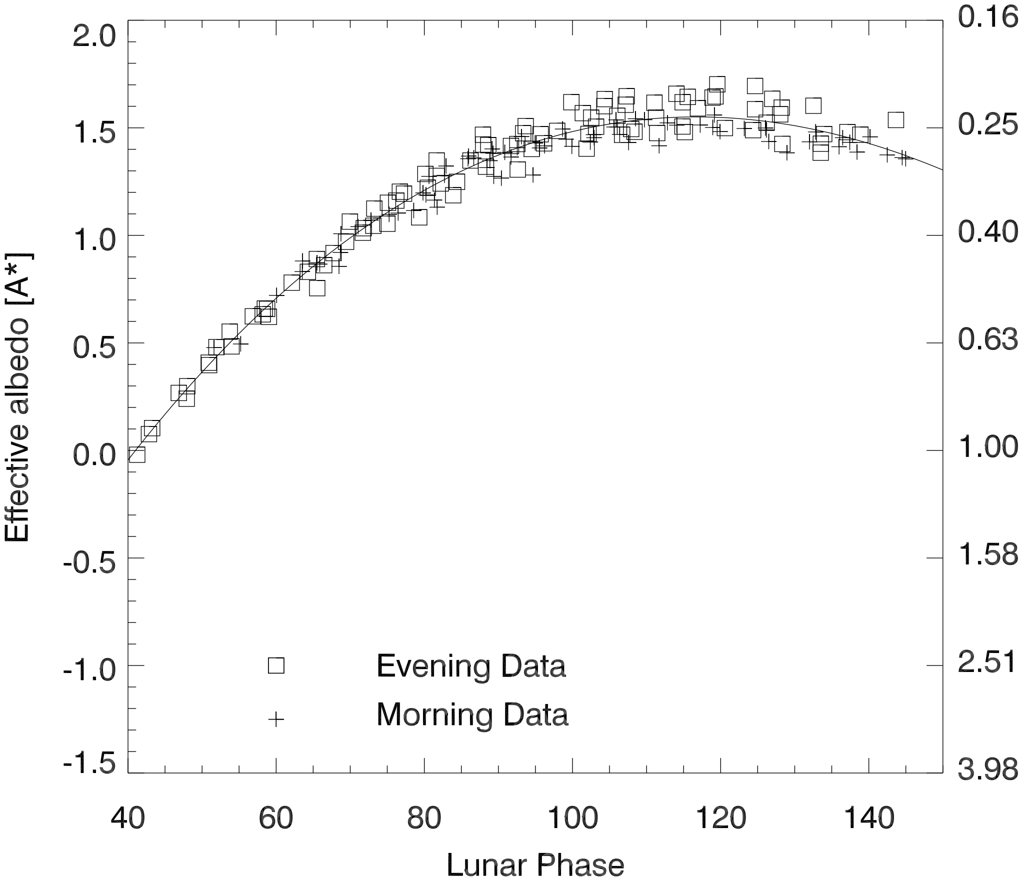

Fig. 20.— Plot of [A*] vs. lunar phase (in absolute value) from simulations covering same phase of the earth as the observational results in Figure 14. Each data point represents the averaged [A*] value throughout one night; "+" indicates morning observation (lunar phase > 0) and "square" indicates evening observation (lunar phase < 0). The solid curve is a 3^{rd} degree polynomial fit of the data points. The solid curve is indistinguishable from the fit to the data shown in Figure 14. On the right-hand y-axis, we show the scale in units of A^*.

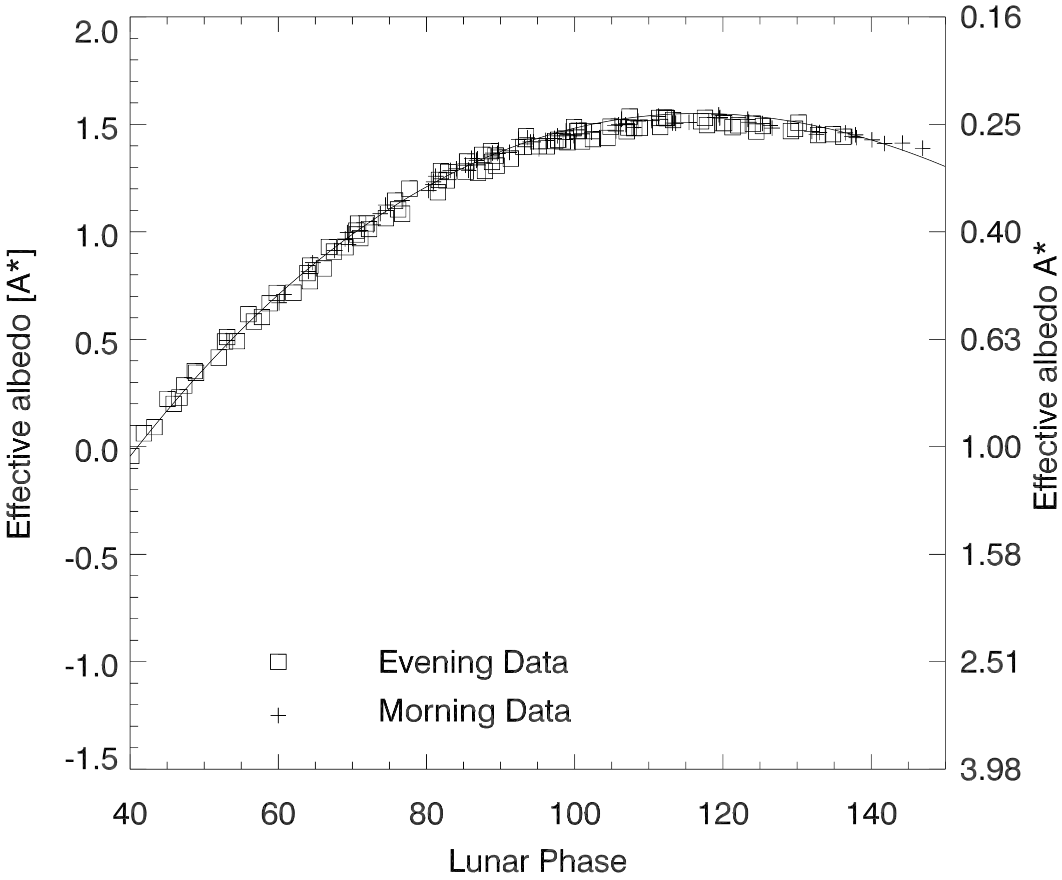

Fig. 21.— Plot of [A*] vs. lunar phase (in absolute value) from simulations covering the whole earth for all days for which we have observations. Each point represents the 24-hour average of UT defined days for which we have earthshine data. The solid curve is a 3^{rd} degree polynomial fit of the data points. The solid curve is indistinguishable from the fit to the data shown in Figure 14. On the right-hand y-axis, we show the scale in units of A^{*}.

