GROUND-BASED MEASUREMENTS OF SOLAR IRRADIANCE VARIATIONS

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ABSTRACT

A brief review, is presented, of observing and data analysis programs being carried out at the San Fernando Observatory. A digital analysis of sunspot area from full disk photographs shows an especially good correlation with areas published in the Solar Geophysical Data Bulletin with scale factor near unity. Results are presented from photoelectric photometry of active regions using the Extreme Limb Photometer. These results suggest energy balance between sunspots and faculae. Preliminary results are presented from a new program of photoelectric photometry using a linear array of diodes. Results are presented for the August 1982 passage of a large active region. This active region caused a maximum dip in the quiet sun irradiance of about 800 parts per million.

INTRODUCTION

This review will be concerned with recent attempts to relate solar features to global indicators of solar variability. I will emphasize that work with which I have been associated since other work will be covered by other speakers at this conference. At the San Fernando Observatory/CSUN we have been studying solar activity and its effect on solar variability for several years. Our work is based on photographic and photoelectric work. Photographic work involves the analysis of full disk photographs obtained at SFO or at other observatories. Photoelectric work has been done at SFO with the Extreme Limb Photometer (ELP) as well as diode arrays mounted on the vacuum spectroheliograph. The analysis of the ELP data is the most advanced and I will end my review with some speculations concerning the energy balance of active regions.

ANALYSIS OF PHOTOGRAPHS

Much of the work relating solar activity to spacecraft measurements of solar irradiance variations has been based on estimates of the area of sunspots, published by the National Bureau of Standards, either the Space Environment Services...
Center or the World Data Center A. These measurements of sunspot area are incorporated into a fluctuation index such as that due to Hudson, the Photometric Sunspot Index, PSI. The PSI is defined by

$$\text{PSI} = a \sum_i S_i \left(\frac{3 \mu_i + 2}{5}\right),$$

(ref. 1). The quantity $a$ represents the bolometric effect of the umbra and penumbra of a sunspot, weighted by their relative area.

We have measured the area of selected sunspots during several months during 1980. The photographs were made available from the synoptic program carried out at the Sacramento Peak Observatory. These full disk photographs, on 35mm film are digitized by an Optronics P-1000 with a square spot of 50 $\mu$m spacing. This corresponds to about 6 arc sec on the sky. The data are calibrated assuming a mid-visible limb darkening.

Relative intensities are determined by normalizing with the quiet sun limb darkening. Figures 1a and 1b show the raw digitized image and the calibrated local contrast, $\Delta I/I$, respectively. The computer can then search for sunspot pixels on the "flattened" solar image, count them, and determine their position. In this way we have obtained quantitative measurements of sunspot areas. The position is used to correct for foreshortening in order to obtain sunspot area in millionths of a hemisphere (ref. 2). We have regressed the SESC and SGD areas against the area from our program, FDAP. The results are shown in figures 2 and 3. We find that the data are more complete in the SESC listing than for the SGD listing. For the period of time from 27 February to 15 May 1980, we find that the linear regression SGD = $a + b^* \text{FDAP}$, gives $a = 4.0 \pm 12.5$ ppm and $b = 0.990 \pm 0.026$ with the linear correlation coefficient $r = 0.975$, where FDAP is the computer-determined area and SGD is the published sunspot area in the Solar-Geophysical Data Bulletin, both areas in millionths of a hemisphere. For this interval the number of data pairs is 78.

For the same period of time, the analysis of SESC data, using SESC = $a + b^* \text{FDAP}$, gives $a = 30.4 \pm 8.1$ and $b = 0.843 \pm 0.018$ with $r = 0.963$. The number of data pairs is 171. In the case of the SGD data, the mean residual is 81 ppm. For the SESC data, the mean residual is 83 ppm. The distribution of the residuals is not quite gaussian and there may be some non-linearities in the determination of sunspot areas. There is clearly a significantly different scale factor for the two
sources of data. The SGD data give a slope very near 1.0 but there is more missing data for this compilation. We are performing further statistical tests on the data with large residuals and this aspect will be discussed in ref. 2. These data will also be used to calculate a PSI (ref. 1) to be compared to fluctuations in the ACRIM signal.

Each photograph requires approximately 3 minutes to digitize and approximately 10 minutes of machine time to copy the tape and run the program FDAP. We believe this analysis points to the need and feasibility of providing objective, digital sunspot areas. The determination of facular or plage area may be as important as for spots but more difficult due to the lower contrast and larger area of facular regions. A computer controlled search for faculae will require the highest quality white-light photographs. Several full disk images so far analyzed by the full disk program, FDAP, show significant non-uniformities across the image (figure 1b). These non-uniformities make it very difficult to detect faculae.

