A CORRELATION BETWEEN CHANGES IN SOLAR LUMINOSITY AND DIFFERENTIAL RADIUS MEASUREMENTS

R. J. Kroll and H. A. Hill

Department of Physics, University of Arizona, Tucson, Arizona 85721

B. J. Beardsley*

Photometrics Limited, Tucson, Arizona 85745

ABSTRACT

Solar luminosity variations occurring during solar cycle 21 can be attributed in large part to the presence of sunspots and faculae. Nevertheless, there remains a residual portion of the luminosity variation distinctly unaccounted for by these phenomena of solar activity. At SCLERA (Santa Catalina Laboratory for Experimental Relativity by Astrometry), observations of the solar limb are capable of detecting changes in the solar limb darkening function by monitoring a quantity known as the differential radius. These observations are utilized in such a way that the effects of solar activity are minimized in order to reveal the more fundamental structure of the photosphere. The results of observations made during solar cycle 21 at various solar latitudes indicate that a measurable change did occur in the global photospheric limb darkening function. It is proposed that the residual luminosity change is associated in part with this change in limb darkening.

Measurements of the solar luminosity made by ACRIM and estimated contributions to the change in luminosity due to sunspots and faculae are given by Willson and Hudson.[1] From 1980 to 1986, the ratio of the fractional change in the residual luminosity to the fractional change in differential radius is $(\delta L/L)/\delta(\Delta r/R) \approx -7$. Because other phenomena may also contribute to the residual luminosity change, the magnitude of this ratio is taken to be the upper limit associated with limb darkening changes.

The feasibility of this hypothesized correlation is apparent when the luminosity change implied by the observed differential radius change from 1976 to 1980 is found to be within the limits allowed by the balloon, rocket, and satellite radiometric data. Additionally, it may explain the discrepancy between observation obtained by ACRIM and ERB and predictions based on some models of solar luminosity change from 1978 to 1981. Further, the residual luminosity change implied by the magnitude of the change in differential radius over the decade beginning in 1973 is great enough to possibly have consequences for the Earth's climate. The validity of this correlation would establish the differential radius as a quantity useful for investigating processes affecting the solar energy output independent of the solar cycle variations.

INTRODUCTION

Understanding the changes in solar luminosity has attained a pre-eminent role in current solar research. This is in part a consequence of the important influence that the solar energy output plays in determining the conditions of the Earth's climate. Important evidence that this connection has already been observed is the association of the Maunder Minimum in sunspot activity and the Little Ice Age of the eighteenth century. Further investigations into the characteristics of

*Burt Beardsley participated in this work as an Adjunct Assistant Research Scientist at the University of Arizona.

solar variability and the Earth's environmental response may uncover how such a connection may arise and whether such events are likely to occur again. Recent improvements in the accuracy of solar luminosity measurements further stimulate the search for the causes of variability. The ability to measure long-term changes in total irradiance to fractions of a percent requires a deeper understanding not only of the phenomena known to be responsible for such changes, but also of other phenomena that may contribute to total irradiance variability. The challenges of explicating the causes of solar luminosity change and the effects of such changes on the Earth are formidable, yet promise substantial rewards.

During the 1980's, the ACRIM instrument aboard the SMM satellite contributed greatly to our ability to monitor the solar irradiance. It has provided measurements of unequaled precision over the long term. The observations indicate measurable changes in solar energy output over time scales ranging from days to years. Much of this variability is found to be associated with the presence of regions of solar activity. The irradiance is seen to diminish with the quantity of sunspots visible and is enhanced by the presence of faculae. In addition to the changes occurring over the lifetimes of active regions, a decreasing trend in the luminosity has been observed during the first two-thirds of the 1980's. This trend appears to be in phase with the solar activity cycle and may be found to have its cause in the features of solar activity. Initial explanations along these lines were found inadequate, which opened the possibility that phenomena other than solar activity are relevant to solar luminosity variability.