We also simulated the earthshine observations shown in Figure 14 covering *the same parts of the earth at the same time.* The results are shown in Figure 20. Note that the distribution is tighter to the fit than in Figure 14. Thus, the greater scatter in Figure 14 cannot be due to different nights for the same lunar phase seeing different parts of the earth because each night's simulation covers exactly the parts of the earth which are observed. We shall return to the origin of the difference in the spread in §6.4. However, like the observational results, there is no clear distinction between the simulations for day and night. It is also clear from the simulations shown in Figure 20 that the evening data have a greater scatter about the mean than do the morning data. This implies a more variable cloud cover over Asia. In Figure 21, we show the same kind of plot as Figure 20, but covering the entire earth for nights for which we have observations and cloud cover data (see the difference in coverage between the solid lines and solid boxes in Figure 18). Since the whole earth simulations average over more of the globe, it is not a surprise that the simulations of the whole earth show considerably less scatter than those of just part of the earth. We also note that the mean albedo, A^*, is larger for the whole earth than it is for the part we see (BY HOW MUCH IN % AND WHY).

Note that the earth looks relatively brighter at small lunar phases (full moon or crescent earth), where the earthshine integrates over a small and highly variable portion of the globe.

6.4. Seasonal Averages of [A*]

The seasonal variation of the earth's reflectance, as determined from our earthshine observations, is shown in Figure 22. As $[A^*]$ is a strong function of lunar phase, we consider the anomaly of each nightly average relative to the best-fit mean trend of all the observations. These anomalies, which are shown as fractional changes in A^*, carry information about weather, climate and surface type.

To compare $[A^*]$'s from different phases, we remove the mean $[A^*]$ for each phase (see Figure 14) and thereby define Δ[A*]. From December 1998 through the beginning of November 2000,

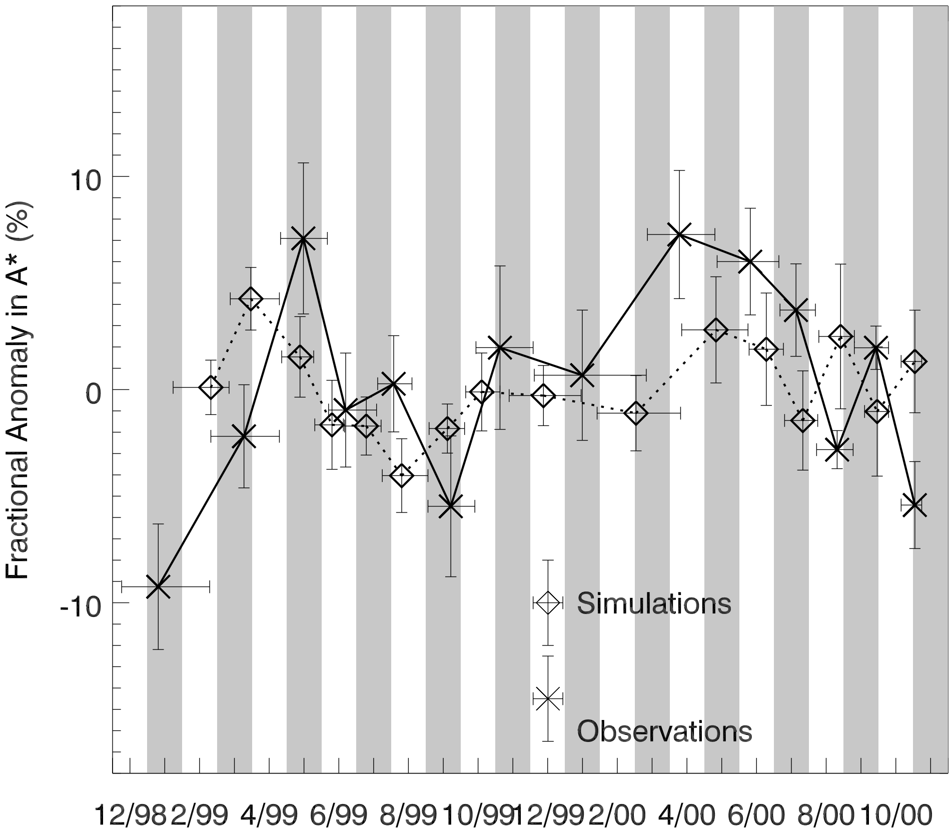

Fig. 22.— Seasonal anomalies in the effective albedo, A^*. From December 1998 through the beginning of November 2000, there are 225 nights of observations with 22 nights in the earliest bin, 23 nights in the next bin and 15 nights in each of remaining 12 bins; the extra nights in the two earliest bins serve to reduce the uncertainties. From January 1999 onward, there are 171 nights for which we have both observations and contemporaneous satellite cloud cover data, which have been averaged in 13 bins with 11 nights in each. The $\times$'s show the mean of the observations, 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. The diamonds indicate the corresponding simulation results.

there are 225 nights of observations with 22 nights in the earliest bin, 23 nights in the next bin and 15 nights in each of remaining 12 bins; the extra nights in the two earliest bins serve to reduce the uncertainties.

As in the whole earth simulations in Figure 19, one can see in Figure 22 a clear seasonal trend with the expected summer minimum, with fall and spring maxima, and the earth being brightest in the spring, when it is also the cloudiest. We see the seasonal trends in spite of the fact that the night to night variations are a significant fraction of the seasonal trends. We emphasize that the large vertical error bars arise from the large night to night variations in the cloud cover, rather than any errors in the data (see also Figure 19). With all of this, we see a nearly 20% variation in A^* from season-to-season.

The observed seasonal variation is correlated with the corresponding simulations with a 95% confidence level. However, the observations show about twice as much variability, with the differences being greatest at the extremes. The seasonal variation of albedo is the essential origin of the relatively greater spread among the observed $[A^*]$'s in Figure 1. The muted seasonal amplitude of the simulations may well derive from the coarse binning of the scene models and/or the use of simulated snow and ice cover. DETAILS LIKE CLOUD COVER BINNING AND WHY THAT IS DONE. We note that the whole earth seasonal simulations in Figure 15 show an even more muted seasonal variation. This is no surprise considering the relative spreads about the mean in Figures 16 and 17.

