THE CONTRAST OF FACULAE NEAR THE SOLAR LIMB

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Abstract. We have measured the contrast of solar faculae near the limb on direct digital video images made with the 65 cm vacuum reflector at the Big Bear Solar Observatory. We used six broad band filters with different wavelengths from red to violet. The range of heliocentric angle covered in our measurements is $0.05 < \mu = \cos\theta < 0.4$ ($\theta = 87°-66°$). About 300 images were measured from observations made during the summers of 1983 and 1985. Over 20000 faculae were measured.

By averaging the contrasts of faculae and plotting them vs heliocentric angle, we found that contrast increases monotonically towards the limb for the shorter wavelengths; for longer wavelengths, contrast has a tendency to peak around $\mu = 0.15$, and then decrease towards the extreme limb. The contrast increases as wavelength decreases.

1. Introduction

Faculae are regions of enhanced magnetic field observed in the continuum. It is well known that the contrast of the facula to the photosphere increases toward the limb (Muller, 1975). But the exact behavior of the contrast function near the extreme limb has been a matter of some dispute. The question was especially active in discussions of measurements of the solar oblateness (Ingersoll and Chapman, 1975), but the center-limb variation of facular brightness is important evidence on the physical nature of faculae. Why the presence of enhanced magnetic field produces these increases is a mystery.

The variation in measurements made by various authors (Muller, 1975; Hirayama, 1978; Chapman and Klabunde, 1982; Libbrecht and Kuhn, 1984, 1985) is summarized in Figure 1 (copied from Libbrecht and Kuhn) where we have included our results. Some of those measurements are from high-resolution observation (with the resolution 1″ or so, Muller, 1975; Hirayama, 1978), they can be used to derive models of magnetic flux tubes. Others are from the low-resolution observation (Muller, 1975; Chapman and Klabunde, 1982; Libbrecht and Kuhn, 1984, 1985), they can be used to estimate the brightness excess of facular area in oblateness measurements or in the sunspot deficit problem. Our measurement is from the high-resolution observation. Almost all the previous measurements are indirect, i.e., all the faculae within a range were measured, and the area are estimated. The wavelength range of the previous data is also limited. The data of Chapman and Klabunde are based on integrated observations of bands of constant μ while that of Muller is based on photographic observations in a single wavelength on four days. There have been no previous digital photometric measurements of individual facular points; this would appear to be the most direct and simple way of measuring the contrast when resolution is adequate. This method also permits

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us to approach closer to the limb than most of previous data. Our data go to $\theta = 87°$, 1.2 arc sec from the limb.

Two kinds of theoretical models which attempt to explain the excess continuum emission of the faculae over the quiet photosphere: (1) The 'Hot Wall' model (Spruit, 1976). (2) The 'Hot Cloud' model (Chapman, 1970; Ingersoll and Chapman, 1975; Schatten *et al.*, 1986). The 'Hot Wall' model predicts that the contrast of facula peaks at a heliocentric angle of $\cos\theta = 0.2$ then decreases rapidly. The 'Hot Cloud' model predicts a rapid increase of the facular contrast when $\mu < 0.2$. The measurements of the center-to-limb variation in facular contrast gives an important test of those models.

2. Instrument and Data Collection

For the present work we used a RCA camera with Newvicon vidicon tube on the 65 cm reflector at Big Bear. Frames were digitized with eight-bit accuracy on the Quantex or Eyecom video images processors. Usually four successive frames were averaged to reduce video noise. The total exposure is thus $\frac{1}{8}$ s. A photograph of one of the plage regions is given in Figure 3. The resolution in the BBSO in the summer is usually about 1 arc sec. A rotating filter wheel made possible rapid change of the wavelength observed.