Among these alternatives are the possibilities that the energy flow out of the Sun was modulated by changes in the photospheric temperature and temperature gradient. Such causes would constitute changes in the global properties of the Sun and, specifically, a change in solar limb darkening. At SCLERA, observations of the solar limb are made and characteristics of the solar limb darkening function are quantified with a parameter known as the differential radius. During the time that the solar luminosity showed a downward trend, the differential radius values were also seen to change. Discussed in the following sections is the concept of the differential radius as a measure of limb darkening and its variation reflecting temperature gradient and solar luminosity changes. The possibility that the differential radius could serve as an indicator of global properties affecting solar luminosity is investigated.

THE DIFFERENTIAL RADIUS

The differential radius is based on a particular definition of the solar edge known as the finite Fourier transform definition, or FFTD.[2] The FFTD locates the solar edge at a distance ρ from the center of the sun such that

$$\int_{-1/2}^{1/2} I(\rho + a \sin \pi s) \cos 2\pi s \, ds = 0 \quad , \qquad (1)$$

where I is the observed solar intensity as a function of radius and a is the scan amplitude, a parameter indicating the amount of the solar limb being scanned. It has been shown[2] that the FFTD has reduced sensitivity to atmospheric seeing when the parameter a is at least as large as the width of the seeing function, but that it is quite sensitive to the shape of the limb darkening function. It is also apparent that Eq. (1) is unchanged by any constant scaling of I and is, therefore, insensitive to spatially large-scale changes in Earth's atmospheric transparency.

Equation (1) shows that the edge position ρ and scan amplitude a are related through the limb darkening exhibited by I. Therefore, for a particular limb intensity profile and latitude on the solar disk θ,

$$\rho = \rho(a, \theta) \quad . \qquad (2)$$

This dependence of limb position on scan amplitude makes it possible to investigate the shape of the limb darkening function. Limb positions can be determined for different scan amplitudes a_i and a_j, and the differential radius is defined as

$$\Delta r(a_i, a_j, \theta) = \rho(a_i, \theta) - \rho(a_j, \theta) \quad . \tag{3}$$

When the solar limb profile is a step function, $\Delta r = 0$. For $a_i < a_j$, the more limb darkening exhibited in an intensity profile, the greater is the differential radius value. Because of this dependence of Δr on the limb darkening function, it can be used to monitor changes in the shape of the limb darkening function over time and, hence, to infer concurrent changes in the photospheric temperature gradient.

THE OBSERVATIONS

The limb darkening observations obtained at SCLERA are made by scanning an image of the Sun across three pairs of diametrically opposed slits. Two of the diameters are rotated by plus and minus one-eighth radian from the central diameter. This allows six limb profiles to be obtained near a chosen solar latitude. The scans are sinusoidal, taking 0.625 seconds each, during which 256 intensity measurements are made for each limb. The intensity of the continuum radiation at 5500 Å (with a bandpass of 100 Å) is digitally recorded for each of the six positions. On days when observations are made, the procedure consists of the constant repetition of scans as the Sun is being tracked for as long as the weather or daylight permits. The entire detector assembly can be rotated so that a particular diameter can be followed during the day or so that limb profiles at various latitudes can be obtained. Since 1979, observations have been obtained in this manner. Prior to this time, the detector consisted of only one pair of slits.

Observations that have been used in earlier long-term variability studies[3,4,5] were made in 1973, 1979, 1981, 1983, 1984, 1986, and through the first part of 1989. This work includes data obtained in the later part of 1989. Table 1 provides information about the data obtained in these years, including the scan amplitudes used to calculate $\rho(a)$. The data-reduction procedure results in a single differential radius value per year per observed latitude for the years prior to and including 1984 and two values per year for 1986 and later. For each solar latitude observed, a time series of differential radius values for each of the six limbs is calculated for given pairs of the four values of scan amplitude available. For the scan amplitude pairs of interest, values from the six differential radius time series at corresponding times are averaged, and any of the six values more than 1.5σ from the mean are removed from the time series, since such variance is likely the effect of solar activity. The 1.5σ cutoff value was found to be the optimum value for rejecting the data points judged bad by visual inspection from the small sample of six data points used. The remaining differential radius values at corresponding times are averaged to produce a time series of mean values for the day. The mean of this time series is calculated, and any single value greater than 2σ from the mean is removed and a final daily mean is calculated. With daily averages of each observed solar latitude available, a seasonal or yearly value is determined for each latitude by averaging the daily values using 2σ as the cutoff value in a two-cycle rejection procedure. This is done in order to eliminate days that are dominated by the effects of faculae or other transient surface phenomena.