6.5. Comparisons with Danjon's Results

To compare our results with those of Danjon, we show in Figure 23 our data analyzed using Danjon's phase function (as shown in in Figure 12). Solid line in the figure shows the fit to the data using the correct lunar phase function. Clearly, the result of using Danjon's phase function is an albedo that is about 0.1 larger than the true value for phases near the quarter moon. These phases are most significant in the determination of the albedo, as can be seen from Figure 20.

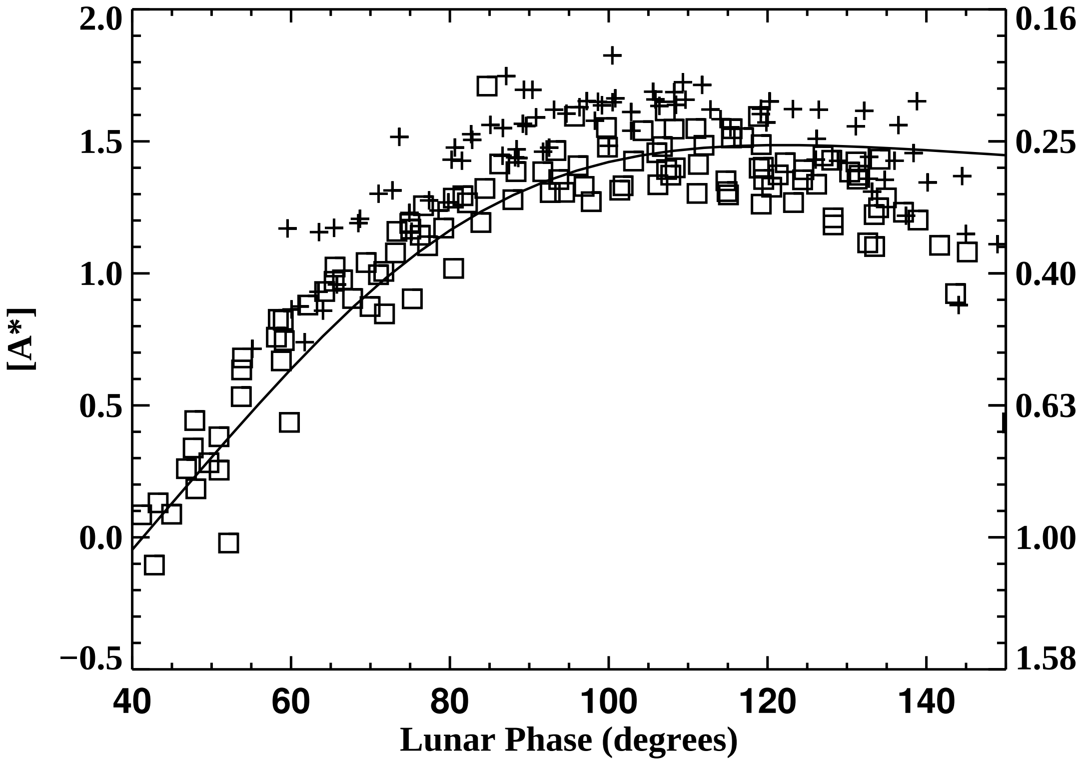

Fig. 23.— Danjon's lunar phase function used to analyzed our observations to obtain $[A^*]$. The solid curve is the regularized fit to the same data calculated using our lunar phase function (see Figure 14). The result from Danjon's phase function is systematically lower than the curve beyond a lunar phase of about 100°, which may explain why Danjon derived an albedo of about 0.4, much higher than our simulated value of about 0.3.

The inconsistency between Danjon's albedo of 0.40 and the satellite derived value of 0.30 comes mainly from Danjon's underestimate of the lunar opposition effect (Flatte et al., 1991; MacDonald and Koonin, 1992) which is carried over to a significant overestimate of the lunar phase function near the quarter moon which dominates the determination of the albedo. COMPARE DANJON'S PHASE FUNCTION WITH THE LATEST ONE.

———————————

TO INCLUDE THE FOLLOWING INTO THE TEXT WE HAVE TO MAKE A FIGURE. THE CORRESPONDING FIGURE IS MISSING NOW. DO I HAVE TO MAKE THIS FIGURE? YES! In Figure 22, we also compare the results with model calculations using monthly averaged cloud cover data combined from 1987. The monthly averaged cloud cover data are from the International Satellite Cloud Climatology Project (ISCCP). The cloud cover which is input to the model cover the same areas as the earthshine. The cloud cover data span the ten year period from the beginning of 1984 through the end of 1993. We chose 1987 because of the availability of processed satellite data. We note that 1987 was a time of a rising new solar cycle, like 1999. We note that the latter calculations do not correlate quite as well with the observational data, as did the former calculations.

NEED MONTHLY AVERAGES FROM ISCCP DATA. ————————————-

7. Determining the Bond Albedo from the $[A^*]$

To determine the Bond albedo, A, from our earthshine observations we need to integrate the $A^*(\theta)$ over all phases of the moon. Combining equations (5), (6) and (8), we find

$$A = \frac{2}{3}\int_{-\pi}^{\pi} d\theta A^*(\theta) f_L(\theta) \sin\theta. \tag{28}$$

The problem is that we cannot measure the earthshine for all phases of the moon. Nonetheless, we can obtain a quite reliable Bond albedo from the data using a constrained least squares, or regularized fit to the data – guided by the simulations. For a review of this method and its utility, see Goode (1995).