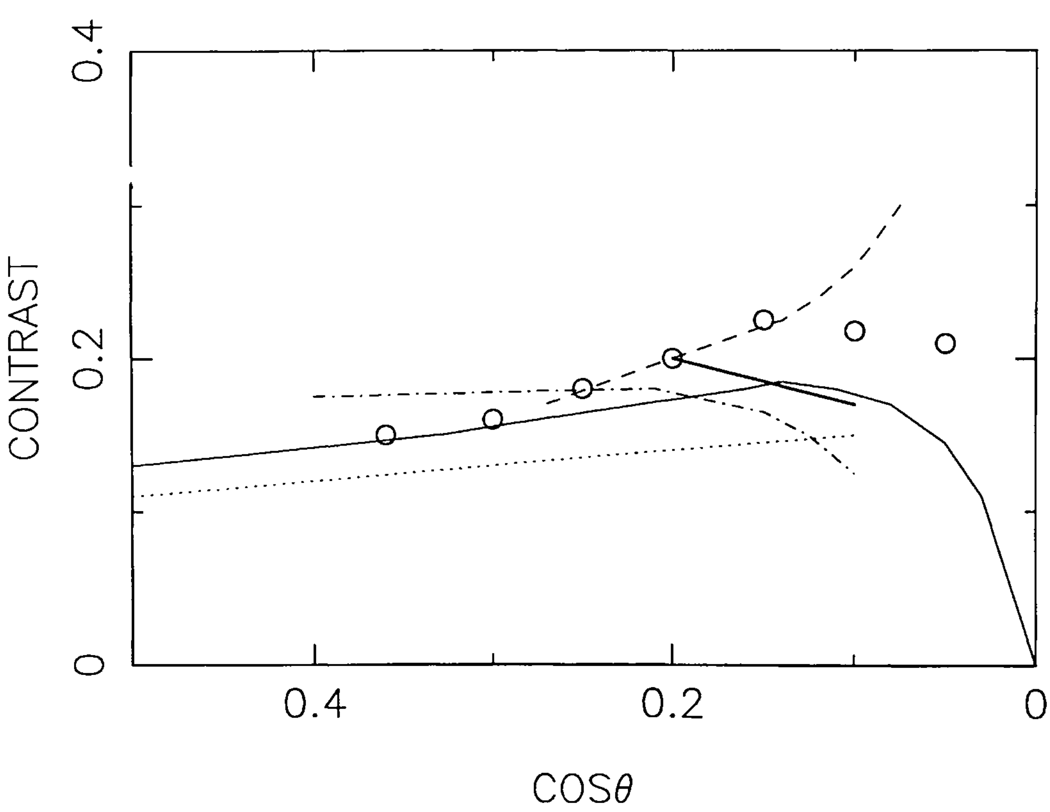

Fig. 1. The facula contrast vs $\cos\theta$. All the measurements are at 5250 Å. Bold solid line is deduced by Libbrecht and Kuhn; lighter solid line is Spruit's theoretical curve assuming a 2000 G magnetic field; the dotted curve is the measurement of Muller; the dot-dashed curve gives the measurement of Hirayama; the dased curve represents the measurement of Chapman and Klabunde, it is normalized to contrast = 0.2 when $\cos\theta = 0.2$; the circles show our 1985's measurements normalized to contrast = 0.2 when $\cos\theta = 0.2$.

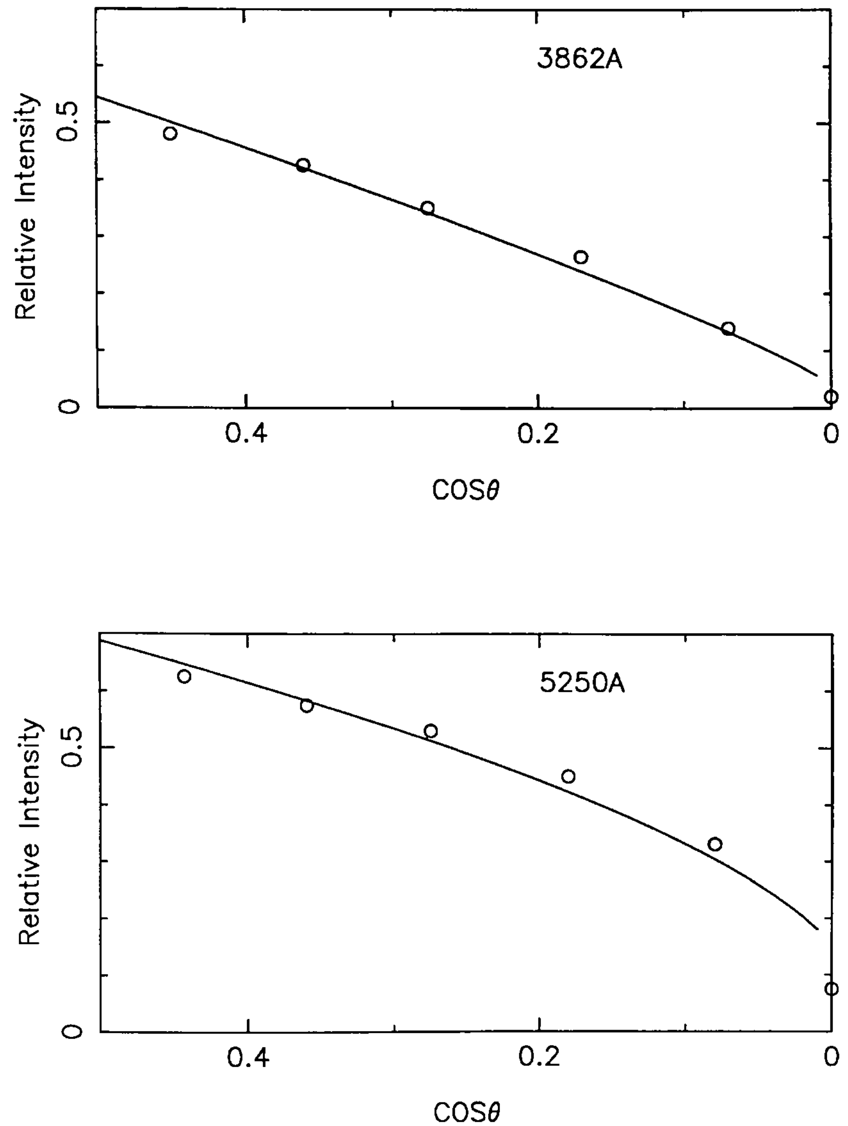

Fig. 2. Limb-darkening curves for 3862 Å and 5250 Å. Solid lines represent theoretical limb-darkening curve by using the parameters from Allen's *Astrophysical Quantities*. The circles show our measurement on May 4, 1983. Because the solar disk center is not covered in our images, we assume the intensity at $\cos\theta = 0.25$ equals to the theoretical value ($\cos\theta = 0.25$ located in the middle of the images) and intensity at other $\cos\theta$ is scaled by it.

