OBSERVATIONS FROM 1982 OF FACULAR LIMB DARKENING
AND EXCESS SOLAR OBLATENESS

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Abstract. Observations of facular regions on 35 days during 1982 obtained with the Extreme Limb Photometer are reported. The data were obtained at a wavelength of 0.53 μm with two apertures, No. 1 covering 36 arc sec and No. 2 covering 11 arc sec, inwards from the limb. The mean contrasts for all regions detected are $1.05 \pm 0.12\%$ and $1.59 \pm 0.16\%$, respectively. The mean contrast of the faculae closer to the limb (aperture 2) is $1.51 \pm 0.23$ times that from aperture No. 1. This contrast ratio can be fit to a $\mu^{-1}$-curve. These results are consistent with those from 1975 and 1979 observations and may be consistent with the facular limb-darkening function determined by Libbrecht and Kuhn (1984, 1985) if our data are normalized by the area of the solar surface. However, no calibrations or corrections are required to obtain the mean facular contrast presented here.

1. Introduction

The variation of the contrast of photospheric faculae near the solar limb is the subject of some debate. The contrast of faculae near the limb is needed in order to properly measure the shape of the Sun, to calculate the effect of faculae on solar luminosity changes, and to develop models of magnetic flux tubes.

Earlier measurements of the contrast of faculae were reported by Chapman and Klabunde (1982). These authors found that the contrast of faculae increased toward the limb to within $\mu = 0.04$, where $\mu$ is the cosine of the heliocentric angle. Libbrecht and Kuhn (1984), from observations made in 1982, deduced a contrast function that linearly decreased towards the limb from $\mu = 0.2$. More recent data, with their apparatus located at Mt. Wilson, confirmed their earlier results (Libbrecht and Kuhn, 1985). See also Dicke, Kuhn, and Libbrecht (1983, 1985, 1986) for a discussion of the oblateness measurements. On the other hand, Hirayama, Hamana, and Mizugaki (1985), using a rotating diode array photometer, found that the facular contrast increases toward the limb. Wang and Zirin (1987) found that facular contrast increased to $\mu = 0.2$ but decreased from there towards the limb. Their results were derived from high resolution TV images and required the identification of individual faculae. The ELP does not require the identification of individual faculae but sums all the facular signal within that part of the active region scanned by the ELP aperture.

This paper presents results from the Extreme Limb Photometer (ELP) for the summer of 1982, the same season as used in the Libbrecht and Kuhn (1984) result.

In Section 2 we give a brief review of the instrument and its data. Section 3 summarizes the results. Section 4 discusses these and related results.

2. Description of the ELP Data

2.1. Data Acquisition

The ELP scans an image of the Sun with one of two apertures. Each aperture is 39 arc sec long and 3 arc sec wide. The long dimension is aligned along a radius of the solar image. The two apertures are independently adjustable so that a limited amount of the solar limb can be scanned. In 1982, the outermost aperture, No. 2, was set to scan approximately 11 arc sec of the limb, while aperture No. 1 was set to scan the outer 36 arc sec of the limb. Scanning is accomplished by rotating an invar disk, centered on the solar image, at a rate of one rotation per second. The light passing through one of the two apertures is reimaged through a band pass filter onto a photodiode. The photocurrent is amplified and electronically filtered at the Nyquist frequency. Each rotation results in 2048 samples with 12 bit precision. These samples are summed in a double precision array (32 bit words) for 25 s. This is the time interval in which telescope drift is less than about 1 arc sec without active guiding. After 25 scans are summed, the data are written to magnetic tape. Calibration scans consist of 10 scans with the rotation axis of the ELP pointed at a location 1.14 solar radii from the limb followed by 10 scans with the rotation axis of the ELP pointed at the solar limb. These scans help determine the brightness scale and the location of the geographic north point on the solar disk with respect to the beginning of the data record. The calibration is not needed to measure facular contrast.