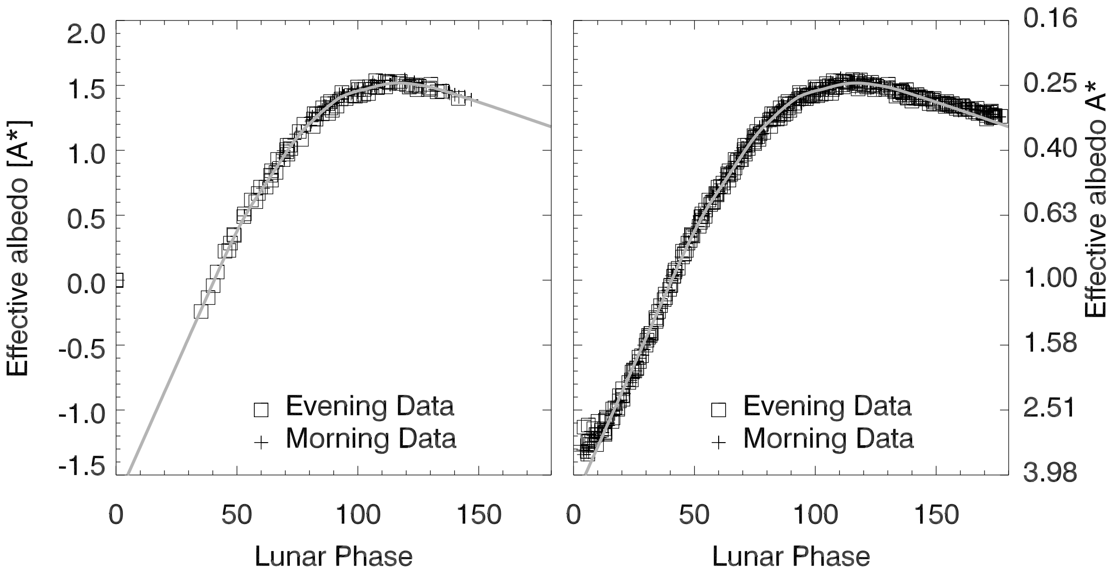

Fig. 24.— left panel) Simulations for nights for which we have earthshine data and cloud cover data (171 nights). (right panel) Simulations for all nights we have cloud cover data (506 nights – 272 mornings and 264 evenings). The gray curve in both panels is derived from the constrained least-squares fit to the left panel.

For the right panel of Figure 20, we can fit the points to determine A^* as a function of lunar phase and then and use Equation (28) to determine a Bond albedo of 0.294±0.002, where the error is defined by the least squares error in the fit to the simulations in the the right panel of Figure 20. For the fit shown in the right panel, we minimized χ^2 (per degree of freedom),

$$\chi^2 = \frac{1}{(N - N_f)} \sum_{j=1}^{N} \left(\frac{\Delta A_j^*}{\sigma_j} \right)^2 , \tag{29}$$

where N and N_f are the number of nights simulated and the number of degrees of freedom in the solution, and where ΔA_j^* and σ_j are the deviation from the fit from A_j^* and the error in the determination of A_j^*, respectively. The value of χ^2 for the simulations in the right panel is ???. This value larger than one because of the large night to night variation in the A^*'s.

For the left panel, we use a regularized fit to extend to larger and smaller phase angles than we have in the data. In the regularization, we minimize

$$\chi^2(1 - \frac{N}{N_f}) + \lambda \int_{-\pi}^{\pi} [\theta^2 \frac{d^2}{d\theta^2}(\frac{\Delta A_j^*}{A^*})]^2 d\theta, \tag{30}$$

where ΔA_j^* is the difference between the j^{th} data point and the fit to the data (the quantity we are determining) in the left panel, while λ is the regularization parameter which is, in reality, a smoothing constraint. In principle, the parameter is adjusted until χ^2 is the same as it was in the right panel of Figure 19. However, the χ^2 space is relatively flat, so one typically weakens λ until short wavelength oscillations almost begin to appear in the fitted A^* function. Other forms of the constraint are certainly possible, but a second derivative constraint seems to work best here. In applying the regularization to the left panel, we have the advantage of being able to check our result against the right panel. In direct application of the method, we find a Bond albedo of 0.296±0.002, which is quite consistent with the result for the right panel. The fit shown in the right panel is the regularized result from the left panel. The fit is fairly insensitive to the choice of λ over nearly an order of magnitude.

Applying the same regularization to the observational data of Figure 14, which is composed of the same nights as the left panel of Figure 20, we find a Bond albedo of 0.297±0.006. The fit is shown in the the left panel of Figure 21. The right panel shows the corresponding fit for the

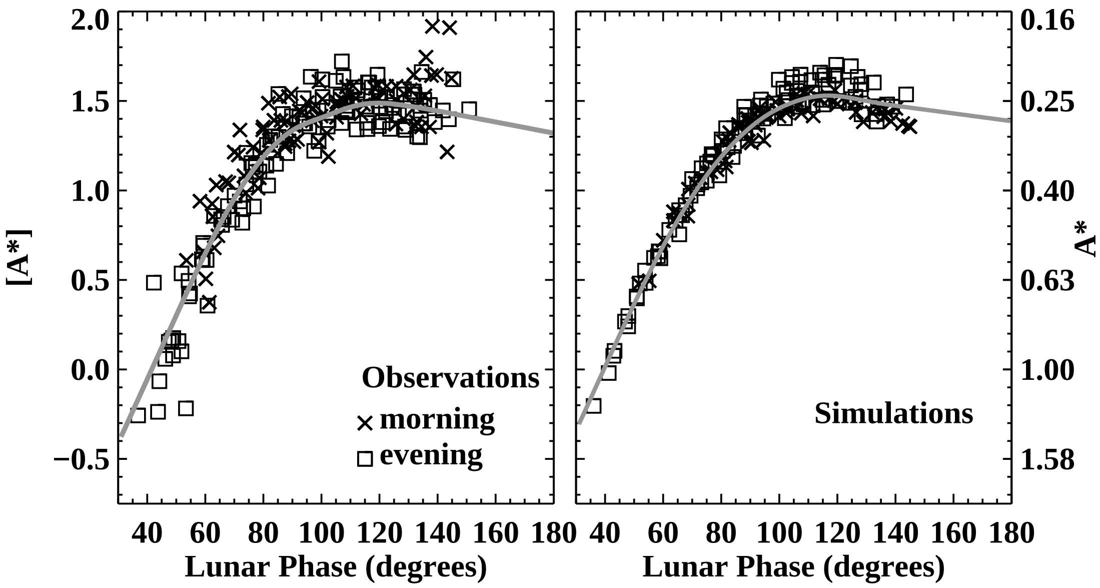

Fig. 25.— left panel) Observed (left panel) $[A^*]$'s plotted against the absolute value of the lunar phase from 225 clear observing nights from December 1998 through the beginning of November 2000. Simulations (right panel) are shown for the 171 nights for which there was also contemporaneous cloud cover data. Each data point represents a nightly average of 0.5-3.0 minute earthshine measurements taken once every five minutes with 0.1-5.0 second moonshine observations interspersed. Error bars would be within the symbols. Constrained least square fits to the data and simulations are shown by the curves. For the 171 nights for which we have observations and simulations, the anomalies relative to the separate fitted curves are correlated at the 95% confidence level.

simulations. The larger errors in observational results are indicative of the greater spread of the observational points about the mean (compare the left and right panels of Figure 21).