The video image processors make possible the direct measurement of intensities within small polygons on the images.

Measurements of step wedges showed our system to be linear within a few percent. For the small contrast of facula to photosphere this is adequate. We placed a small piece of neutral filter with a transmittance around 50–80% in front of the TV camera for gain calibration.

We checked scattered light by measuring the scattered light off the limb. For most images it was below the Newvicon threshold, or less than a few percent. As a check, we obtained limb-darkening curves for 3862 Å and 5250 Å which are presented in Figure 2. They are compared with the limb-darkening curves from the parameters in

Allen's *Astrophysical Quantities*. Our observed curves coincide within 5% with Allen's curve except at $\mu = 0$. That means scattered light is not significant and we made no scattered light correction. A filter wheel was used to shift rapidly from one to another of six wavelengths; neutral filters were used to keep the images within the range of the vidicon. The accuracy and repeatibility of a single measurement with this system is about 1%, but the accuracy for a facular point is somewhat less because of calibration and position registration errors.

The video images in Figure 3 were obtained on May 4, 1983 at 3862 Å and 7140 Å; they are the results after averaging four successive frames. The scale size of the faculae is marked. We see that the plage is an array of small points or strings of points, many of which are about 1 arc sec. Due to the 1″ resolution, they are either some large isolated facular points or some unresolved clusters of small adjacent facular points.

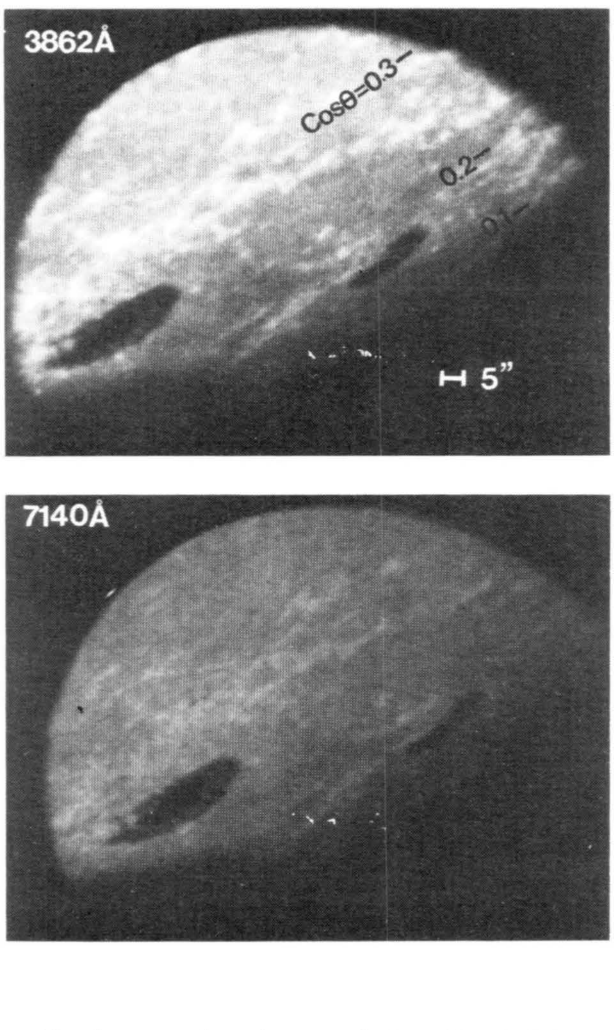

Fig. 3. Photograph of the video image at the solar west limb at 20 : 15 UT on May 4, 1983. Observed at 3862 Å and 7140 Å with the 65 cm vacuum telescope.

3. Data Analysis

Our measurements were obtained in the summer of 1983 and 1985 on about 35 active regins on 25 days. The broad band filters used were 3470, 3862, 4642, 5250, 5700, and 7150 Å for 1983; and 3862, 4642, 5250, 5700 Å, for 1985.

We used two different analysis methods to reduce our data.

(a) For the 1983 data, we randomly selected many faculae, averaged the peak contrast of every facula within bins of $\delta\mu = 0.05$, then plotted the contrast vs μ. We used about 150 images, 10 to 20 points in each.

