ON THE FACULAR CONTRAST NEAR THE SOLAR LIMB

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ABSTRACT

We present an improved measurement of the continuum contrast of solar faculae in wavelength bands centered at 800 and 525 nm. Our findings confirm our earlier result that near the extreme solar limb the contrast decreases with decreasing distance to the limb. Parameterizing the contrast function with \( \Delta I/I = 0.2 + a(\mu - 0.2) \) over the range 0.08 < \( \mu \) < 0.2, where \( \mu \) is the cosine of the heliocentric angle, we obtain the best-fit values of \( a \); \( a_{red} = 0.25 \pm 0.10 \), \( a_{green} = 0.30 \pm 0.10 \).

Subject heading: Sun: faculae

I. INTRODUCTION

The continuum contrast of solar photospheric faculae, defined by the contrast function \( \Delta I/I = (I_{fac} - I_{phot})/I_{phot} \), has been observed to increase from \( \sim 0 \) at the center of the solar disk to \( \Delta I/I \approx 0.2 \) at \( \mu = 0.2 \) (\( \mu = \cos \theta \); the distance from disk center is given by \( r = R \sin \theta \)) (Muller 1975; Hirayama 1978; Ingersoll and Chapman 1975; Badalyan and Prudkovskii 1973; Rogerson 1961). Closer to the limb a good measurement of the contrast function is important for comparison with various facular models. Spruit’s “hot wall” model (Spruit 1976) predicts a contrast function that peaks at \( \mu \approx 0.2 \) and decreases to zero with decreasing \( \mu \). Chapman’s “hot cloud” model (Chapman 1970; Ingersoll and Chapman 1975) predicts a rapidly increasing \( \sim \mu^{-1} \) function in the same region. Accurate knowledge of the facular contrast is also important in understanding the Sun’s total energy output (Chapman 1984).

In an earlier paper (Libbrecht and Kuhn 1984, hereafter LK84) we presented a measurement of the continuum contrast of solar faculae in wavelength bands centered at 800 and 525 nm with widths \( \sim 300 \) and 75 nm, respectively. The measurement showed essentially that the facular contrast decreases with decreasing distance to the solar limb in the range 0.08 < \( \mu \) < 0.2. This result was in contradiction to a previous measurement of the facular contrast near the limb by Chapman and Klabunde (1982), where the contrast was found to vary rapidly toward the limb, fitting a \( \mu^{-1} \) dependence. We suggested selection effects in the Chapman and Klabunde data which might explain the discrepancy.

The result in LK84 was based on limb photometer data taken in 1982 with the Princeton Solar Distortion Telescope located at Princeton. These data were not of the best quality (although they were sufficient for the analysis presented), mainly because of the large number of cloudy days one finds in New Jersey. Therefore to derive a contrast function from those data a rather complicated analysis procedure was followed. Since that time the instrument has been moved to Mount Wilson, California, and was operated on over 130 days during the summer of 1983 and on over 100 days in 1984. The new data set has allowed a determination of the facular contrast near the solar limb.

II. DATA AND ANALYSIS

The instrument used to collect the data presented here has been described by Libbrecht and Kuhn (1984) and more completely by Libbrecht (1984). Basically a solar image was centered on an occulting disk, and the integrated flux beyond the disk was measured as a function of position angle \( \phi \) at 256 points around the disk. In 1983 three different occulting disks were used to obtain data with different amounts of exposed limb, while in 1984 this was done by changing the telescope magnification. The different limb exposures and flux ratios are given in Table 1.