One of the prices paid using regularization is that the point to point values of the solution are correlated, implying that the meaning of the errors is somewhat damaged. The damage is reflected in errors that are smaller than they are in reality. For instance, if the constraint were dominant, the error at each point in the solution would be the standard deviation of the mean. To ascertain whether the errors quoted in this section are significantly too small, we determine the errors in a completely different way which does not suffer from the limitations imposed by regularization (see §7.1).

One possible concern about earthshine as a precision measure of the albedo is the amount of anisotropy in the earth's scattering. At any instant, the moon subtends $0^\circ.5$ as seen from the earth and the obliquity of the moon's orbit extends this coverage over the lunar month to only 6° on either side of the ecliptic; thus, earthshine is not sensitive to light scattered out of the ecliptic. The significance of this fact for albedo determinations can be assessed by assuming that for all lunar phases the earthshine does not depend on the azimuthal scattering angle and testing equation (28),

$$\bar{A} = \frac{4}{3}\int_0^\pi d\theta \overline{A^*(\theta)} f_L(\theta) \sin\theta, \tag{28}$$

where θ is given in Figure 1. If we define $\overline{A^*(\theta)} = 10^{-0.4\overline{A^*(\theta)}}$, we calculate the right-hand side of this expression to be 0.294 (WHAT IS THE VALUE FOR US?), to be compared to $\bar{A}$=0.299. The relative brightness of the polar regions is responsible for this discrepancy.

It can seen in Figure 23 that the integrand in equation (28) peaks near the quarter moon, when the moon shows a relatively sizeable earthshine, while its phase is not so large that the earthshine is visible only briefly near sunset or sunrise. Although the integrand peaks near $\theta = 130^\circ$, evaluation of equation (28) to an accuracy of 0.002 requires data for $\theta \geq 30^\circ$, so that earthshine observations for most lunar phases are needed for an absolute value for the albedo, while observations near the new moon are most sensitive to variations in the albedo.

The precession of the lunar nodes with a period of 18.6 years also interacts with the anisotropy of the light scattered by the earth to influence the earthshine. For example, when the declination of the new moon is a maximum (some 29°) near the northern-summer solitice, more of the arctic polar ice cap is visible and the earthshine will be brighter. Some nine years later, the lunar declination under the same conditions will be only 18°, and the earthshine will be a minimum. We have performed simulations to study this effect and conclude that it perturbs $[A^{*}]$ only at the $0^{m}.001$ level or less.

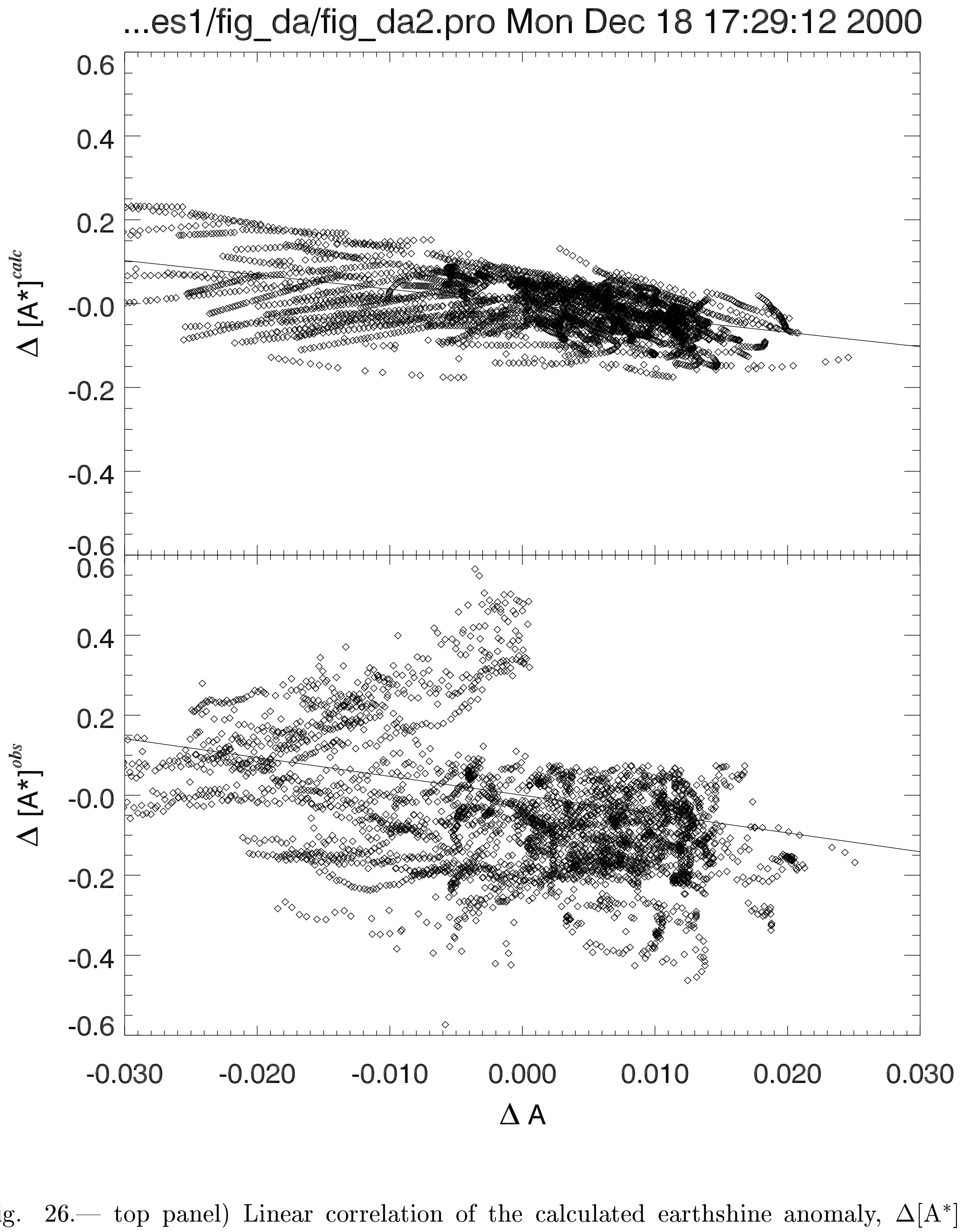

Fig. 26.— top panel) Linear correlation of the calculated earthshine anomaly, $\Delta[\mathrm{A}^*]^{\mathrm{calc}}$, with the calculated global albedo anomaly, ΔA for 3702 calculations for lunar phase angles for which $140° \geq |\theta| \geq 40°$. bottom panel) Linear fit to observational anomalies, $\Delta[\mathrm{A}^*]^{\mathrm{obs}}$, for the same 3702 time points, assuming ΔA is the same as that from the calculations.