(b) For 1985 data, in order to get rid of any bias in selecting faculae, we used a more automatic technique. We plotted a profile parallel to the limb of the Sun and found the average intensity and noise (i.e., standard deviation) along this line. Any point on this line with contrast larger than 3 times the noise level, was chosen as a facula. We repeated

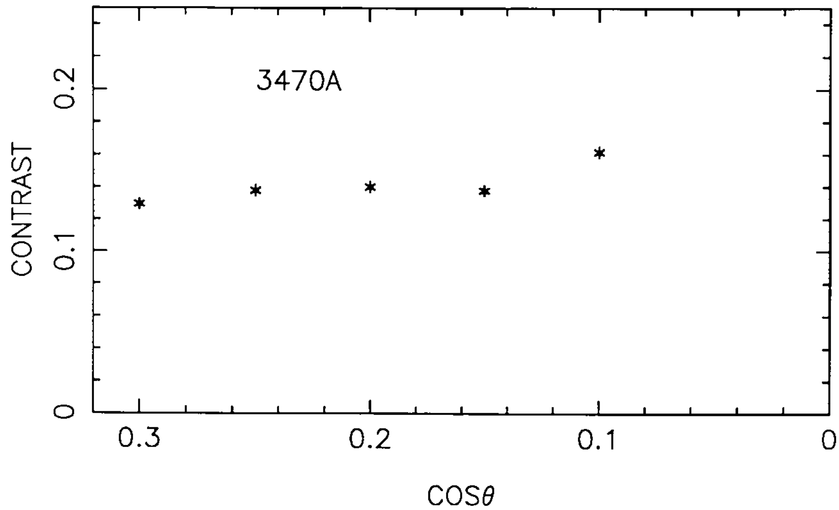

Fig. 4a.

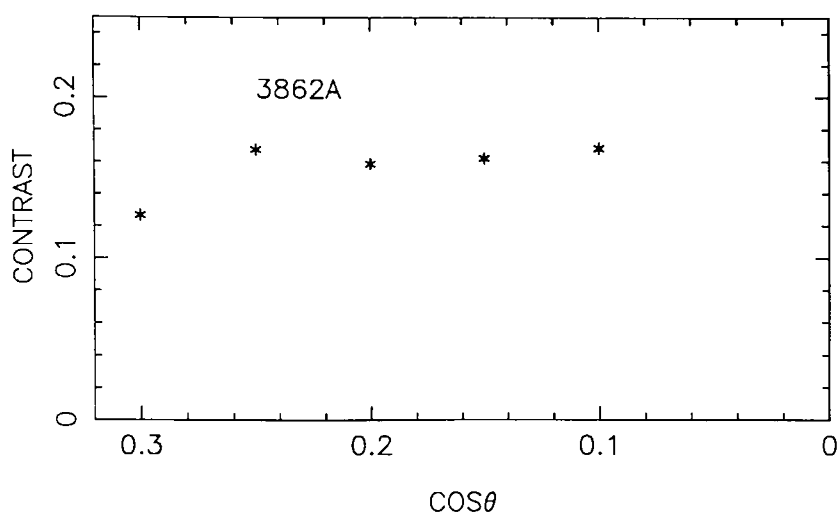

Fig. 4b.

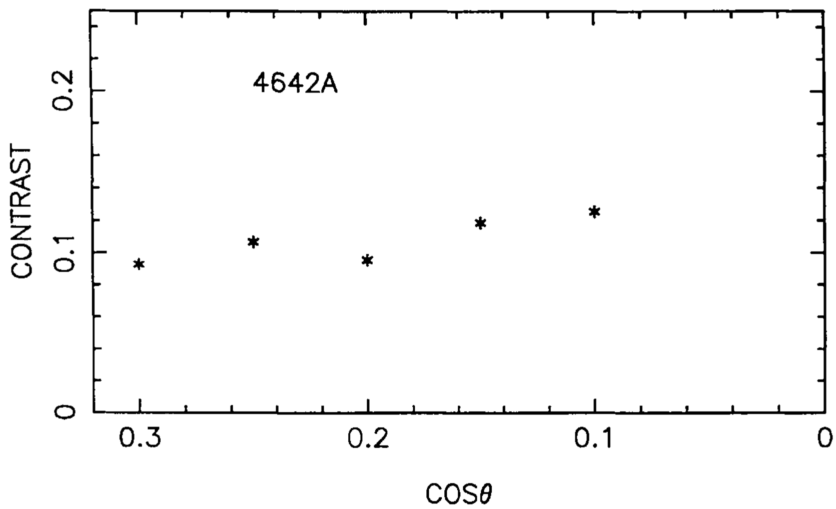

Fig. 4c.

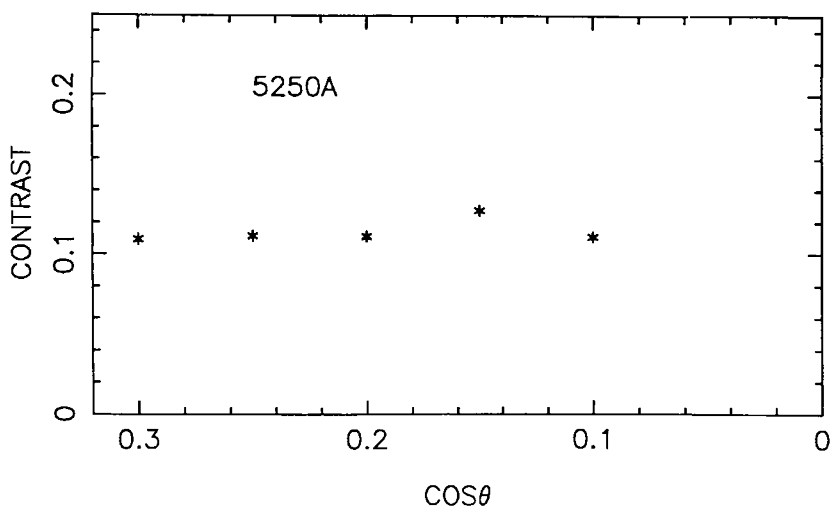

Fig. 4d.

