CENTRE TO LIMB INTENSITY VARIATION OF MAGNETIC BRIGHT POINTS

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Abstract. The solar activity cycle is strongly related and rooted to photospheric magnetic fields. Up to the present, it was mostly or even solely studied by extended fields such as sunspots, sunspot groups or active regions. Interestingly, the domain of magnetic fields on the Sun is not only limited to extended and strong magnetic fields but reaches down to small elements like single flux tubes. These flux elements can be identified in G-band filtergrams as so called magnetic bright points (MBPs). In this study we want to investigate the centre limb variation of the mean MBP intensity for the period of the recent solar minimum up to present (10/2008 - 10/2011). We found that a 4th order polynomial describes the centre limb variation fairly well. Furthermore we established for the symmetrized and normalized centre limb variation (for which the 1st and 3rd order parameter of the polynomial is fixed to zero) a relationship between the 2nd and 4th order fit parameter. Hence it is possible to derive a description with only one free parameter. Finally, we studied the variation with time of this parameter for the period of October 2008 to present, showing a slight increase and a weak correlation to solar activity as given by the relative sunspot number.

Key words: small scale magnetic fields - photosphere - high resolution observations - centre limb variation - solar cycle - Hinode/SOT

1. Introduction

The most obvious feature of the Sun’s surface are sunspots (see review by Solanki, 2003) and the related active regions. Sunspots comprise extended and large magnetic fields but are by far not the only magnetic elements in the Sun’s atmosphere. A complete series of different features exist, covering...
the whole range from active regions down to single flux tubes or flux fibers (see Zwaan, 1987). Furthermore it is well known and studied since a long time that sunspots are connected to the solar activity cycle. Since Schwabe (1844) mentioned for the first time a periodicity in the sunspot numbers, numerous basic facts and constraining parameters about the sunspot cycle and the magnetic field were gained. Many of those important findings can be concluded from the butterfly diagram in which the occurrence rate and position of sunspots is plotted over a time axis. For this study the most interesting and relevant finding is that sunspots appear largely in so called activity belts. During an ongoing cycle, these belts tend to migrate from mid latitudes towards the equator. This gives rise to the interesting question if something similar can be observed for small scale magnetic fields too. For more detailed information about the solar activity cycle see e.g. Hathaway (2010). The scientifically interesting and not yet sufficiently addressed question is if such a behaviour (or a vice-versa trend - migration towards the pole) can be observed and described in detail for small scale magnetic fields.

In the present work we will investigate small scale magnetic fields via the measurement of proxies. A good proxy for those magnetic fields are magnetic bright points (MBPs; see e.g. Berger and Title, 2001). MBPs are manifestations of flux concentrations in the solar photosphere reaching field strengths of kG levels with diameters of hundreds of km. They show an enhanced intensity in magnetic sensitive spectral bands like the G-band and appear very bright (for the relation of magnetic fields and the G-band see e.g. Shelyag et al., 2004). They can be found in intergranular lanes and showing a splitting and merging dynamic. Their velocities reach several km per second and the lifetimes are in the range of minutes (see Utz et al., 2010). On the solar limb, MBPs can be found as so called faculae (see e.g. Hirzberger and Wiehr, 2005). Faculae are closely linked to MBPs and transform in one another when going from the limb of the Sun to the centre (see Kobel et al. 2009). In the present study we will investigate the centre to limb variation (CLV) of MBP intensities and the evolution of the CLV with time over the recent years. A changing CLV of MBP intensities over time is likely related to a migration or to active latitudes of small scale magnetic fields and thus will help us to gain more insight into the solar cycle. The analysis is done with Hinode data and consists of monthly north south scans of the solar disc taken in the G-band.
Figure 1: A typical variation of image contrasts during a Hinode north-south scan. This graph was done with the October 2010 data. The telescope actually scanned from south to north. The upper panel illustrates the full range of data while in the middle panel a detail of the CLV of the contrast is shown. The lower panel displays the ratio between the contrast measurements at equal distances from the disc centre. A linear fit is applied and reveals an increase of the contrast ratio to the disc centre.
2. Data

The data used in this study were provided by the Japanese/US/European Hinode spacecraft mission (Kosugi et al., 2007) and taken by the solar optical telescope (SOT; Tsuneta et al., 2008). We used G-band north south scan data sets provided by the broadband filter imager (BFI). Those scans comprise usually 40 exposures at 20 different solar disc positions (each position is imaged twice). The field of view (FOV) of the images is about 220 by 110 arcsec$^2$ and consists of 2048 by 1024 pixel$^2$ (2 by 2 binning applied on the spacecraft) yielding a pixel sampling of 0.108 arcsec/pixel. The time difference to take exposures at two different positions on the solar disc is roughly half an hour while it takes about 3 minutes at one position to take the double exposure. A complete scan needs about 9.5 hours.

