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Centre-to-limb variation of photospheric facular radiance and image resolution

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Abstract

We study the effect of the angular resolution on the determination of the angular properties of the facular radiance. We analyze photospheric intensity in the continuum, around the Ni 676.8 nm line, and longitudinal magnetic field along the line of sight, measured by the MDI instrument aboard SOHO with two spatial resolutions, 4″ and 1.2″ (2″ and 0.6″ pixels, respectively). The effect of the limited photometric sensitivity of the instrument and the limited information on the angular structure of the magnetic field tubes are considered. Our study of the high-resolution data shows that intensity contrast of magnetic features between 80 and 600 Gauss increases from centre to limb up to a maximum that occurs at higher heliocentric angles (θ) when obtained with higher resolution data than for lower resolution data. There is a suggestion that at heliocentric angles below about 75° there is only a monotonic increase in the contrast as one goes from $\cos(\theta) = 1$ to $\cos(\theta) = 0.2$.

Keywords: Solar irradiance; Solar photosphere magnetism; Solar atmosphere; Network; Faculae

1. Introduction

Magnetic field tubes emerging in the photosphere are the dominant contributors to the solar irradiance variations with time (i.e., Solanki and Fligge, 2002). The knowledge of the radiative properties of the photospheric magnetic field elements is, therefore, of interest for understanding solar irradiance. A traditional way of quantifying the angular distribution of their radiative properties is the measurement of the contrast between their radiance and that from the surrounding photosphere as a function of their heliocentric angle location, known as centre-to-limb-variation (CLV). There are many published measurements of the CLV of photospheric small magnetic elements, mostly on faculae and magnetic network, made under different conditions and giving different results (Lawrence and Chapman, 1988; Walton et al., 1998; Topka et al., 1997; Ortiz et al., 2002; Ermolli et al., 2003; Centrone and Ermolli, 2003; Foukal et al., 2004). One of the parameters that may be different from one observation to another is the angular resolution.

The change in the aspect angle with which we measure the magnetic field, and the change in luminous intensity, due to the slanted view of the solar atmosphere, make any centre-to-limb measurement difficult to quantify unambiguously. There is also variability in the background noise.

The Stanford University and Lockheed Martin Solar and Astrophysics Laboratory Michelson Doppler Imager, MDI, (Scherrer et al., 1995) instrument on SOHO produces a continuous set of full solar disk

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magnetograms and intensity images at the Ni I 676.8 nm line, now more than 9 years long. The MDI data are particularly useful because of their regularity and uniformity. The full disk images have a 4″ resolution. An optical zoom facility provides a magnification by a factor of 3.2 (1.2″ resolution) over an $11' \times 11'$ field of view, fixed at the centre of the solar disk. On 20 August 2002 SOHO was exceptionally off-pointed for a few periods

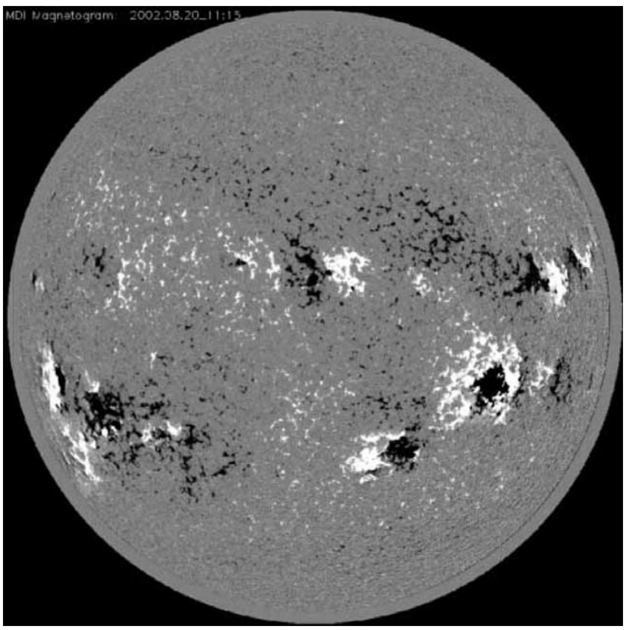

Fig. 1. Full solar disk MDI magnetogram on 20 August 2002.