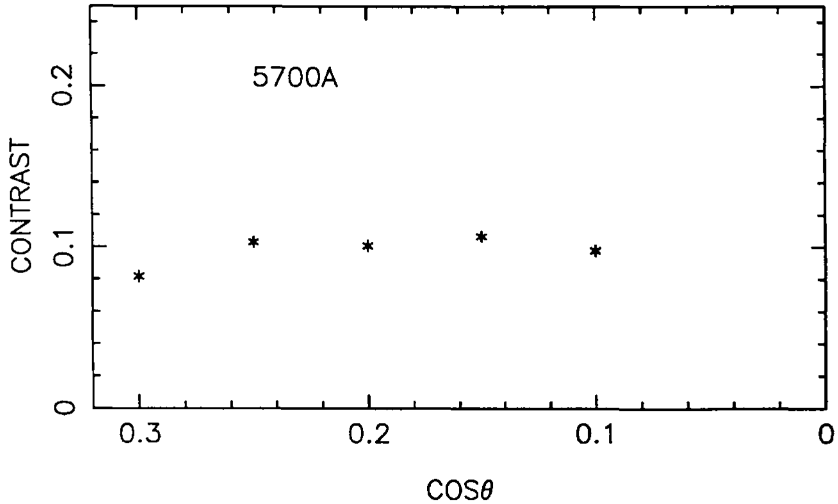

Fig. 4e.

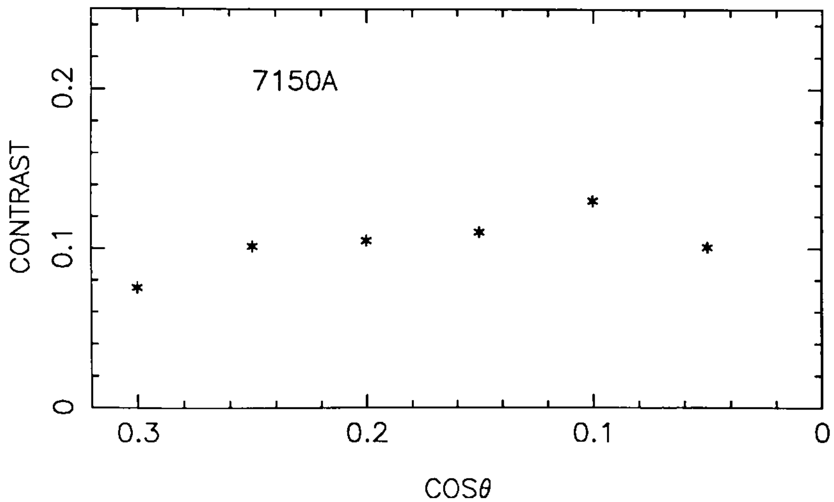

Fig. 4f.

Fig. 4a–f. The averaged facula contrast vs cos θ for 1983.

this procedure for about 130 images in 4 wavelengths. On the average, about 2000 faculae are identified in each image. Finally, we averaged the contrast within bins of $\delta\mu = 0.05$, and then plotted contrast vs μ. There is one problem in this method, i.e., the ratio noise/average intensity increases as μ decreases, which removes the low contrast faculae from our sample. This tends to increase the contrast measured close to the limb. In order to solve this problem, we did the following and we call this procedure *normalization*.

Suppose the facular contrast has the Gaussian distribution:

$$n(I) = a\,e^{-bI^2}\,, \tag{1}$$

a, b are constants and I is the contrast.

The total observed number of faculae within the bin i is

$$N_i = a_i \int_{3S_i}^{\infty} e^{-b_i I^2}\,\mathrm{d}I\,, \tag{2}$$

S_i is the average noise/photosphere signal in given μ bin. The observed average contrast within the bin is

$$\bar{I}_i = \frac{\int_{3S_i}^{\infty} I\,e^{-b_i I^2}\,\mathrm{d}I}{\int_{3S_i}^{\infty} e^{-b_i I^2}\,\mathrm{d}I}\,. \tag{3}$$

Combining Equations (2) and (3), b_i can be found. Finally, we set noise/intensity = S_0 for all the bins, so that the normalized average contrast is

$$(\bar{I}_i)_0 = \frac{\int_{3S_0}^{\infty} I e^{-b_i I^2} \mathrm{d}I}{\int_{3S_0}^{\infty} e^{-b_i I^2} \mathrm{d}I} . \quad (4)$$

The effect of the *normalization* will be discussed in the next section.

