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# The center to limb variation of photospheric facular contrast

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**Abstract.** The center-to-limb variation (CLV) in the contrast of photospheric faculae is of importance both to the physics of magnetic flux tubes and to the understanding of variations in the total solar irradiance. Measurements of the CLV of faculae are difficult and have resulted in widely disparate results. We tried an accurate measurement of the photospheric facular contrast by using both PSPT and SOHO/MDI observations, with the aim of understanding the reasons of the different results of facular photospheric contrast measurements already presented in literature.

**Key words.** Solar Atmosphere – Solar variability

## 1. Introduction

Solar irradiance variations on scales of days up to the solar activity cycle length are closely related to the evolution of the solar surface magnetic field, because the emergence and the evolution of active regions on the solar surface is reflected in the irradiance records. Sunspots and active regions faculae are considered to be the dominant contributors to solar irradiance changes on time scales of days to weeks while it is expected that small scale magnetic elements that compose the network contribute to the observed irradiance increase during activity maximum. Uncertainties in the contrast of faculae and the network are yet one of the major sources of errors in the modeling of solar irradiance variations. Incidentally, because of these errors it is still debated whether other mechanisms of non-magnetic origin like temporal changes in latitude dependent surface temperature of the Sun, may contribute significantly to the measured irradiance variations.

Measurements of the CLV of faculae are difficult and have resulted in widely disparate results. Some measurements have been restricted to near the limb, while others have been near disk center. In some cases, attempts have been made to study facular contrast across the solar disk at moderate resolution or at fairly low spatial resolution. The result of these investigations has not given a clear picture of the CLV of the faculae. Part of the problem is the randomness in the appearance of facular patches

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which causes changes in the filling factor, i.e. the density of flux tubes within a facular patch. The different spatial resolution between the different investigations is also of importance. Another problem is the very low contrast of faculae as one approaches the center of the solar disk making identification very difficult. Facular contrast has been reported with negative, zero or positive values near disk center depending on the magnetic flux of the flux tubes. The change in aspect as one views faculae at the different positions leads to difficulties in interpretation of contrast observations. As a result of these difficulties, there are a variety of physical models of facular flux tubes and collections of flux tubes. For a review of the experimental results see Ahern and Chapman (2000), while for a review of physical models of facular flux tubes see Steiner (1994).

Since uncertainties in the CLV of faculae at different wavelengths makes modeling of irradiance variations due to faculae a difficult task (Solanki and Unruh 1998, Harvey and White 1999, Unruh Solanki and Fligge 1999), we tried an accurate measurement of the facular contrast with the aim of understanding the reasons of the different results already presented in literature.

## 2. Observations and data analysis

In order to determine the CLV of both the facular and network contrast and to study the dependence of the CLVs on the solar activity, feature geometry and feature identification criteria, we analyzed near simultaneous full-disk images obtained at three pass-band and the line-of-sight magnetic field measurements provided respectively by the PSPT network and MDI on board of SOHO. In particular, we analyzed 591 1kx1k images extracted from the archive of the daily observations carried out with the PSPT a the Rome Observatory (Ermolli et al. 1997, Centrone et al. 2001) during the latest four Summer seasons (from 1999 up to 2002) on 197 observing days. The images analyzed correspond to the observations acquired each day in sequence in less than two minutes, at the three band-pass centered at CaIIK (393.3±0.25nm), Blue continuum (409.2±0.25nm) and Red continuum (607.1±0.5nm). The sample of images analyzed shows active regions spread over almost all $\mu$ values. They are also separated in time so duplications are avoided. All the images analyzed have been calibrated for the instrumental effects (i.e. dark and flat-field corrections) and corrected for the center-to-limb variation of the quiet Sun. The latter correction was done computing the average radial profile of the intensity over the solar disk, excluding active regions from this computation through an intensity threshold criterion. Together to the PSPT images, we analyzed also magnetograms obtained by MDI on board of SOHO during Summer 2002, acquired near simultaneously to the PSPT images. All the images were first resized in order to get the same solar disk size, then have been rotated to co-align them and to compare images pixel by pixel. Care has been taken to use images as close in time each other as possible. In all cases but one, the images analyzed were recorded within 10 minutes of each other. The facular regions were identified on the sample of images analyzed by applying three different automated methods, based on intensity threshold of contiguous bright regions to pairs of images, like described in detail in the following.