In 1983 the telescope magnification was changed every few days to compensate for the changing apparent size of the Sun. Thus the limb exposures listed for that year in Table 1 represent seasonal means, while the actual day-to-day exposed limb varied from this value by as much as 0.75. In 1984 the

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### Table 1

<table>
<thead>
<tr>
<th>Disk</th>
<th>Color</th>
<th>Exposed Limb</th>
<th>( (F_0/I_0)/(F/I) )</th>
<th>( (\Delta F_0/I_0)/(\Delta F/I) )</th>
<th>( R_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>red</td>
<td>17.7 ± 0.1</td>
<td>1.000</td>
<td>1.000</td>
<td>0.19</td>
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<tr>
<td>2</td>
<td>red</td>
<td>11.4</td>
<td>0.708 ± 0.005</td>
<td>0.682 ± 0.005</td>
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<tr>
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<td>4.9</td>
<td>0.454</td>
<td>0.411</td>
<td>0.10</td>
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<tr>
<td>1</td>
<td>green</td>
<td>21.5</td>
<td>1.000</td>
<td>1.000</td>
<td>0.21</td>
</tr>
<tr>
<td>2</td>
<td>green</td>
<td>15.2</td>
<td>0.707</td>
<td>0.699</td>
<td>0.18</td>
</tr>
<tr>
<td>3</td>
<td>green</td>
<td>8.7</td>
<td>0.443</td>
<td>0.399</td>
<td>0.13</td>
</tr>
</tbody>
</table>

1983

<table>
<thead>
<tr>
<th>Disk</th>
<th>Color</th>
<th>Exposed Limb</th>
<th>( (F_0/I_0)/(F/I) )</th>
<th>( (\Delta F_0/I_0)/(\Delta F/I) )</th>
<th>( R_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>red</td>
<td>19.9 ± 0.1</td>
<td>1.000</td>
<td>1.000</td>
<td>0.20</td>
</tr>
<tr>
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<td>0.711 ± 0.005</td>
<td>0.695 ± 0.005</td>
<td>0.16</td>
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<td>6.2</td>
<td>0.449</td>
<td>0.379</td>
<td>0.11</td>
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<tr>
<td>1</td>
<td>green</td>
<td>22.2</td>
<td>1.000</td>
<td>1.000</td>
<td>0.21</td>
</tr>
<tr>
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<td>0.772</td>
<td>0.742</td>
<td>0.18</td>
</tr>
<tr>
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<td>10.4</td>
<td>0.553</td>
<td>0.468</td>
<td>0.15</td>
</tr>
</tbody>
</table>

1984
For each occulting disk $i$ the flux measurements $F_i(\phi)$ were normalized by dividing by the brightness $I_i$ at the edge of the disk, giving a flux profile $F_i(\phi)/I_i$ measured in arc seconds (see LK84). The $I_i$ were derived from calibration data which measured the integrated flux at 10 closely spaced limb exposures. These calibration runs were made every 30 minutes in 1983 and every 40 minutes in 1984. In 1983 two stepped calibrator occulting disks were used for this purpose, while in 1984 the telescope magnification was quickly cycled through the 10 limb exposures.

Solar active regions, both faculae and sunspots, were identified from weighted daily mean limb profiles using a robust fitting procedure described in LK84. Excluding the day's identified active region channels, each flux profile was fitted by least-squares to a mean plus second harmonic ellipticity. The same active region channels were excluded for all three disks on a given day. The 1983 seasonal stacked residuals after subtracting the fits are shown in Figure 1. It is seen from this plot that the excess brightness from active regions is strongly dependent on the amount of exposed limb, as is expected, and that near the limb the flux excess from faculae is greater than the flux deficit due to sunspots. In 131 daily averaged limb flux profiles from 1983, 124 showed a localized flux excess which we take to be faculae, while only 10 showed a net localized flux deficit indicative of a sunspot. The near absence of net flux deficits due to sunspots is also shown in Figure 3 of LK84. The effect is simply a result of the increased facular contrast near the solar limb combined with the Wilson depression of sunspots.

Figure 1 shows simply the time-averaged excess flux from faculae (neglecting the small sunspot contribution) near the solar limb. Taking the time average of equation (4) in LK84 gives the time-averaged excess flux

$$\langle \Delta F_i \rangle = \langle A \rangle \int_0^\infty I(x)dx \left[ \frac{1}{2} - \frac{1}{2} \text{erf} \left( \frac{x - x_i}{\sigma} \right) \right] dx ,$$

where we have assumed that in the time average faculae are uniformly distributed in longitude on the Sun. If we then parameterize $\Delta I/I$ near the limb of the Sun by $\Delta I/I = a + b\mu$, we have