4. Results

Our results are given in the figures. Figure 1 shows those for 5250 Å compared to those of other authors. Our results, shown by circles, show neither the sharp dropoff deduced by Libbrecht and Kuhn (1984) nor the sharp increase found by Chapman and Klabunde (1982). Instead the slowly rising contrast reaches a maximum near $\mu = 0.15$.

The contrast vs $\cos\theta$ is plotted in Figure 4 for 1983's observations. The facular contrast increases monotonically towards the limb at shorter wavelengths. At longer wavelength, the contrast increases towards a maximum around $\cos\theta = 0.15$ to 0.10, then decreases limbwards.

In Figure 5, we include the μ and contrast relation for three different situations. (1) Before the normalization; (2) after the normalization, set $S_0 = 0.0$; (3) after the normalization, set S_0 = average noise/intensity over all the bins.

The normalization increased the number of weaker facular points in our sample as $\cos\theta$ approaches the limb. We can see that after the normalization, the qualitative behavior of the contrast is independent of the choice of S_0, i.e., the facular contrast increases monotonically towards the limb at shorter wavelengths. At longer wavelength, the contrast increases towards a maximum around $\cos\theta = 0.15$ to 0.10, then decreases limbwards. It is same as the conclusion we got from 1983's data. However, if the smaller

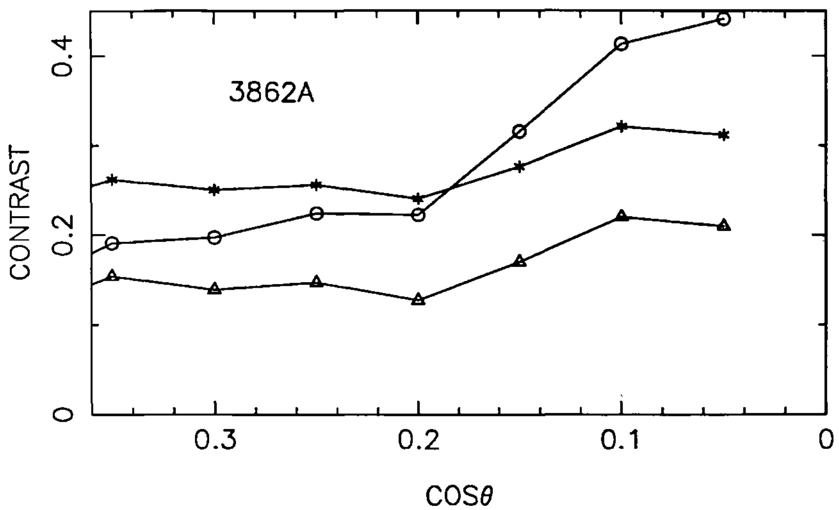

Fig. 5a.

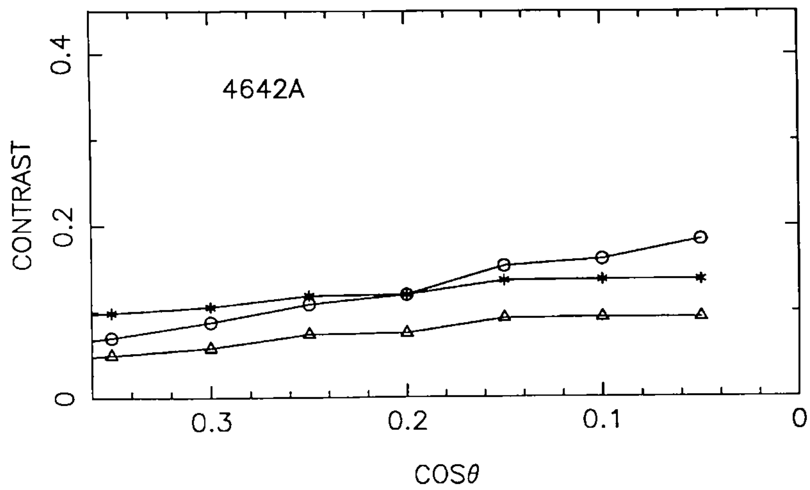

Fig. 5b.

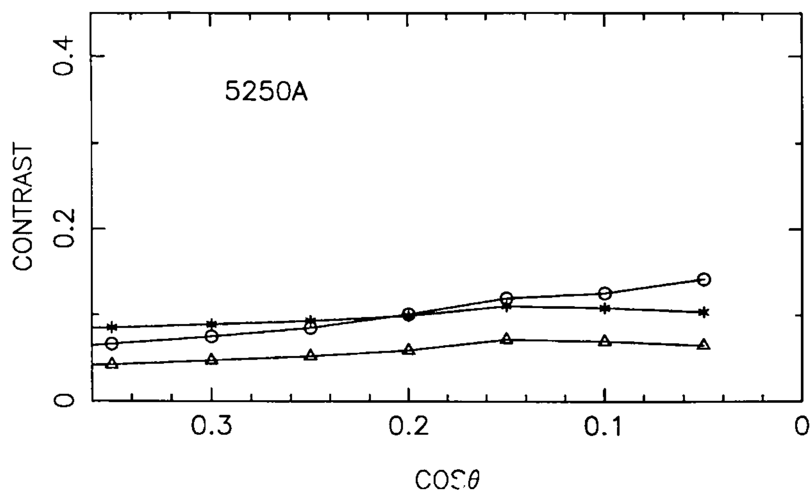

Fig. 5c.