7.1. Alternate Determination of Errors in the Bond Albedo

In calculating the Bond albedo, we need to connect the precision to which we determine the $[A^*]$ to the accuracy to which we determine A. To do this, we use the daily cloud cover map and calculated the earth albedo A, effective earth's albedo $[A^*]$ and their variation during the full day. For the calculations, we use a third-order polynominal fit to $[A^*]$ as in Figure 14, which defines a mean calculated effective albedo for the earth, $\overline{[A^*(\theta)]}$, and residuals, $\Delta[A^*]^{calc} = [A^*] - \overline{[A^*(\theta)]}$; these latter carry information about the weather, climate and surface type. Their correlation with the calculated global albedo anomalies ($\Delta A = A - \overline{A}$) is shown in the top panel of Figure 26, where we have included all nights we have cloud cover and observations. In the plot, we used only 142 nights — the ones for which we have observations. Further, in $[A^*]$ we only include the times for which we have observations (3702 time points).

For the observational data, we make a scatter plot for the same time points, and assume they correlate with ΔA, as shown in the lower panel of Figure 26. In detail, we show a third-order polynomial fit like used in Figure 14, which defines a mean observed effective albedo $\overline{[A^*(\theta)]}$ and observed residuals $\Delta[A^*]^{obs}$. Their correlation with the global calculated albedo anomalies ($\Delta A = A - \overline{A}$) is shown in the lower panel of Figure 26. For each time point in each night, we assume ΔA is the same as the corresponding calculated point. This figure gives us insight into how accurately we can measure the albedo.

Using Figure 26, we note that a variation in A of 0.01 corresponds to a 4.7% (for $[A^*]^{obs}$) and a 3.4% (for $[A^*]^{calc}$) change in the effective albedo ($0^m.047 - 0^m.034$ in $[A^*]$). Equivalently, a 1% earthshine measurement determines the albedo with a precision of 0.002. To place this precision in context, we note that independent satellite determinations of the monthly mean albedo can differ by 0.005 or more and that the seasonal range of the monthly mean albedo is 0.015 or more.

Our nightly $\sim$ 2% observational error in each nights measurement of A^* corresponds to an error in of $\sim 0^m.02$ $[A^*]$ which implies measuring A to ± 0.006. This value is comparable to that from satellite data. Averaging over a year, implies measuring A to 0.006 – even though we have observed a about a third of the nights in the year. These errors are smaller than those we determined using constrained least-squares for A. Thus, we conclude that the regularization has not underestimated the errors in a meaningful way.

7.2. Simulating the Earth's Albedo, 1984-1993

In §6.2, we compared the observed effective albedo betweeen the present time (1999-2000) of high solar activity and the most recent previous time of low solar activity (1994-1995). Here we use the ISCCP-D2 data to compare simulations of albedo from the previous solar cycle. Following Willson and Hudson (1991), we compare the simulated albedo changes between 1986 and 1990. These two times correspond to the solar activity minimum and a time near maximum. Actually, 1991 was the maximum, but we chose 1990 because 1986 and 1990 are roughly at the same phase of the El Niño and Mt. Pinatubo erupted in June of 1991. Over the four years between 1986 and 1990, the solar irradiance increases by about 0.1% (see Figure 17), while the simulated albedo decreases by about 0.004. To compare, we use equation (1) to find

$$\frac{\delta P_{\rm in}}{P_{\rm in}} = \frac{\delta C}{C} - \frac{\delta A}{1-A}. \tag{29}$$

Using Figure 17 we To compare these, we find $\frac{\delta C}{C} \sim 0.001$ and using Figure 29, we have $\frac{-\delta A}{1-A} \sim 0.006 \pm 0.001$. The two contributions have the same sign, but the effect of the albedo is about five times larger. This compares quite favorably the $\frac{-\delta A}{1-A} \sim 0.011 \pm 0.007$ from the difference betweeen our 1999-2000 observations and those from 1994-1995. However, for the simulations, we do not have to assume scaling between the A's and the A^*'s.

7.3. Mean Albedos from Different Cloud Cover Data

Figure 28 shows binned, monthly mean earth's albedos calculated using the ISCCP (thin solid curves) and the WSI data (diamonds, thick line). The ISCCP data set includes 10 years of satellite observations. Solid thick curve shows an averaged over 10 years monthly mean albedo.

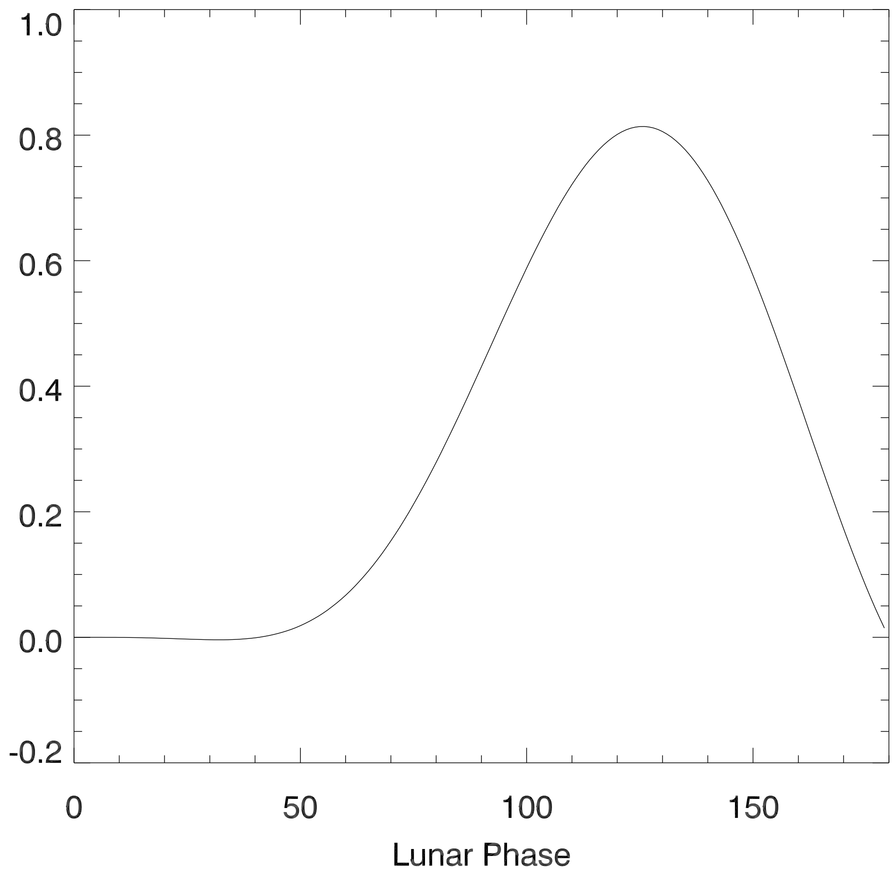

Fig. 27.— The kernel from which the Bond albedo is determined (see equation 28). Its behavior is dominated by the phase function for small phase angles, and by $\sin\theta$ for large phase angles.

