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Research Note

Three colour photometry of solar limb faculae

C.R. de Boer[1], **G. Stellmacher**[2], **and E. Wiehr**[3]

[1] Max-Planck-Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany
[2] Institut d'Astrophysique CNRS, 98*bis* Bvd. d'Arago, F-75014 Paris, France
[3] Universitäts-Sternwarte, Geismarlandstr.11, D-37083 Göttingen, Germany

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Abstract. The contrasts of limb faculae at various heliocentric angles are observed in three continuum windows largely free of absorption lines. Observations with interference filters show a contrast decrease with wavelength which is not found when using an 'UBF' to select the shortest continuum window. Limb faculae in speckle-reconstructed images yield contrasts being typically 1.2 times higher than those deduced from the 'best images' of the corresponding bursts.

The fit of the wavelength dependence ('colour index') to a black-body law is significantly better for the contrasts deduced from the reconstructed images than for the contrasts from the best images. The uncorrected contrasts yield a mean facular temperature excess of 200-300 K; those from the reconstructed images yield about 470 K. The center-to-limb variation is found to be much smaller than the fluctuations between individual faculae.

Key words: Sun: faculae, plages

1. Introduction

Faculae occur as photospheric brightenings near the solar limb and are composed of sub-arcsec elements. At a spatial resolution of 0.23 arcsec Auffret and Muller (1991) observe mean continuum contrasts increasing from $\phi^{fac} = I^{fac}/I^{phot} = 1.08$ at disc center to 1.26 at $\cos\vartheta = 0.3$, then decreasing to 1.24 at $\cos\vartheta = 0.175$. Brightest facular grains reach $\phi^{fac} = 1.4$ at $\cos\vartheta = 0.3$.

White light limb faculae are associated with chromospheric Ca^{+}K plages. Near disk center, such plages manifest themselves in spatially high resolved continuum pictures as the 'solar filigree' (Dunn and Zirker 1973) which is co-spatial with small magnetic regions (Stenflo 1973, Wiehr 1978). Photometry of exceptionally high resolved continuum photographs by Koutchmy (1977) yields a corrected filigree contrast at disc center up to $\phi^{fil} = 1.8$ for $\lambda = 6000$ Å. The corresponding filigree size is of the order of the point-spread-function of the Sacramento-Peak Vacuum-Tower-Telescope (0.136 arcsec). This result fully agrees with CCD observations by von der Lühe (1987) and with Zhang & Engvold (1993). Also in deepest layers at the opacity minimum near $\lambda = 1.6\mu$, Darvann & Koutchmy (1994) still obtain positive contrasts for magnetic elements at disc center.

Spatial averaging of an adapted filigree model atmosphere (e.g. Koutchmy & Stellmacher 1978) over a realistic resolution area, representing the actual filling (Stellmacher & Wiehr 1979, 1991b), is able to reproduce observed spectroscopic faculae data such as line-core weakenings ('gaps'), line-wing enhancements ('moustache-effect'), and corresponding magnetic line broadenings. However, these models do not reproduce the observed center-to-limb variation (CLV) of limb faculae, which is then supposed (cf. Stellmacher & Wiehr 1974) to originate from the particular fluxtube geometry (see also Rees 1974).

Various authors have tried to model such geometric effects. Spruit (1976) shows that models matching the observed CLV of faculae yield negative contrast (i.e. dark faculae) at disc center. Knölker et al. (1988) obtain a slightly better fit assuming several fluxtubes along the line-of-sight, but still significant discrepancies with the observed CLV. An interesting alternative to these fluxtube models characterized by a Wilson-depession analogous to spots and pores was proposed by Schatten et al.(1986), who assume a dynamical model where deeper layers become visible by their elevation above the surrounding photosphere. This 'hillock model' reproduces observed contrast increase but not a decrease at the very limb. A geometrical elevation of the iso-tau levels in limb faculae has been found by Stellmacher & Wiehr (1991a).