$$\Delta F_i/\Delta F_j = F_i(a + R_i b)/F_j(a + R_j b) ,$$

where the $R_i$ are constant factors dependent on color and the amount of exposed limb. Assuming $\sigma = 5'$ (which includes telescope diffraction as well as atmospheric seeing), the $R_i$ are easily estimated and are tabulated in Table 1. The $R_i$ are not very sensitive to changes in the seeing function. Note from the above that if $a = 0$, i.e., the contrast function is a constant near the limb, then $\Delta F_i/\Delta F_j = F_i/F_j$ independent of atmospheric scattering, and if the facular contrast is decreasing toward the limb, then $\Delta F_i/\Delta F_j < F_i/F_j$. The relative facular signal strengths calculated using a simple scaling fit to the curves in Figure 1 are given in Table 1. Thus we see immediately from Table 1 that the contrast function is decreasing toward the limb. This conclusion holds even if our simple parameterization of the facular contrast is not an accurate representation of the actual function. A small residual brightness signal near the poles can also be seen in Figure 1. This is described in detail elsewhere (Kuhn, Libbrecht, and Dicke 1985), and has little effect on the numbers in Table 1 since the disk and color dependence of the brightness signal is nearly the same as the facular signal. Sunspots included in the Figure 1 data tend to inflate the measured $(\Delta F_i/I_i)/(\Delta F_j/I_j)$. 

Fig. 1.—Seasonal average normalized flux profiles $\Delta F/I$ for the three disks in two colors. In computing the average, a mean and second harmonic signal were fitted to each flux profile, not including the day's marked facular channels (see text), and the fit was subtracted from that profile before it was included in the average. Approximately 2200 limb profiles are included in each of the six averaged curves.
Fig. 2.—Excess facular signal $\Delta f/I$ plotted for various disks using 1984 data. Data points come from individual channel data of the daily mean limb profiles. The fit slopes of the solid lines are 0.345, 0.673, 0.516, 0.443, 0.730, and 0.612.
This result is almost completely independent of the atmospheric scattering present in the measurement, unlike all previous determinations of the facular contrast near the limb (with the exception of LK84). Contrast measurements which rely on imaging detectors are very sensitive to scattered light near the limb since the solar surface brightness drops precipitously near the extreme limb. In addition, faculae near the extreme limb are usually impossible to recognize on a solar image unless they are very bright, leading to an important selection effect if individual faculae are identified only by brightness. The analysis just described cannot suffer from any such selection effects since faculae need never be singled out; the plots in Figure 1 include the entire solar profile, and the \( F_i/I \), in Table 1 are negligibly perturbed by the influence of the small excess facular brightness.

We can demonstrate the same result in a more graphic fashion by plotting \( \Delta F_i/I \) versus \( \Delta F_i/I_p \), as in Figure 2. Here again we see that the facular contrast is decreasing toward the limb. Points with \( \Delta F_i < 0 \) were excluded from this plot and from the linear fits, so we expect that the sunspot contribution to the derived slopes is even smaller than for the Table 1 values. Using the linear fits shown in the figure and equation (2), and parameterizing the contrast function as \( \Delta I/I = 0.2 + \alpha(\mu - 0.2) \) for \( \mu > 0.2 \), we find \( \alpha_{\text{red}} = 0.34 \) and \( \alpha_{\text{green}} = 0.40 \). Using instead the \( \Delta F_i/I \) from Table 1, we find \( \alpha_{\text{red}} = 0.17 \) and \( \alpha_{\text{green}} = 0.20 \) for 1983 and \( \alpha_{\text{red}} = 0.26 \) and \( \alpha_{\text{green}} = 0.34 \) for 1984. These results are consistent with the results of LK84. Assigning standard errors to these fits is difficult for two reasons: (1) we used an overly simple one-parameter representation of the contrast function; and (2) our integrated flux measurements do not allow very accurate single-point determinations of the contrast function. The errors quoted in the abstract were obtained from the scatter in the above three determinations of \( \alpha \). However, despite these problems, it is very clear from the data that the facular contrast in fact decreases toward the solar limb for \( \mu < 0.2 \).

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REFERENCES


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