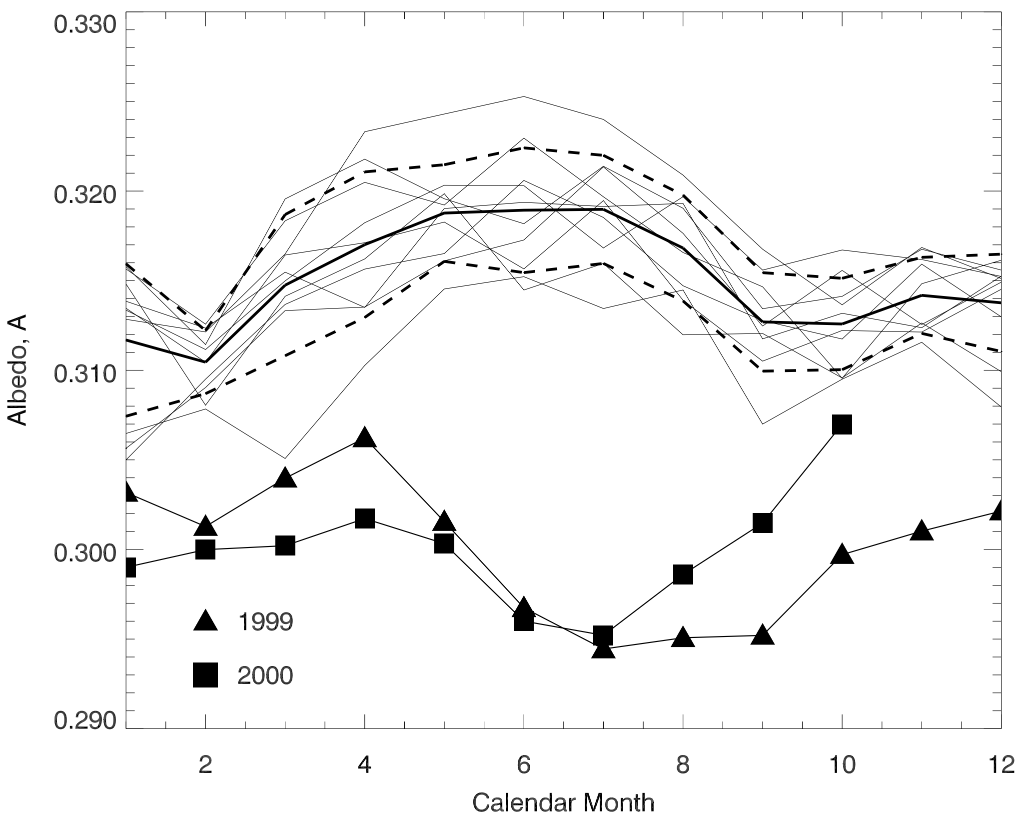

Fig. 28.— Comparison of albedos using different datasets. The WSI results for 1999 and 2000 are indicated by the lines which are connected by the symbols. The ISCCP-D2 results cover 1985-1993 and are indicated by the band of light solid lines. The solid line is the mean of 1985-1993 and the dashed lines give the $\pm 1\sigma$ bands about the mean.

The error bar for each year is determined from the quality of the fit to the averaged monthly variation in the earthshine. In Figure 28, we see a decrease in A of about 0.008 between 1986 and 1993. As we have seen, this accuracy is well within what we can measure.

WE ARE MISSING THE FIGURE FOR THE FOLLOWING TEXT. WHAT ABOUT THE OFFSET IMPLIED IN THIS PARAGRAPH?? Figure 23 shows apparent difference between albedos obtained using different data sets. The WSI albedo is significantly lower than the ISCCP one. The computed averaged ISCCP albedo $\overline{A}$, is 0.315 and the WSI averaged albedo $\overline{A}$ is 0.299. The latter is in good agreement with the satellite-derived value of 0.30 (Gibson et al. 1990; Rossow and Lacis 1990). The seasonal variation shows the expected August minimum and November and May maxima (Danjon 1928; Dubois 1942; Dubois 1947). The dominant source of the seasonal variability is the interplay of the annual cycle of snow/ice cover with the cloud cover; the greater land fraction in the northern hemisphere plays only a small role.

8. Discussion

From BBSO, we have observed the earthshine for two years. We determined a large scale average of the earth's albedo for major areas in Europe, Africa and the Atlantic Ocean in our morning observations, when the sun is high in Africa and the Atlantic Ocean and the moon is in its declining phase. We also measured the albedo for large areas in southeast Asia and the Pacific in our evening observations during the rising phase of the moon.

We have compared our results with models of the earth's scenes inputting contemporaneous snow/ice cover from models and cloud cover from satellites. We find a close correlation between the observed and calculated results, with the calculated results uniformly showing milder seasonal variations. 'From this, we suggest that the models are overly smoothed. We argue that the earthshine data provide an important complement to satellite observations of the earth.