As noted in Eq. (3), the differential radius is a function of the amplitude at which the solar image is scanned. As seen in Table 1, the scan amplitude for different years has varied and therefore must be taken into account in order to meaningfully compare differential radius values over the years. To do this, the differential radius is adjusted to standard scan amplitudes of 8 and 24 arcseconds. This adjustment is implemented by determining the dependence of the limb position on the scan amplitude using the mean limb darkening function found in 1987 and 1988. Because for any year there are scan amplitudes available which differed by only a few arcseconds from the standard 8 and 24 arcsecond values, any errors acquired in this adjustment are estimated to be of

TABLE 1
Summary of SCLERA Observations for Long-Term Variability

Year	Number of Days	Latitude Angles	Measured Scan Amplitude (arcseconds)
1973	7	±15°, ±105°	27.2, 20.4, 13.6, 6.8
1979	16	0°	25.6, 19.2, 12.8, 6.4
1981	13	±13°, ±39°, ±64°, ±90°	22.5, 16.9, 11.3, 6.3
1983	59	0°, ±45°, ±90°	21.5, 16.1, 10.8, 5.4
1984	21	0°, ±45°, ±90°	21.5, 16.1, 10.8, 5.4
1986	65	0°	33.0, 24.8, 16.5, 8.3
1987	82	0°	31.0, 23.3, 15.5, 7.8
1988	59	0°, ±45°, ±90°	31.2, 23.4, 15.6, 7.8
1989	42	0°, ±45°, ±90°	31.0, 23.3, 15.5, 7.8

the order of a few milliarcseconds. For a given scan amplitude, the actual amount of solar radius observed will vary throughout the year due to the change in the Earth-Sun distance. This variation can result in seasonal systematic trends if not corrected. Daily differential values are normalized to correspond to the amount of limb that would be scanned if the Sun were at aphelion in early July. This time is used because most of the observations were made near this time of year, so the corrections are minimized. The yearly and seasonal values determined as per the foregoing analysis are displayed in Fig. 1.

The other observations of interest are the total irradiance measurements made with the ACRIM instrument aboard the Solar Maximum Mission satellite. The satellite was launched in 1980 and relayed precision measurements of the solar luminosity until a failure in the pointing system in late 1980. Lower-quality data continued until its repair in March 1984 when precision data again resumed. The following analysis utilizes the results of Willson and Hudson[1] who used the data from the periods when the satellite was in the "precision solar-pointed" mode.

COMPARISON OF DIFFERENTIAL RADIUS AND ACRIM OBSERVATIONS

In order to compare the changes in differential radius with the changes in solar luminosity, differential radius values available at or near the times of the ACRIM observations analyzed by Willson and Hudson[1] are used. Differential radius values for 1979 and 1981 are combined in order to estimate a value for 1980, and values for 1984 and 1986 are combined and used as a measure of 1984 through 1986 values. These estimates can then approximate the changes in differential radius for comparison with the ACRIM observations.