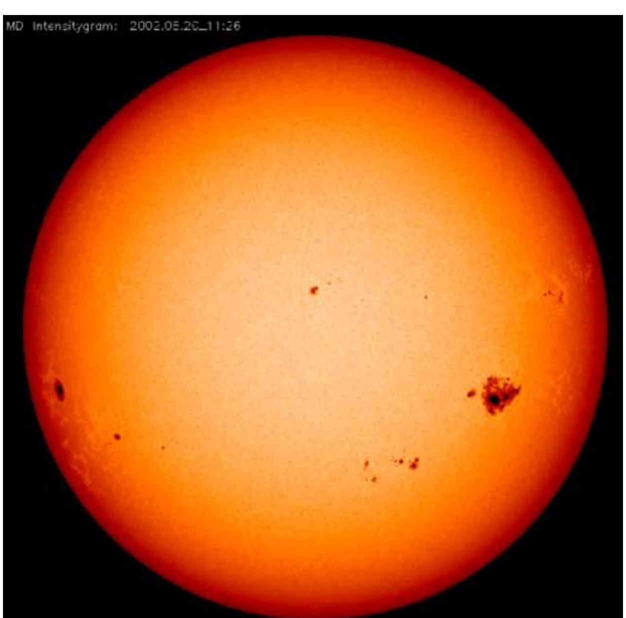

Fig. 2. Full solar disk MDI continuum intensity image on 20 August 2002.

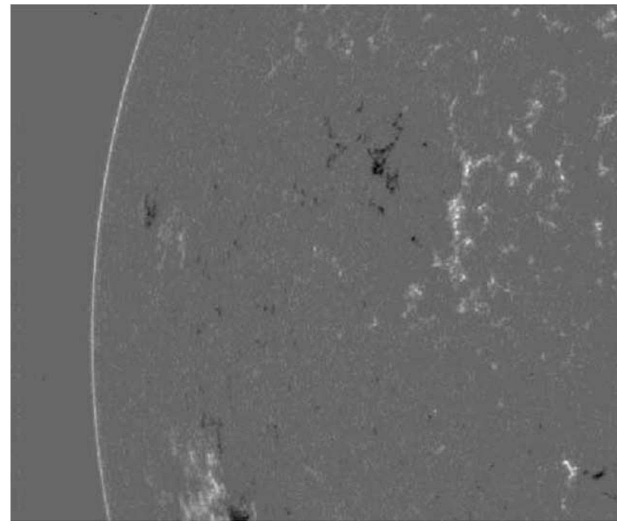

Fig. 3. Zoomed MDI magnetogram image of the Sun at the east limb on 20 August 2002.

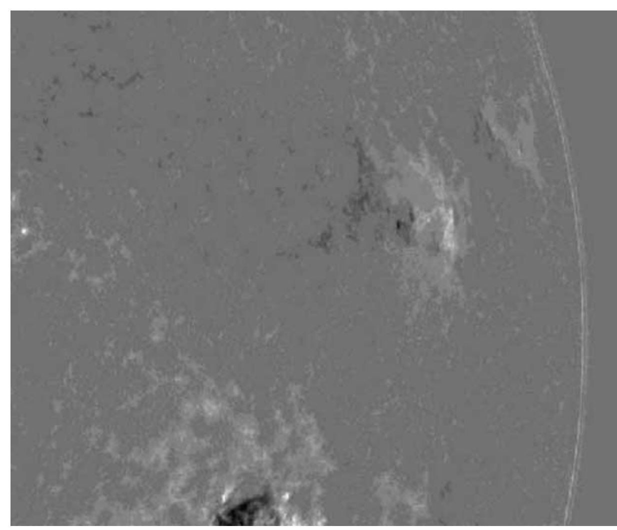

Fig. 4. Zoomed MDI magnetogram image of the Sun at the west limb on 20 August 2002.

of 20 min to allow the observation of high-resolution magnetograms and intensity images near the limb (Figs. 1–4).

We have analysed the off-pointed high-resolution images to complement our previous study of centre-to-limb variation of facular irradiance in full disk MDI images of magnetograms and intensity continuum (Ortiz et al., 2002). In the following sections, we describe comparisons between high-resolution measurements and full disk measurements obtained on the same day. The MDI was not designed for photometry, but for Doppler studies, and therefore the intensity images are a by-product with limited performance. Yet, the long duration and stability of the instrument operation make of it an outstanding source of solar radiance data.

2. Data analysis

We analyse the high-resolution magnetograms and images obtained when SOHO was off-pointed on 20 August 2002 and compare them with two full disk magnetograms and continuum intensity images obtained on the same day. All analysis reported was performed with one minute data: two full disk images and 10 high-resolution images at each off-pointed location (East, West and North) have been used. The full disk intensity continuum images are derived from the five images used to calculate the Dopplergrams and the magnetograms, while the high-resolution images are direct filtergrams in the intensity continuum. Although there is a significant difference in the limb darkening distribution between the calculated intensity continuum and the filtergram, the contrast values should be comparable as they are obtained comparing the intensity with its surrounding local quiet sun. Following a technique derived from Harvey (1994), we have divided the images into active and quiet sun regions, though the separation level is somewhat arbitrary.