2.2. Data Analysis

The analysis of the data is carried out on the CSUN Cyber 170/750. An analysis of the non-Sun centered data for this season has been carried out and published in Chapman and Meyer (1986). The analysis of the Sun centered data begins by adding together all of the observations obtained with a particular aperture. Because of variations in optical efficiency we are forced to filter out low-frequency variations in the signal as a function of rotation angle. These low-frequency variations are also caused, in part, by seeing and telescope motion. The program also searches the filtered signal for dark and bright features whose contrast exceeds a criterion defined by iterative determinations of the noise level. For the analysis reported here this search criterion was plus or minus 2 times the r.m.s. noise level. The reliability of this scheme was checked by making pen plots before and after filtering with the active region limits determined by the program displayed. Active regions found by the computer program were identified with those published in the Solar Geophysical Data Bulletin in all but a few cases. A complete description of these procedures is available in Oseas (1985).

3. Presentation of Results

Typically, the Sun-centered observations for each day consisted of 150 scans with aperture 2 (δ = 11 arc sec) and 50 scans with aperture 1 (δ = 36 arc sec), where δ is the
amount of exposed limb. Other ELP observations during the day were non-Sun-centered in order to measure the integrated contrast of selected active regions further from the limbs.

Figures 1 and 2 show processed data from the two apertures from 8 and 9 July, 1982. Figure 1 shows the 8th of July divided into two time periods. Temporal changes are clearly evident. The prominent feature is due to the faculae and sunspots of Hale region 18474. The middle part of each graph is a five-times magnification of the upper plot after low frequency smoothing by least squares. The vertical lines underneath the filtered

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Fig. 1. (a) ELP scans from 8 July, 1982 obtained with aperture 1 (upper) and 2 (lower). The upper and lower plots are the averages of 50 and 175 scans, respectively. The smoothed curve has been filtered to remove variations in optical transmission. (b) ELP scans from the second half of 8 July, 1982. Time changes are clearly evident as Hale region No. 18474 is moving into view at the east limb. The upper and lower plots are as in (a) except that only 150 scans are averaged in the lower (aperture 2) curve. The vertical scale is relative intensity from zero to unity and the horizontal scale is from step 1 on the left to 2048 on the right. Step 1 is geographic north and south for aperture 1 and 2, respectively. The filtered ELP is magnified by a factor of five and plotted in the middle of the graph.
Fig. 2. ELP scans from 9 July, 1982 showing, primarily, Hale region No. 18474. The sunspots of the region have now moved primarily into aperture 1 ($\delta = 36$ arc sec) and are no longer visible in aperture 2 ($\delta = 11$ arc sec). The upper and lower curves are the averages of 75 and 175 scans corresponding to apertures 1 and 2, respectively.

curve show the iteratively determined active region limits. Figure 2 shows this same active region on 9 July, 1982. Since the two ELP apertures are on opposite sides of the scanning disk, the regions are shifted by 1024 steps when viewed by one aperture relative to the other. Figure 3 shows an active region observed on 24 July, 1982 with aperture 2. This region can also be seen at lower resolution in Figure 2 of Libbrecht and Kuhn (1984).
4. Discussion of Results

The principle result from the 1982 season is that the mean contrast of faculae was greater in the aperture closer to the limb. The mean contrast in the outer aperture was approximately 1.5 times that in the inner aperture. This result holds for both the mean contrast and the integrated contrast (see Table I). The mean contrast is the contrast of the facular region smeared over the annular patch defined by the ELP. (See Chapman and Klabunde, 1982, for definitions of these terms.) The detection of faculae with the ELP does not depend on resolving features against the rapidly changing photospheric limb intensity and so the results reported here do not suffer the problems of feature identification and background removal as is the case with an imaging system.