Data obtained in 1979 and 1986 are different from that obtained in 1981 and 1984 in that the 1979 and 1986 observations were restricted to near the equator, while 1984 observations include the polar and ±45° regions in addition to the equator, and 1981 observations include the pole and latitudes at 25.71° increments from the pole. Thus, by determining the yearly averages first, the combination of different kinds of data sets is facilitated. Whereas 1979 and 1986 observations contain information solely about the equatorial limb darkening, the 1981 and 1984 values reflect a globally averaged limb darkening function. This, it is felt, is a better indicator of conditions in the

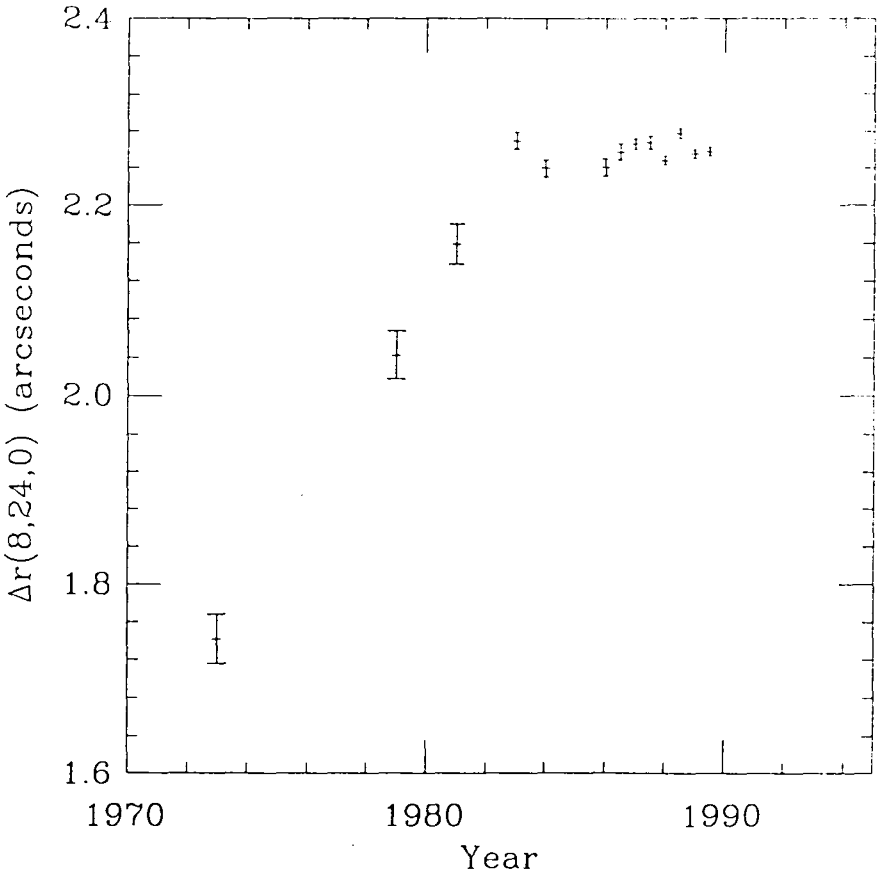

Figure 1. Differential radius results, corrected to standard scan amplitudes of 8 and 24 arcseconds, from observations made from 1973 to 1989.

photosphere than just the equatorial value when comparing to total irradiance. It should be noted, however, that even though differential radius values sometimes depend on the solar latitude, the equatorial values are a good indicator of values at other latitudes. In other words, differences between differential radius values at various latitudes are small compared to differential radius changes from year to year.

The ACRIM observations used here have been analyzed and presented by Willson and Hudson.[1] As mentioned earlier, the data from 1980 and from mid-1984 to 1986 are used in their analysis. Briefly, their analysis attempts to account for the luminosity variation between the two time periods by calculating the contributions of sunspots and faculae. The sunspot deficit is quantified with the photometric sunspot index (PSI) calculated from the observed sunspot areas and brightnesses in terms of their positions on the solar disk. Likewise, the facular excess is calculated based on Ca-plage areas and their brightnesses as a function of position on the disk and designated the photometric facular index (PFI). Figure 3 of their paper shows the relationship between the sunspot-corrected observations (ACRIM+PSI) and the facular concentration as measured by the PFI. It is seen that the data concentrate in two groups -- the data from 1980 lying above the data from 1984-1986. The figure shows straight line fits to both groupings of data. Our analysis proceeds by extrapolating the linear fits to zero facular concentration. This effectively estimates the total irradiance for the two time periods corrected for both sunspot blocking and facular enhancement. The difference between the two intercept values reveals the residual change in solar luminosity during the time span in question.