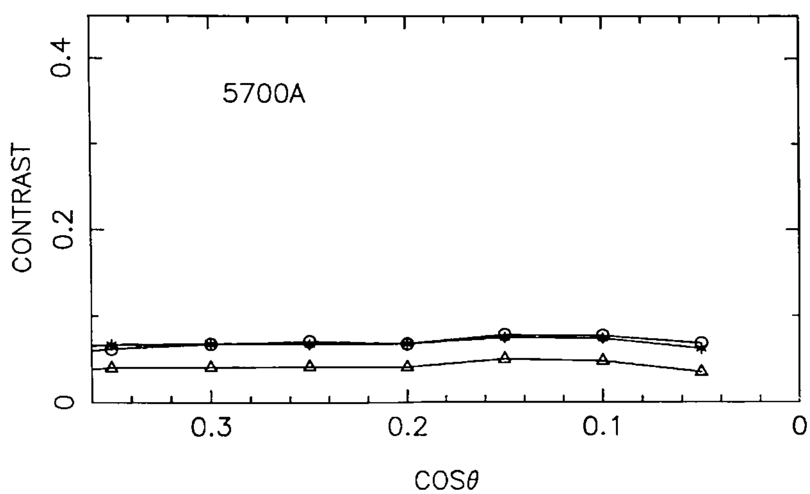

Fig. 5d.

Fig. 5a–d. The averaged facula contrast vs cos θ for 1985. Circles are from the data before normalization; triangles represent the data after normalization by setting $S_0 = 0$; stars represent the data after normalization by setting S_0 = average noise/intensity, 0.068 for 3862 Å, 0.029 for 4642 Å, 0.025 for 5250 Å, 0.017 for 5700 Å.