New observations of the wavelength dependence of facular continuum contrasts may help to refine the depth-variation of the temperature at the layers where the different continua are formed. Such observations at moderate resolution by Wang and Zirin (1987) and by Lawrence (1988) near $\mu = 0.3$ show that the contrast decreases with increasing wavelenth. This behaviour

Send offprint requests to: E. Wiehr

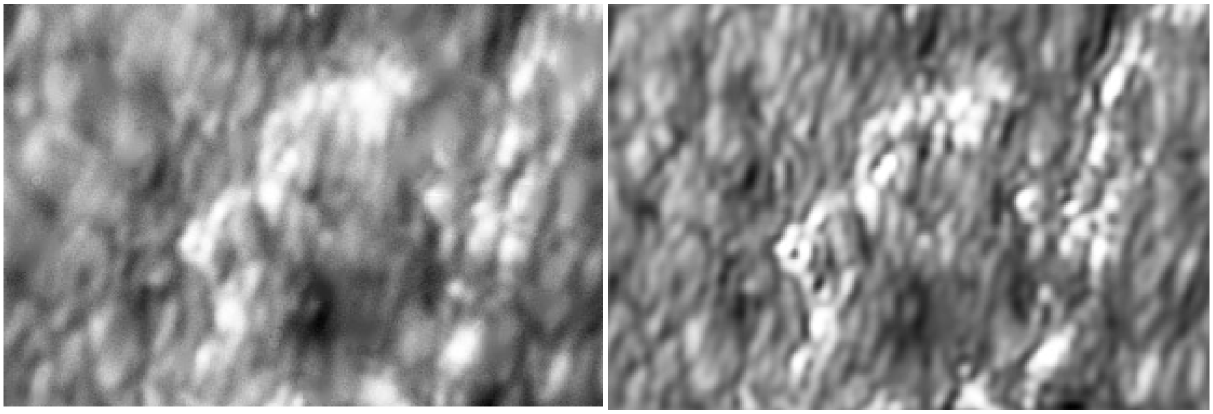

Fig. 1. White light faculae near the solar limb observed on April 4, 1996, with the Vacuum Gregory Telescope at 6587 Å; left panel: best image of the burst; right panel: Speckle reconstructed image; spatial area $10'' \times 15.5''$

continues up to λ = 2.2 and 3.75 μ where Kotov & Koutchmy (1994) observe limb facular contrasts up to ϕ^{fac} = 1.03.

In contrast, Keller & Koutchmy (1991) find for the continuum contrasts of filigree at disc center a slight increase from 4451 Å to 6019 Å.

2. Observations

We observed various faculae at different limb distances in spectral ranges largely free of absorption lines (quasi-continuum windows) using the two German vacuum telescopes at Tenerife, the VTT and the Gregory, respectively. On May 14, 1994, limb faculae were observed simultaneously in the continuum windows at 8635 and 5827 Å, selected by 20 Å wide interference filters, and at 5190 Å, selected by an 'universal birefringent filter' (UBF) with $<$ 1.5 Å half width using the observational set-up at the VTT described by Kentischer (1995). On June 26, 1996, single images were taken directly in the Coudé focus of the Gregory telescope using interference filters for the windows at 4505, 6587, and 8635 Å sequentially at very short time intervals (i.e. 'quasi-simultaneously') at interation times of 5 ms.

In order to estimate the influence of seeing on the observed contrasts of the facula elements, speckle reconstructed images were deduced for the first time from observations at the evacuated Gregory telescope on April, 4, 1996 (cf. Fig. 1). For this purpose, a new instrumental set-up was constructed: the Coudé image was enlarged by a factor of 1.5, replacing spectrograph slit and pre-disperser by an f=10 cm achromat. This adapts the image scale to the pixel size of the 1024 $\times$ 1024 CCD without further optical elements. For a fast repetition rate, only a suitable sub-area of the CCD was read out integrating over 5 ms.