**ACTIVE REGION PHOTOMETRY WITH THE ELP**

Two-dimensional or areal photometry has been carried out with the Extreme Limb Photometer (ELP) of active regions at various disk positions (ref. 3). This photometer has been described in ref. 4 and ref. 5. Measurements reported here were carried out in October 1980 and the summer of 1982. The ELP scans in a circular path using a slit with dimensions 3" by 39". A circular swath across an active region has a resolution given by this slit size. It has been determined that during 1980 and 1982, over 45 active regions were well mapped by one or more swaths with the ELP at a wavelength of 525 nm. The detailed results will be published (ref. 6). The ELP cannot determine the "intrinsic contrast" of sunspots or faculae because of its rather long slit. It can "map" or photometer a complete active region with only a few separate pointings of the telescope. By a knowledge of the position of the swaths, either from a sunspot map, or from the ELP data, the brightness fluctuations of the active region from the separate swaths can be combined into a brightness fluctuation for the entire region, relative to the quiet sun.

An example of several swaths covering an active region is shown in figure 4. This active region was several days from the limb yet the facular emission can be seen to be roughly equal to the sunspot deficit. This effect cannot be explained
by scattered light, since scattering will cause a loss of the positive facular signal as well as the negative sunspot signal. We have found, in general, that sunspots dominate in the central regions of the disk but faculae dominate near the limb.

We have correlated the Photometric Sunspot Index, PSI, (ref. 1), and the Photometric Facular Index, PFI, (ref. 7), with the sunspot and facular signals from the ELP. The PSI and PFI are defined by

\[ \text{PSI} = C_S A_S \mu (3\mu + 2) \]

and

\[ \text{PFI} = C_P A_P (\mu - 3\mu^2 + 2), \]

where \( A_S \) and \( A_P \) are the areas of the sunspots and Calcium plage, respectively, in millionths of a hemisphere published in the Solar-Geophysical Data Bulletin. The ELP photometry of an active region has been divided into a sunspot brightness fluctuation, \((\Delta B/B)_S\) and a facular brightness fluctuation, \((\Delta B/B)_F\). The sum of \((\Delta B/B)_F\) and \((\Delta B/B)_S\) gives the net brightness fluctuation of the active region in units of millionths of the quiet sun irradiance, assumed constant.

From an analysis of 45 active regions at various points on the solar disk and at various stages in their lifetime, we find \( C_S = 0.164 \pm 0.0083 \) and \( C_P = 0.0092 \pm 0.0014 \). Applying bolometric corrections to these monochromatic contrasts (ref. 4) gives \( C_S = 0.143 \pm 0.0073 \) and \( C_P = 0.0078 \pm 0.0012 \).

Integrating PSI and PFI over \( \mu \), we find that the flux deficit, per unit area, due to sunspots is 24 times that due to faculae. The area of Ca plage has been found to be approximately 25 times that of sunspots (ref. 8). The near equality of these ratios strongly suggests that there exists energy balance within an active region.

Statistical comparisons with ACRIM data (ref. 9) support the energy balance, which was suggested earlier (ref. 10) from a more extensive statistical analysis of modeled ground-based synoptic data with ACRIM data. Sofia et al. (ref. 10) suggested, implicitly, that the energy balance was rather immediate. The ELP results suggest that there must be energy storage within the active region. I will return to this point in the conclusion.
DIODE ARRAY PHOTOMETRY

The use of linear diode arrays allows the photometry of a large area yet with relatively high spatial and spectral resolution. Considerable work with this type of detector has been carried out by Foukal and collaborators (ref. 11,12). The advantages of diode arrays over film are linearity and large dynamic range. At the SFO we are using Reticon S-series arrays. These arrays are reported to have a dynamic range up to $10^4$:1. The results obtained so far from the 1982 data are reported in more detail by Lawrence et al. (ref. 13).

Photometry in 1982 at SFO was carried out, for the most part, in a 1.5A band near 6264A in a continuum region clear of absorption lines in the photospheric and the sunspot spectrum. Placed over the exit port of the vacuum spectroheliograph, the diode array is read out at approximately 5 lines per second. At this speed, we have a dynamic range of about 3000:1 with a signal-to-noise of about 103. The data are converted to a 12-bit binary number and written onto tape for subsequent processing. Some data were also obtained at three other wavelengths, 5245A, 7824A, and 10,000A on some days. These data will be used to determine bolometric corrections.

As a rule, observations were obtained that included the limb and sky. These data will combined with ELP calibration scans, going out into the sky 2.4 solar radii, to yield corrections for scattered light.

Data for several active regions have been obtained for up to 4 solar rotations. We intend to study the irradiance balance during the disk passage of as many regions as can be identified during the observing season. Analysis procedures have been carried out mainly on one large active region, BBSO no. 18511, from 3-16 August 1982. These data are shown in figure 5. For a more complete discussion see ref. 13. The curve connects daily points from diode array photometry. Several aspects deserve mention: (1) The curve appears to be relatively smooth indicating noise is not overwhelming, (2) the diode array results follow, approximately, the PSI values, indicated by x's, and (3) at both limb transits, there exists a net excess in the irradiance fluctuations, indicating the importance of facular emission. More recent analysis brings the diode array excess up to or higher than the squares, which represent the ELP results.