The residual change in total irradiance δL is found to be -1.65 W/m^2. With the average irradiance L = 1367.72 W/m^2, $\delta L/L = -1.2 \times 10^{-3}$. The change in differential radius $\delta(\Delta r)$ from the 1979-1981 time period to the 1984-1986 time period is found to be 0.14 arcseconds. Using R = 945 arcseconds as the aphelion value to which all of the differential radius values are normalized, $\delta(\Delta r)/R = 1.6 \times 10^{-4}$. For the hypothesis that 100% of the residual change in total irradiance is associated with the observed change in differential radius, then the ratio of fractional change in irradiance to a correlated fractional change in differential radius is $(\delta L/L)/\delta(\Delta r/R) \approx -7$. This ratio is a quantity that can be monitored during the upcoming maximum of the solar cycle. Comparison of the most recent ACRIM observations with the latest differential radius values can test the degree to which the limb darkening, as measured by the differential radius, correlates with solar luminosity changes. It should be noted, however, that there is evidence which indicates that the correlation between the residual luminosity change and differential radius change is, in fact, less than 100%.

One question regards how well the Ca-plage areas account for the contribution of faculae to the total irradiance. Willson and Hudson[1] suggest that much of the scatter in the ACRIM data introduced by applying the facular correction is due to the inadequacy of plage areas providing an accurate measure of facular contributions. Studies involving the variability of the CaK line indicate why this could be the case. With data obtained by White and Livingston,[6] Skumanich et al.[7] show that it is not possible to model the variability in the K1.0 index with quiet sun (super granular cells and network) and plage components with realistic values of parameters characterizing these features. By introducing a third component, the "active network," which results when large active region faculae decay into unstructured remnants of magnetic flux, a much better accounting of CaK variability is found. Based on the correlation of HeI equivalent widths and full-disk CaK variations, Foukal and Lean[8] find that the HeI line is a good indicator of the sunspot-corrected total irradiance, including the downward trend occurring between 1981 and 1984. Livingston et al.[9] suggest that a combination of the Mn5394 and CN3883 line strengths are even better indicators of irradiance variability over the entire solar cycle. In any case, there appear to be better parameters with which to account for the facular enhancement of the total irradiance than the plage index alone. The amount of residual irradiance change may, therefore, be somewhat smaller than that used in the preceding analysis, reducing the magnitude of the ratio $(\delta L/L)/\delta(\Delta r/R)$. The magnitude of the value stated above may well serve as an upper limit on the degree to which total irradiance variability is associated with changes in differential radius.

A second process which may account for a significant portion of the residual luminosity change is that of Kuhn et al.[10] This explanation proposes that changes in the energy transport result from variations of convective flow during the solar cycle. This causes the surface temperature and presumably the temperature gradient to vary with latitude and time, causing net changes in total irradiance.

One consequence of the hypothesis of 100% correlation is revealed when taking into account differential radius values obtained prior to 1980. Differential radius values were calculated for the years 1973, 1979, and 1981. These values are consistent with a linear increase which continues into 1983-1984. By using a linear fit to the data from these five years, the change occurring from 1976 to 1980, based on the 100% correlation hypothesis, implies $\delta L/L \approx -0.15\%$. As indicated by Willson,[11] ±0.2% is the maximum long-term luminosity change that could have occurred during that time period, based on the results of rocket, balloon, and ACRIM experiments. Thus a 100% correlation hypothesis is not in conflict with the observations of total irradiance and differential radius prior to 1980. On this basis, global changes in the photosphere may well have occurred over the decade beginning in 1976.

An important additional consequence of the observed differential radius change between 1973 and 1983 is that $\delta L/L \approx -0.4\%$ during this time for the 100% correlation hypothesis. It is believed that this value is large enough to be considered climatically significant. It should be emphasized, however, that the magnitude of this value may be an upper limit. This also indicates that the differential radius measurements may have the sensitivity to measure changes in the photosphere which potentially change the solar luminosity to the degree that affects the conditions on Earth.