We argue that the albedo we determine is as precise as determined from satellites, while providing an excellent complement. One of the obvious advantages of earthshine observations is

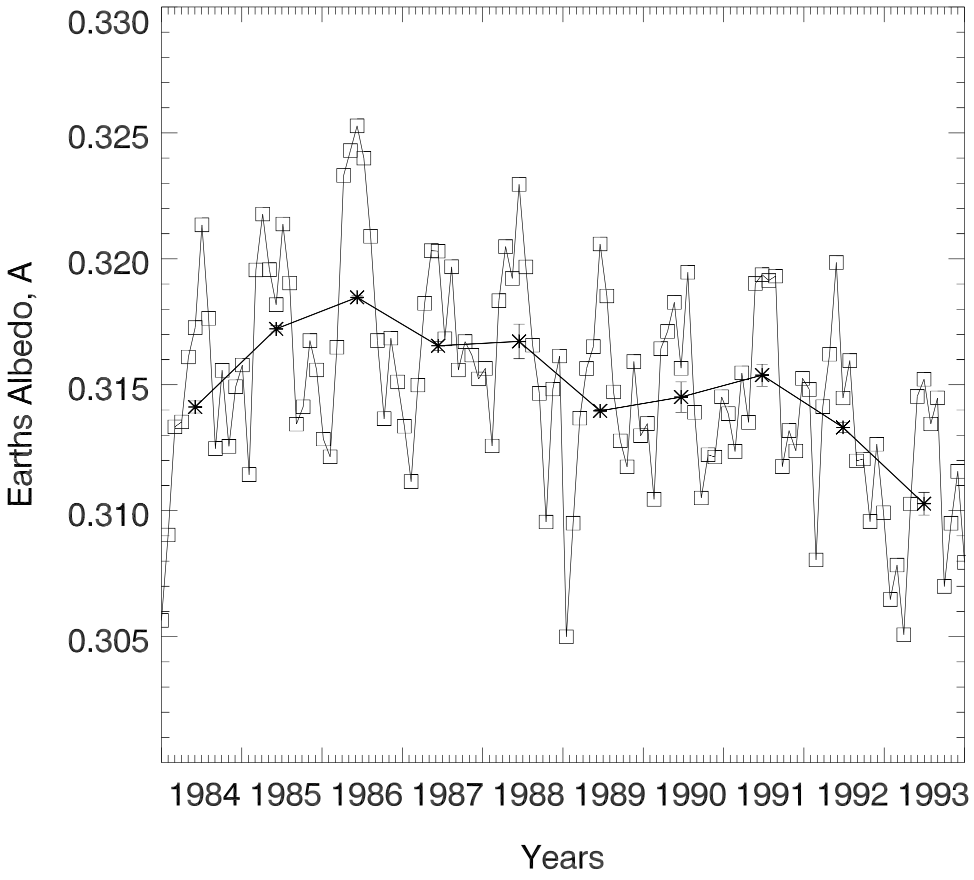

Fig. 29.— Using monthly average cloud cover data from the ISCCP data as input to the scene model, we calculate monthly average of A that are shown by the boxes. We also show the annual averages of A including calculated error bars. The averages are plotted against year.

Fig. 30.— Plot of the solar irradiance vs. time

having an absolute calibration coming from the bright side of the moon. A clear drawback of earthshine observations has determining the lunar phase function – the reflection of light from the moon as a function of the phase of the moon. We have solved this problem, as demonstrated in §5, so that we know the standard deviation of the phase function to within 0.5%.

From the earthshine data, we see that southeast Asia and West Africa/Southern Europe have very nearly the same albedo. However, the evening obsrvations show a greater spread about the mean which is due to the relatively greater cloud cover variability in southeast Asia. We also see that the albedo is the largest in the spring.

With our level of accuracy, we can track longer time frame changes in the earth's albedo if they are at a climatologically significant level. By extrapolation, we seem to have confirmed the dependence of the earth's albedo on solar activity. We have found that the change in the net sunlight into the climate system from a time of high activity to low activity from varying cloud cover is several times greater than changes in the sun's irradiance. However, the two effects work in concert. From our observations, we find from 1994-1995 to 1999-200 $\frac{\delta P_{\rm in}}{P_{\rm in}}$ increased by 0.012±0.007. Whereas, our simulations show from 1986 to 1990 $\frac{\delta P_{\rm in}}{P_{\rm in}}$ increased by 0.007±0.001. Are these sufficient to be climatologically significant over the solar cycle? The observed change implies an effective increase in the solar irradiance of 11.5±6.7 W/m^2, or a surface averaged (i.e., divide by four) increase of 2.9±1.7 W/m^2 over the five year span. We change here to a surface-averaged value, since that is the way in which the climate model results are presented. The Intergovernmental Panel on Climate Change (IPCC) argues for the same 2.4 W/m^2 increase in greenhouse gas forcing since 1850. The greenhouse gasses are dominated by CO_2, and include CH_4, N_2O and CFCs. IPCC also argues that greenhouse gasses have dominated climate change since the industrial revolution. The 2.4 W/m^2 is larger than changes in the sun's irradiance, aerosols and their effect on clouds. These latter changes are typically associated with global warming. Contrasting the similar size changes due to varying albedo and that due to greenhouse gasses, the change arising from the albedo, over just five years is too abrupt to change the global climate – considering the thermal inertia of the oceans. However, Stevens and North (1996) have used ocean surface temperature data to suggest a subtle variation, with an eleven year period, since 1850.

Svensmark and Friis-Christensen (1997) have argued that changes in the earth's albedo are anti-correlated with changes in solar activity. They argue that the solar wind more effectively shields the earth from galactic cosmic rays at activity maximum, and that the cosmic rays seed clouds. Thus, they explain their observation that there is a greater cloud cover at activity minimum. They argue for a 1.3 W/m^2 increase in surface-averaged flux from 1987 to 1990. Using Figure 22 and the second term on the right hand side of equation (28), we find a comparable increase of 1.0 W/m^2 over the same span. Kirkby (1998 UPDATED REFERENCE) argues that the whole of the warming since the beginning of the industrial revolution may be attributable to the interplay of cosmic rays and cloud formation. One key to the argument comes from the study of ^{10}Be concentration in Greenland ice cores by Beer, Raisbeck and Yiou (1991) to show that the cosmic ray flux at activity maximum a hundred years ago was greater than it is now at activity minimum. ^{10}Be is created by cosmic rays and falls to earth in about two years. As such, it is a good proxy for the cosmic ray flux. Of course, placing solar magnetism at the heart of terrestrial climate change is controversial, but merits consideration based on the results here and from Svensmark and Friis-Christensen.

Relating these changes in flux to changes in the earth's surface temperature is problematic. We focus here on changes in the earth's emission temperature as would be seen in the IR near 15.5 μm. In those terms, we have from equation (2) that

$$\frac{\delta P_{\mathrm{out}}}{P_{\mathrm{out}}} = \frac{4\delta T_e}{T_e}, \tag{29}$$

under the assumption the ϵ in equation (1) doesn't change. Taking $T_e \approx 255K$, we find a temperature perturbation due to the sun of about 0.1 K and about 0.5 K from the albedo. We note that the largest variations in Figure 22 correspond to temperature variations of about 1 K for the earth. The temperature changes here are simply related to changes in the net sunlight into the climate system, not changes in the temperature of the earth's surface.

We plan an automated network of earthshine telescopes so that we can have long-term data covering all geographic regions.

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