We see clear evidence, near central meridian passage, for a rapid change in the irradiance deficit, probably indicative
of sunspot evolution. Such changes point out the need for accurate photometry at intervals of less than 1 day, perhaps as little as 6 hours.

CONCLUSION

As discussed, it appears possible that there exists energy balance within an active region between sunspots and faculae. Since there is a considerable difference in the lifetimes of these two phenomena, there must be energy storage. Since sunspots and faculae are, in most cases, magnetically connected it follows that the energy "blocked" by sunspots is stored in the magnetic fields of the active region. Since it is difficult to imagine thermal energy being stored in magnetic flux tubes, I suggest that the energy is converted into magnetic energy (ref. 14) which later is degraded back to heat in the faculae.

The complete understanding of irradiance changes will require improved synoptic ground-based observations, improved in accuracy over current practices and improved in temporal coverage.
REFERENCES


FIGURE CAPTIONS

Figure 1(a). Printer plot of digitized full disk photograph for 7 April 1980 from Sacramento Peak Observatory (L. Gilliam). The film density is represented by symbols. (b) Printer plot of calibrated contrast relative to published limb darkening (ref. 2).

Figure 2. A linear regression of the published sunspot areas, published in the Solar Geophysical Data Bulletin (SGD) versus the areas from the Full Disk Analysis Program (FDAP) using synoptic "white-light" images from the Sacramento Peak Observatory.

Figure 3. A linear regression of SESC sunspot areas, published in the weekly forecasts of solar activity. The linear regression coefficient is further from unity than in the first case but the number of data pair are twice as great.

Figure 4. Adjacent scans with the Extreme Limb Photometer (ELP) across active region 18474 on 20 July 1982. The scans are displaced for clarity.

Figure 5. Monochromatic brightness fluctuation of active region BBSO #18511. The brightness fluctuation, $\Delta B/B$, is the net fluctuation faculae minus sunspot, in units of millionths of the quiet sun irradiance. The preliminary diode array results are open circles connected by solid lines (the dashed line bridges a missing day). The error bars are $\pm 1$ standard deviation except where only two observations have been examined in which case the error bars are the separation of the two data points from the mean (6 Aug. 82). Where no error bars are shown, they are within the circle (these are formal errors and do not include any systematic errors). The open squares represent results from the ELP corrected to this wavelength, 6264 A. Recent improvements in the quiet sun limb darkening have raised the diode array results, near the limb, to or above the ELP data points shown here. The other symbols are discussed in ref. 13.
POINTS 78

Y INTERCEPT 3.96  S.D 12.539
SLOPE 0.99  S.D 0.026
LINEAR CORR. 0.9748

Figure 2
POINTS 171
Y INTERCEPT 30.43 S.D 8.114
SLOPE 0.84 S.D 0.018
LINEAR CORR. 0.9628

Figure 3
DISCUSSION OF CHAPMAN PRESENTATION

RABIN: How large are the photographic density gradients across the image?

CHAPMAN: Seven percent.

SKUMANICH: Does scattered light affect the conclusion that the facular emission outweighs the spot deficit?

CHAPMAN: No.

MOORE: But this is only true very near the limb.

CHAPMAN: The spot wins out three to four days from the limb. The spot loses at one day from the limb.

POUKAL: Scattered light and seeing will change this result by a factor of two.

CHAPMAN: No, the measured intensity is an integral over the 38 arc second slit length, so we do a set of scans and just sum. We use an area of 200 by 200 arc seconds, so nearby scattering doesn't matter.

POUKAL: It depends on the measured area of the spots and faculae.

CHAPMAN: We don't measure the areas, just sum the intensities.

POUKAL: Then it depends upon the zero level.

CHAPMAN: The zero level is unknown to a few percent.

POUKAL: Then you can't know the true total well.

MOORE: Do faculae look dark at disk center in the continuum?

CHAPMAN: No, but the data aren't good enough.

POUKAL: How deep is the spot if magnetic energy is to match the energy not emitted?

CHAPMAN: The depth of the convection zone.

POUKAL: That's pretty large!

HUDSON: It depends on the variation of the field strength with depth.

HEATH: Since an observer at the poles can see faculae in the active latitudes better than the spots, there is a net excess of emission from the Sun toward the polar directions, which must affect the spot-faculae balance.

HUDSON: The angular dependence of the emission is included in the integrals.
NEWKIRK: What bandpasses do you use?

CHAPMAN: We have three or four filters from UV to the near IR.

SCHATTEN: I don't see how kinetic energy gets transformed into magnetic energy.

CHAPMAN: There is no model, but it is inferred from the balance of the spot and facular emission.

SCHATTEN: Why don't the spots just keep growing bigger and bigger?

CHAPMAN: I don't know.