## 3. The identification of facular regions

We use both the structural and the photometric properties of facular regions to perform their identification on the solar disk. The first identification method applied is very often presented in literature, i.e. use CaII K images to identify facular regions on corresponding continuum images with results largely dependent on the intensity threshold used. In fact, first we identify isolated long-lived bright regions on the disk (step 1), finding pixel whose contrast is greater a given value on a spatially filtered binary image, that is obtained selecting all the bright pixel in the CaII K image. We then applied a straightforward intensity threshold on the pre-identified connected bright regions, to point out non redundant chromospheric regions to be used to pick up the corresponding photospheric facular regions. Note that photospheric faculae are obtained excluding from the contrast computation all the pixels corresponding to photospheric spots and pores, like selected in the continuum images analyzed, by excluding all connected pixels with negative contrast. The second method applied, not so often presented in literature with respect to the previous, uses pairs of corresponding magnetic and intensity images to select facular region by threshold of magnetic flux values on the solar disk. In particular, we applied a threshold criterion of magnetic flux values on the long-lived bright regions on the disk isolated at step 1. At last, we tried the identification of photospheric facular regions through straight photometric properties of the photospheric facular regions. In particular, we computed a color image by the difference of the two continuum images (Blue minus Red), in order to isolate the magnetic regions by differential photometry, like proposed by Foukal and Duvall (1985). The difference signal of continuum images is sensitive to changes in the temperature gradient near $\tau_{5000} = 1$ between quiet photosphere and faculae. We identified the photospheric facular regions by thresholding the color image on the preselected bright long lived regions isolated at step 1.

Using the three identification methods we make three masks of facular regions for each day, that are used to compute the facular contrast dependence over the disk.

The contrast of the facular regions identified is defined, for each heliocentric angle, from the ratio between the intensity of the facular pixels belonging to the angle, for heliocentric annuli of equal area, and the value of the quiet sun intensity.

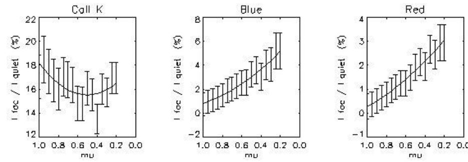


**Fig. 1.** Center to limb variation of the facular contrast: first identification method (CaIIK intensity).

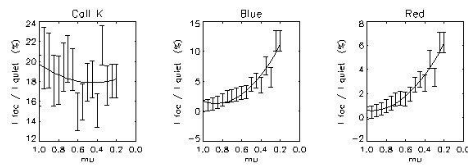


**Fig. 2.** Center to limb variation of the facular contrast: second identification method (magnetic flux).

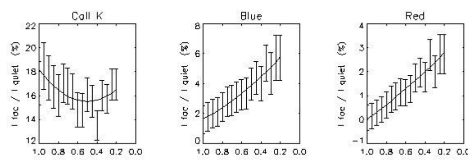


**Fig. 3.** Center to limb variation of the facular contrast: third identification method (differential photometry).

## 4. Results

We have analyzed the facular contrast dependence on the disk position, on the activity level and on the automated method used to identify the facular regions over the solar disk. The simultaneous use of three different methods to identify facular regions allows us to explain some of the differences among the results of the measurements of the CLV of the facular contrast already presented in literature. Figures 1, 2, 3 show the facular contrast dependence on the disk position by the three identification methods. The contrast of the facular regions identified at the disk center in the images acquired with the two PSPT continuum pass-bands are positives, in accordance with the results previously ob-

tained by authors that do not used identifications methods based on magnetic field flux thresholds or dynamic intensity thresholds. A negative value for the contrast of facular regions at the disk center is found without excluding from the analyzed regions small spots or pores.
The CLV of the facular regions at the disk edge does not change with the magnetic activity. In particular, It is still increasing up to $\mu = 0.2$. The contrast value close to the disk edge depends sensitively from the identification method used to select facular regions. In particular, the use of a dynamical threshold criterion, changing with the position on the solar disk (i.e. a constant threshold on the magnetic flux value or an intensity threshold changing with $\mu$) produces an increase of the mean contrast computed, up to a factor two.

## 5. Discussion

Comparison with other contrast observations is not easy because of the differences in selected wavelength, spatial resolution, range of studied heliocentric angles, magnetic filling factor and size of the analyzed features. All these factors contribute to the scatter between the existing contrast measurements. Anyway, by the present work, we can assert the contrast dependence over the disk depends sensibly from the identification method used to develop one's own study.

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