3. Results

For well-defined white light facular points, the peak intensities were determined in units of the neighbouring mean photosphere. The center-to-limb variation of the facular contrasts observed at the VTT in the λ = 5827 Å window is shown in Fig. 2 in

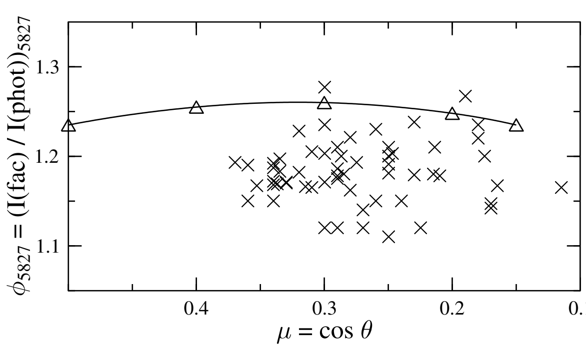

Fig. 2. CLV of facular contrasts observed in the continuum window at 5827 Å in comparison with mean data (triangles) at 5750 Å by Auffret & Muller (1991)

comparison with the data at 5750 Å by Auffret & Muller (1991; Fig. 5). Their slightly higher mean contrasts can be attributed to the influence of line-core brightenings from the larger number of Fraunhofer lines in their wavelength range of 60 Å width and by slightly higher spatial resolution.

The wavelength dependence of the contrasts is given in Fig. 3 for mean values at $0.1 < \mu < 0.4$ since the scatter between individual faclulae is much higher than the center-to-limb variation, CLV.. The data from the Gregory telescope, which were obtained exclusively with interference filters, show a continuous decrease with wavelength, as do the broadband measurements by Wang & Zirin (1987) and the narrowband observations by Lawrence (1988).

In contrast, the observations at the VTT, where the UBF was used for the λ = 5190 Å window, yield almost equal contrasts at both short wavelengths (5190 and 5827 Å) and a decrease towards the infrared (Fig. 3). This trend is similar to that found by Keller & Koutchmy (1991) for filigree at disc center. Our small contrasts at λ = 5190Å can not arise from a miscentering of the UBF, since the known line-core brightening ('gap'; cf. Stellmacher & Wiehr 1971) would yield still higher contrasts. We thus reasonably assume that the missing contrast increase