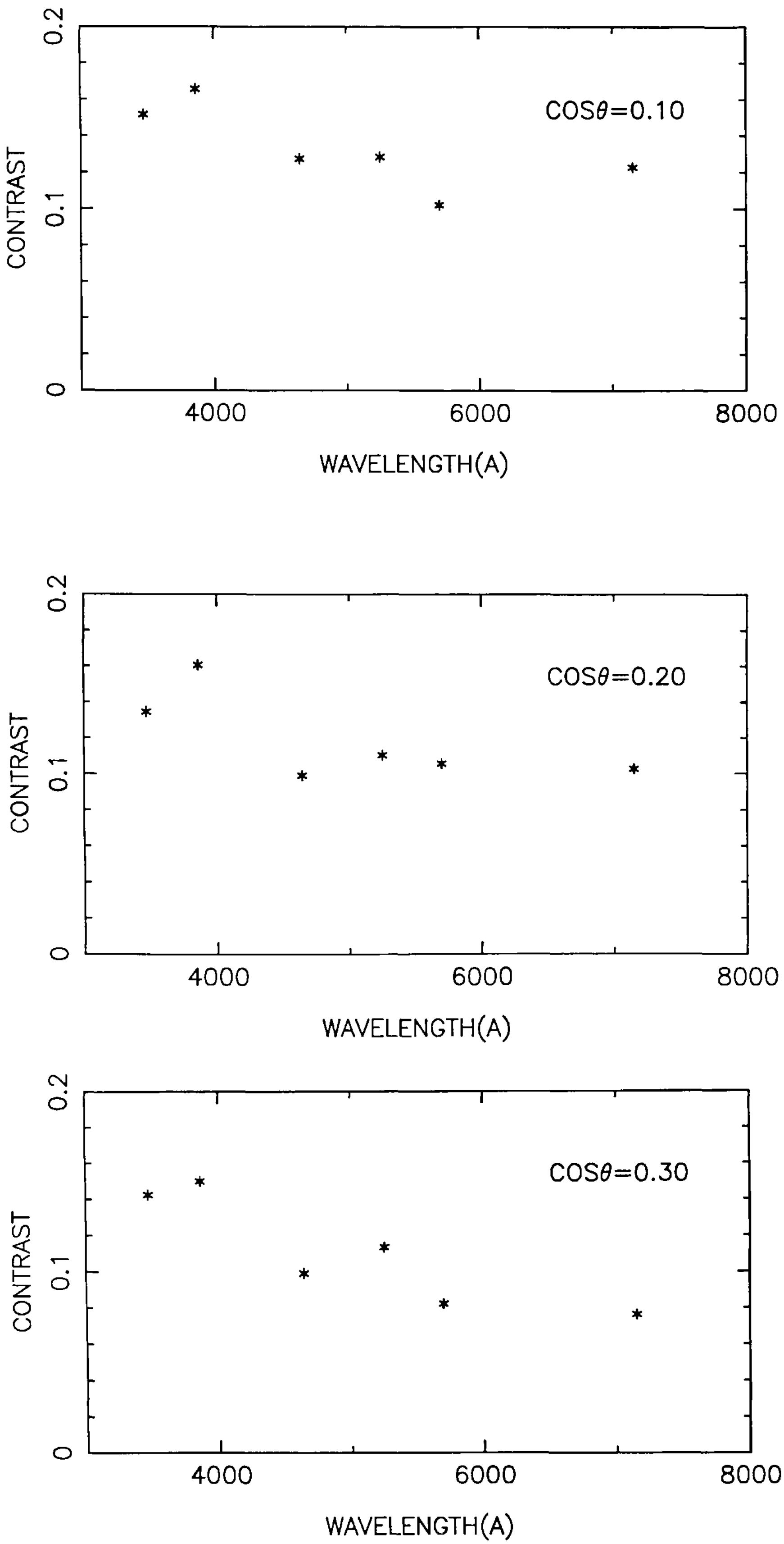

Fig. 6a–c. The averaged contrast of faculae as a function of wavelength. It was averaged for 1983's data.

S_0 is chosen, the facular contrast is reduced systematically. The normalization has a significant effect only at the two bluest wavelengths.

The contrast of the facula as a function of wavelength is plotted in Figure 6. From Figures 4, 5, and 6, it is obvious that the contrast increases as wavelength decreases at the same $\cos\theta$.

The method we used supposed that with a large sample the distribution of facular brightness at any position angle to be independent of time. One might think a better way would be to measure the change in individual faculae in the course of a full day's observations. We did this in three cases, obtaining seven-hour sequences covering $\mu = 0.2$ to $\mu = 0.15$. While we had no difficulty identifying the faculae in these sequences, the curve of the contrast turned out to be the diurnal seeing curve, the contrast peaking at noon when the seeing was best. We also tried to measure the same facula from day to day, but found it impossible to identify more than a few faculae from one day to the next. Those results are, therefore, not significant and not included here.

The statistical analysis appears the most practical way to find how the contrast varies with the heliocentric angle. The average brightness of all the points appears to be a stable and repeatable measurement.

5. Error Analysis

There are several sources of error in this data, as follows:

(a) The limb fit: the points which have maximum pixel value gradient in an image were chosen as the locus of the limb. The error arising from this limb fit could be about 3–5 pixels. So when $\mu > 0.1$, the error for μ is less than 10%.

(b) Calibration: the system is slightly nonlinear (D. Chou and Z. Shi, personal communication). If the contrast is less than 30%, the error from nonlinearity is less than 5%. So the nonlinearity is more important for large sunspots than for faculae.

(c) Selection effect for 1983 observation, i.e., the tendency to miss weak faculae near the extreme limb, increases the average contrast of those points measured near the extreme limb.

(d) Because many of the points are unresolved, the true contrast of the facular points must be greater than that measured. But since brightness is averaged over pixels, the total brightness of the facular point is unaffected.

The difficulty involved in obtaining accurate measures of facular intensity is obvious. The faculae may change in intensity from day to day. The seeing may change. Because of the variations in faculae, we felt that a large sample (in this case, about 20 000 faculae) would give a reasonable representation of the run of facular brightness. The relatively low scatter of the results suggests that it does.

6. Discussion

Our statistical measurements of a large number of faculae show that they behave as one would expect from cursory examination of a high-resolution photo. At a given $\cos\theta$, the contrast increases with wavelength. For shorter wavelengths, the facular contrast increases monotonically limbwards; for longer wavelengths the facular contrast shows less change with position and at 7150 Å peaks around $\mu = 0.1$ to 0.15, and then decreases slightly towards the limb. We find no great deviation near the extreme limb; the facular contrast neither dives nor skyrockets, as has been suggested by various indirect measurements.

Our results do not show the high contrast near the extreme limb, as obtained by Chapman and Klabunde, since we observed all the faculae directly, there is no way in which objects of such high contrast could have been missed.

Another important result lies in the fact that we make an integral brightness measurement in several wavelengths. It has been suggested by Stenflo (1976) and others that the magnetic elements involved in faculae are extremely small, rather strong (1000 G or more) and unresolved by magnetograms. If the bright faculae correspond to these magnetic elements and also fill only a small fraction of our resolution element, high temperatures and large blue enhancements would be required. We find the color curve we observed is fitted by a black-body curve at 5900 deg. This gives a brightness increase of about 15% at 4000 Å and fits the other data shown. If the bright elements were very small they would have to be much hotter and bluer than observed.

While some of the added contrast in the blue is explained by Planck curve effects, the enhanced contrast may be the result of enhanced line absorption; spectroheliograms in blue windows near the CN band head by Sheeley (unpublished) show no faculae at disk center, while those in the band head are well marked. Similarly pictures in the UV (Foing and Bonnet, 1984) show strong facular contrast at 1600 Å.

The peak in contrast at $\mu = 0.1$ in the near IR may be due to surface roughness. Roughness of the order 20 km in the granule top would provide such a flattening if the facula is slightly depressed.

Acknowledgements

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