We compare the CLV of the contrast of the intensity continuum signal produced by small magnetic elements in full-disk images (4″ resolution) and in high-resolution (1.2″ resolution) using similar selection criteria as those used in Ortiz et al. (2002): to separate magnetic signal from noise, we define a pixel in a magnetogram as active if its absolute value ($|B|$) is greater than three times the "standard deviation" of the magnetic field measured values, typically about 9 gauss. To avoid the influence of active magnetic elements on the definition of the baseline noise level we create a fictitious standard deviation map defined by choosing for each pixel location the minimum standard deviation of a sliding 40×40 pixels square centred on the pixel. We select the magnetic elements by choosing 'active pixels' that are in contact with at least another 'active pixel'. Fig. 5 shows a comparison of contrast values obtained from the full-disk or low-resolution image data (continuous line) with the contrast values obtained from the data of the high-resolution images (broken and dotted lines).

Given the magnification ratio between high-resolution and full-disk data, a square of 9 pixels of the high-resolution data corresponds to about the same size on the solar disc as one pixel of the full-disk data. Therefore, for comparison we select as active magnetic elements in the high-resolution data groups of 3×3 'active pixels'. There are several caveats in the implied assumptions for the comparison of the two kinds of data but in principle it is qualitatively correct. In absence of the point spread function for either the high-resolution data or the full-disk low-resolution data we have performed an analysis of the distribution of both the intensity continuum and the magnetic flux in 3×3 pixel binned high-resolution images prior to the off-pointing exercise and in a rectangle carved out of a full-disk images acquired 1.5 h after. The standard deviation of the distributions is about equal, within 15% and 5%, for the intensity and for the magnetic field, respectively. Figs. 6(a)–(c) display example plots of CLV values for full disk and binned high-resolution data selected outside active regions for three well defined B/μ ranges. As can be expected (see Krivova and Solanki, 2004) the contrast at high resolution is slightly larger than at low resolution. But it is also interesting to note that

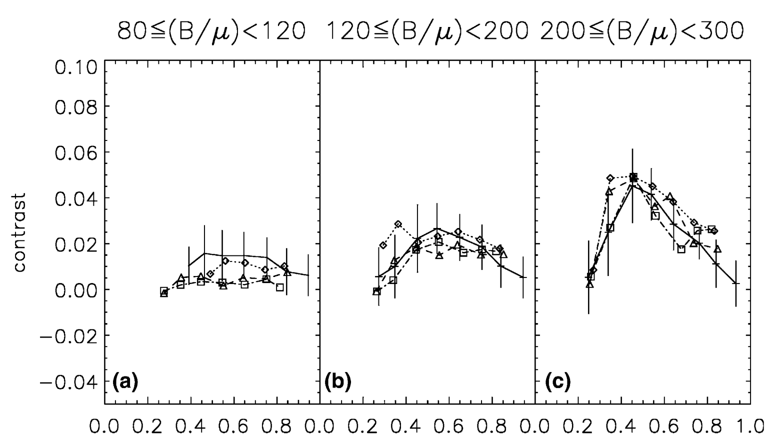

Fig. 5. (a)–(c) Centre to limb variation of the intensity contrast of the intensity in the continuum at 676.8 nm produced by photospheric magnetic elements versus the cosine of the heliocentric angle at three ranges of magnetic intensity (a, b and c, respectively). The magnetic elements have been sampled outside active regions. In all Figs. 5–7: *continuous line* – full disk (≈ 4″ resolution), selection is one active pixel associated to other active pixels. *Dotted line and diamonds* – high-resolution (≈ 1.2″), active pixels in zoomed region east. *Dashed line and triangles* – high-resolution zoomed region west. *Dash-dotted line and squares* – high-resolution zoomed region north. The magnetic field B is reported in Gauss, as defined by MDI, without further corrections. Error bars indicating 1 standard deviation of the dispersion have been plotted only for the full-disk data, to avoid over crowding.

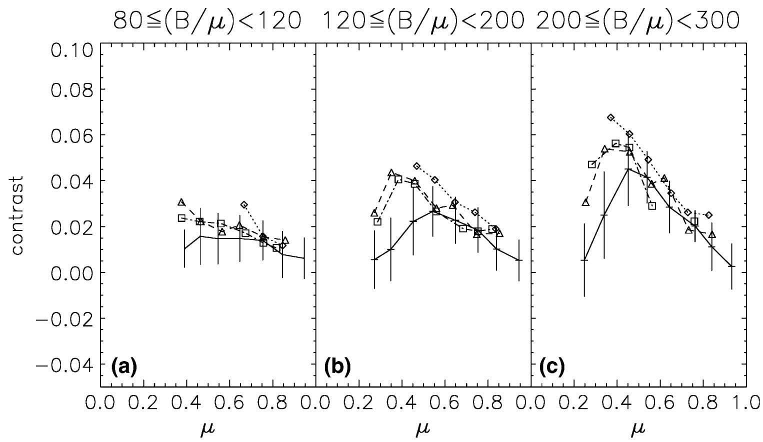

Fig. 6. (a)–(c) Same as Fig. 5, but for the zoomed or high-resolution data a 3×3 pixel box has been selected in each case, while maintaining the continuous line for the full disk single pixel.