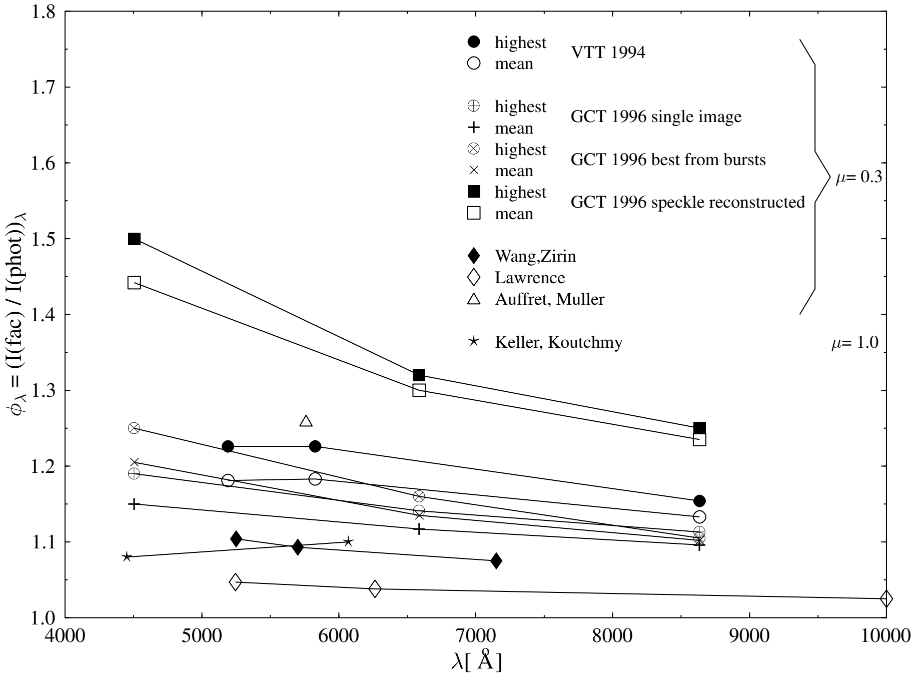

Fig. 3. Wavelength dependence of facula contrasts observed at $0.1 < \mu < 0.4$; open symbols: average of all ; full symbols: mean values of 25% of the brightest grains. Comparison with results by Wang & Zirin (1987), Lawrence (1988), Auffret & Muller (1991), and by Keller & Koutchmy (1991)

towards the blue in the VTT data arises from the UBF – possibly due to scattered light within the filter. This may also be the reason for the decrease of filigree contrast towards the blue observed by Koutchmy & Keller (1991).

The images for the speckle reconstruction were deduced from the bursts of 99 images observed on April 4, 1996 with the Gregory telescope. In a first step, the 'best image' from each burst has been selected. The facular contrasts from these images significantly exceed those deduced from the single exposures taken on June 26 with the Gregrory telescope (cf. Fig. 3). Since the integration time is 5 ms equally for both data sets, this difference may be explained by the better chance to find an exceptionally good image in the bursts or by better seeing on April 4, 1996.

Finally, the images of each burst were processed in the way described by de Boer (1996). An example of a reconstructed image is shown in Fig. 1 in comparison with the corresponding 'best image' of the burst. The brightest facula-grains in the reconstructed images give mean contrasts of 1.5, 1.32, 1.25 in the three continua. These contrasts exceed those from the corresponding best images by factors of about 1.2.

4. Discussion

Assuming that the continuous radiation of faculae corresponds to that of a black body one would expect that the relative contrasts ('color index') behave according to Wien's approximation:

$$\frac{ln(I^f/I^{phot})_{red}}{ln(I^f/I^{phot})_{blue}} = \lambda_{blue}/\lambda_{red}$$

This relation fits the contrasts from the speckle reconstructed images almost perfectly, but less well the contrasts in the 'frame selected best images'. Evidently, time variation of seeing between the quasi-simultaneous observations in the three wavelengths is largely removed by the speckle techniques. This indicates that speckle reconstructed intensities may well be regarded as a quantitative measure in spite of the difficulties to reconstruct the sharp lunar limb (de Boer 1995).

Wien's law fits the observed mean contrasts better than the corresponding highest contrasts. This may be due to the averaging procedure which minimizes different seeing between the quasi-simultaneous observations. The temperature excess deduced from the highest facular contrasts in the single images and from the selected best images of the bursts amounts to 200 - 300 K over that of the neighbouring photosphere. The contrasts of the brightest faculae in the speckle reconstructed images even yield a temperature excess of 470 K.

Since white faculae presumably consist of clusters of small fluxtubes, it is tempting to adapt an LTE stratification to the wavelength dependence of the continuum contrasts from speckle reconstructed images. The strong contrast increase towards short wavelengths can not be reproduced by an 'upscaled' model of the photosphere (e.g. Holweger 1967). Instead, the difference between the photospheric and the facular temperature stratification must strongly increase towards deep layers. Faculae would thus exhibit a steeper temperature gradient than the undisturbed photosphere. A steeper-than-photospheric gradient deduced for sunspot umbrae was interpreted by Stellmacher & Wiehr (1975) as an indication for reduced convective energy transport. For the much smaller facula elements, however, such one-dimensional calculations can only be considered as a very rough approximation. Two-dimensional calculations are required to explore the geometry and to investigate the amount of convective and radiative energy transport in faculae. They should consider that the almost perfect fit of the colour index to Wien's law indicates that faculae radiate as a black body even near the solar limb.

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