The possible contribution to the total irradiance change indicated by differential radius change may be relevant to the behavior of the satellite radiometers aboard both the SMM and Nimbus 7 satellites during the early years of their operation. Both instruments recorded definite decreases in the solar total irradiance since their respective launches until the minimum of solar cycle 21. In contrast to these observations, the modeling of the total irradiance modulation by Foukal and Lean,[8] based on the correlations with HeI 10830 equivalent width, suggest an increase in total irradiance over that time period until the maximum occurring in 1981. They suggest that instrumental degradation may explain this discrepancy, but allow that other processes not accounted for by their modeling may have influenced the total irradiance prior to 1981. From 1978 to 1981, the Foukal and Lean model indicates a luminosity increase of about 0.05% due to solar activity. Based on the linear fit to the differential radius data and a 100% correlation hypothesis between $\delta(\Delta R)$ and δL, the solar output δL, the residual change in luminosity, may have decreased approximately 0.1% during the same time period. The combined effect of the residual change and the change associated with solar activity suggests a net decrease in solar total irradiance, eliminating the conflict with the satellite observations.

The possible connection between the differential radius and the total irradiance demonstrates that the differential radius may serve, along with other observations, as a useful tool to probe the mechanisms operating in the solar atmosphere that affect the total irradiance. The illumination of these mechanisms could establish the differential radius as a quantity which can quantify changes in the solar luminosity that are of long-term consequence, as distinct from changes connected with the solar activity cycle. Indeed, such changes, as seen in Fig. 1, show little connection with the solar cycle, yet indicate that significant changes have occurred in the photosphere. The changes are of such magnitude that effects on the Earth's climate are possible. Solidifying the connection between differential radius and total irradiance will stand as both a scientific and practical achievement.

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REFERENCES

1. R. C. Willson and H. S. Hudson, "Solar Luminosity Variations in Solar Cycle 21," Nature 332, 810 (1988).

2. H. A. Hill, R. T. Stebbins, and J. R. Oleson, "The Finite Fourier Transform Definition of an Edge on the Solar Disk," Ap. J. 200, 484-498 (1975).

3. B. J. Beardsley, W. M. Czarnowski, R. J.Kroll, C. S. Cornuelle, L Yi, and H. A. Hill, "Variations in Solar Luminosity Since 1957 Using Differential Radius Observations," Bull. Am. Astron. Soc. 20, No. 4, 1011 (1988).

4. B. J. Beardsley, H. A. Hill, C. S. Cornuelle, and R. J. Kroll, "Solar Constant Variations Found from Secular and Latitudinal Changes in the Limb Darkening Function," paper presented at The Sun in Time Conference, March 1989, Tucson, Arizona.

5. R. J. Kroll, B. J. Beardsley, and H. A. Hill, "Recent Differential Radius Results at SCLERA," Bull. Am. Astron. Soc. 22, No. 1, 742 (1990).

6. O. R. White and W. C. Livingston, "Solar Luminosity Variation. III. Calcium K Variation from Solar Minimum to Maximum in Cycle 21," Ap. J. 249, 798 (1981).

7. A. Skumanich, J. L. Lean, O. R. White, and W. C. Livingston, "The Sun as a Star: Three-Component Analysis of Chromospheric Variability in the Calcium K Line," Ap. J. 282, 776 (1984).

8. P. Foukal and J. Lean, "Magnetic Modulation of Solar Luminosity, Ap. J. 328, 347 (1988).

9. W. C. Livingston, L. Wallace, O. R. White, "Spectrum Line Intensity as a Surrogate for Solar Irradiance Variations," Science 240, 1765 (1988).

10. J. R. Kuhn, K. G. Libbrecht, and R. H. Dicke, "The Surface Temperature of the Sun and Changes in the Solar Constant," Science 242, 908 (1988).

11. R. C. Willson, "Measurements of Solar Total Irradiance and its Variability," Space Science Reviews 38, 203 (1984).