Figure 4 shows the facular excess oblateness for the summer of 1982 as measured by the ELP (filled circles) and the Princeton Distortion Telescope (open circles). Considering the different observing days, the results are in reasonable agreement. The excess oblateness signal associated with the faculae observed here is given in Table II. The

<table>
<thead>
<tr>
<th>Aperture</th>
<th>$\beta$ (steps)</th>
<th>$c \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.590 ± 0.092</td>
<td>10.54 ± 1.23</td>
</tr>
<tr>
<td>2</td>
<td>0.892 ± 0.132</td>
<td>15.92 ± 1.63</td>
</tr>
<tr>
<td>Ap. 2/Ap. 1</td>
<td>1.51 ± 0.32</td>
<td>1.51 ± 0.23</td>
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excess oblateness due to faculae, averaged over the 35 days of observation in the summer of 1982 is \((2.13 \pm 0.31) \times 10^{-5}\) for a limb exposure of 11 arc sec. This value is to be compared with the excess oblateness of \((1.6 \pm 0.06) \times 10^{-5}\) reported by Dicke, Kuhn, and Libbrecht (1983) for 49 observing days during the same summer. This value is estimated by linearly interpolating between the facular oblateness contribution reported for limb exposures \(\delta = 8\) arc sec and 14.5 arc sec. For these values of \(\delta\), Dicke, Kuhn, and Libbrecht (1983) give the facular oblateness contribution of \(10.4 \pm 0.5\) and \(20.3 \pm 0.7\) m arc sec, respectively. The true errors may be substantially larger than indicated here. Dicke, Kuhn, and Libbrecht (1985, 1986) suggest that the error may be

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Fig. 4. Facular excess oblateness for 1982. The filled circles are the results from the Extreme Limb Photometer (Table II). Error bars are the formal standard deviation whose value is dominated by solar variations, not instrumental noise. The open circles are from Dicke, Kuhn, and Libbrecht (1983) with error bars as suggested in Dicke, Kuhn, and Libbrecht (1985).

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**TABLE II**

ELP excess oblateness due to faculae, 1982

<table>
<thead>
<tr>
<th>Aperture</th>
<th>(\delta) (arc sec)</th>
<th>(\Delta r/r) ((\times 10^{-5}))</th>
<th>(\Delta r) (m arc sec)</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>35.7</td>
<td>4.12 \pm 0.64</td>
<td>38.98 \pm 6.07</td>
</tr>
<tr>
<td>2</td>
<td>11.0</td>
<td>2.13 \pm 0.31</td>
<td>20.19 \pm 2.90</td>
</tr>
</tbody>
</table>

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closer to $\pm 4$ m arc sec. Thus the mean excessoblateness in 1982 determined by Dicke, Kuhn, and Libbrecht (1983) may be $(1.6 \pm 0.4) \times 10^{-5}$.

Given the uncertainties in interpolation between differing amounts of exposed limb in the two experiments and the differences in observing days that make up the data sets, the excessoblateness measured by the ELP is in reasonable agreement with the excess oblateness for 1982 reported by Dicke, Kuhn, and Libbrecht (1983). Thus we confirm that the excess facular oblateness signal is an important, if not a dominant, contribution to measurements of solar oblateness.

It seems appropriate to point out that the data that have been analyzed from 1982 include all data that were obtained.

5. Summary

We find that the magnitude and limb dependence of the facular excess oblateness measured by the ELP is consistent with that measured by the Princeton distortion telescope (Dicke, Kuhn, and Libbrecht, 1983). The results on facular contrast are entirely consistent with those reported earlier from the same apparatus, that is that the integrated and mean contrast of facular regions increase toward the limb, at least for $\mu = 0.1$ or 0.2. The center-to-limb dependence of the mean contrast may be consistent with the Monte-Carlo analysis of the Princeton distortion telescope signal (Libbrecht and Kuhn, 1984, 1985) assuming their analysis corrects their data so that it applies to individual, unresolved fluxtubes. The ELP data presented here have not been corrected for the greater amount of solar surface area per arc sec of exposed limb. The facular contrast of unresolved fluxtubes from photometric data will be discussed in Lawrence and Chapman (1988).

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References