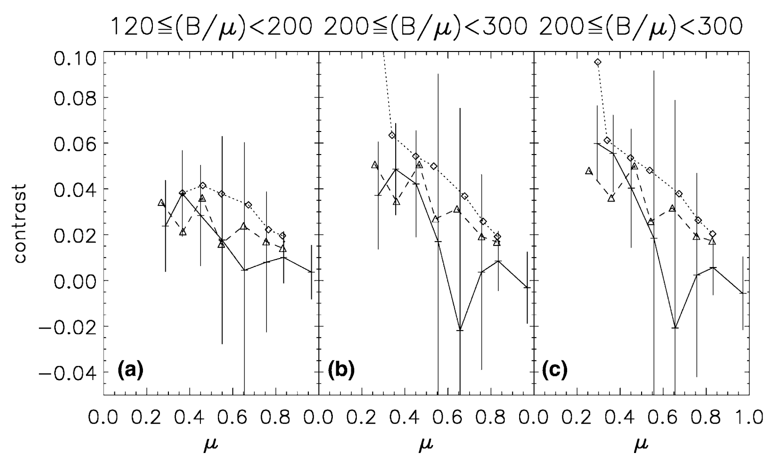

Fig. 7. (a) and (b) Same as for Figs. 6(b) and (c), respectively, but for active regions. (c) Selection is a 2×2 box of active pixels: *continuous line* – full disk (≈ 4″ resolution). *Dotted line and diamonds* – high-resolution (≈ 1.2″), zoomed region east. *Dashed line and triangles* – high-resolution zoomed region west.

the high-resolution data measurements produce a CLV of the contrast that increases monotonically toward low μ up to a maximum that is significantly at lower μ values than the one observed in the full-disk data.

Figs. 7(a) and (b) show examples of the same representation as in Fig. 6 for typical ranges of magnetic field, in active regions. Now, we see a monotonic increase of the contrast as the heliocentric angle increases with no maximum.

We find that isolated one-pixel magnetic elements correspond to continuum intensity pixels with no significant signal-to-noise value, in agreement with Meunier (2003) who claims that magnetic elements smaller than four pixels, in MDI full disk magnetograms, are too noisy to be studied. Therefore, there is a temptation to explain the decrease of the CLV toward the limb by supposing that at low μ values the average contrast is contaminated by noisy values. A sort of test of the idea that one pixel magnetic elements cannot be separated from noise and contaminate the CLV distribution is shown in Fig. 7(c), where we display the CLV of magnetic elements that require four pixels in a 2×2 square to be 'active'. In spite of the data limitations (poor statistics), it is evident that there is no bending of the distribution toward low contrast at low μ values. The requirement of four contiguous active pixels is likely to eliminate most of the random noise detections as active pixels.

3. Discussion and conclusion

The most noticeable feature on the contrast versus heliocentric angle (μ) plots is the change in the behaviour of the distribution at low μ values. It appears that for $0.2 < \mu < 0.4$ the contrast is measurably affected by the image resolution. Penza et al. (2004) demonstrate that in the measurement of the centre-to-limb variation of the contrast there is a decrease at low μ due to a foreshortening effect that induces an increase in the amount of background 'quiet sun' that gets blended into the magnetic element signal.

The contrast reduction at low μ is readily observable for small, isolated magnetic elements in quiet sun regions where the effect described by Penza et al. would be at work, but not for facular regions that often appear as a blanket of contiguous 'active' pixels with no room for contaminating background. Alternatively, it can also be considered that given the fact that the filling factor is very low, in regions with a more uniform filling factor (active regions) the centre-to-limb contrast should increase as the size of the solar surface covered by the pixel increases, i.e., as $1/\cos(\theta)$, while in regions of isolated flux elements the CLV would decline due to a decrease in visibility.

It would appear that the foreshortening effect near the limbs hides the bright network points, and that their visibility is contingent on the instrumental angular resolution, i.e., they are made visible when measuring with higher resolution. For instance, Fig. 6 would indicate that for magnetic field elements around 150 Gauss the inflexion point, where the micro bright-points start to be invisible occurs at $\mu \approx 0.55$ for the $4''$ resolution measurements, while it would occur at $\mu \approx 0.3$ in the high-resolution measurements.

In conclusion, this preliminary work suggests that higher resolution and high photometric quality measurements are required to improve our knowledge of the solar radiance produced by photospheric magnetic elements.

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