The scanning programme is executed normally once a month. During the considered time frame (October 2008 to October 2011), the scan programme was not performed in several months. Furthermore it is evident that during several scans single images or complete positions were lost. Some scans seem to be broken in the middle. One example for such a scan are the data from February 2011. This scan consists of data taken at y position $-945$ arcsec to y position 635 arcsec. The last 3 positions were not covered (either data loss occurred or an interruption of the scan programme). For the analysis we did not use any broken series. If only one of the two exposures per position was taken during the scan, we used the taken exposure also as a replacement for the twin exposure. If the centre position was lost, we used exposures from the normal synoptic programme (this programme observes up to 3 times a day in all BFI wavelengths the solar disc centre in full FOV).

3. Analysis

The data were processed using the standard SSW-IDL reduction codes of the Hinode mission namely with the routine fg_prep. This gives us dark current corrected and flat fielded images. The next step consisted of the application of an automated segmentation and identification algorithm as described in Utz et al. (2009, 2010). This gives us fully segmented images and identified MBP structures within the images. Furthermore a data structure containing interesting information such as size and intensity of the identified MBPs is created. The applied MBP identification algorithm is sensitive to contrast
centred to limb intensity variation of magnetic bright points

Figure 2: A typical centre to limb variation of the mean image intensity (lower curve; stars) and the mean MBP intensity (upper curve; crosses). The data are shown together with the applied 4th order polynomial fits.

changes. Therefore it is necessary to check the image quality for stability and image contrast. As one can see in Figure 1, the contrast during a scan over the solar disc shows a typical pattern from limb to centre with very high contrast values close to the limb, decreasing to local minima further inside the solar disc and then steadily increasing to the centre. The curve is asymmetric and depending on the scanning direction (north-south, south-north). This behaviour and a possible explanation by instrumental effects were already discussed by Utz et al. (2011). Due to this contrast evolution found in the north-south scans we decided to symmetrize the problem in order to minimize the influence of the telescope. This means that measured values of one hemisphere are projected onto the other hemisphere in equal distance to the centre of the solar disc. For the following analysis of the intensity of MBPs with solar latitude we used a polynomial function of 4th order. Because we have symmetrized the distribution, we discarded the 1st and 3rd order of the polynomial and used the following fit function:

$$I(x) = A_0 + A_1 \cdot x^2 + A_2 \cdot x^4,$$

where $A_0$ is the intensity at the solar disc centre, $A_1$ is the coefficient of the quadratic term, $A_2$ is the coefficient of the forth order term, $x$ gives the dis-
tance from the solar centre and $I$ is the measured intensity. A typical result for the October 2010 scan is shown in Figure 2. The upper curve displays the CLV of the mean MBP intensities while the lower curve illustrates the CLV of the mean image intensities. Both curves were fitted by Equation 1.

In order to perform comparisons of the fitting coefficients for the 3 years of analysed data sets, the CLV was normalized to the centre intensity and to the solar disc diameter\(^1\). The normalization to the centre intensity is necessary as the filters of the Hinode mission show an ageing effect and a yearly trend. Both of these effects can be seen in Figure 3. The upper panel shows the evolution of the $A_0$ fit parameter (mean MBP centre intensity). Clearly a yearly pattern and steady decrease is visible. The middle panel gives the solar activity during this period of time as observed by the relative sunspot number provided by the Solar Influences Data analysis Center (SIDC). The third panel displays the nominal and the actual (measured) exposure time of the G-band images.

### 4. Results

For all available data sets (north-south scans) we derived the normalized $A_1$ and $A_2$ fitting parameter of the CLV of the mean MBP intensity. In the following we investigated the correlation between the two parameters. We found a correlation coefficient of $-0.95$ between the two parameters. Due to the high correlation coefficient between the two parameters only one independent parameter is necessary (the other one is linearly dependent on the aforementioned) to describe the centre limb variation. Figure 4 shows a scatter plot between the two normalized fit parameters and an applied linear fit.

From the figure as well as from the derived correlation coefficient follows a linear relationship between the two fit coefficients of Equation 1. The derived fit coefficients for this relationship have values of $d = -0.60 \pm 0.01$ for the y-intercept and $k = -1.24 \pm 0.01$ for the slope. Hence the normalized CLV equation for the intensity of MBPs looks (under the use of the linear dependence model between the parameters) as follows:

$$I_n(x) = 1 + A_1 \cdot x^2 + (d + k \cdot A_1) \cdot x^4$$  \hspace{1cm} (2)

\(^1\)The diameter of the solar disc varies slightly due to the revolution of the earth (and thus the Hinode spacecraft) around the Sun.
Figure 3: The upper panel shows the evolution of the mean intensity of identified MBPs at solar disc centre as measured with the Hinode G-band filter. The middle panel gives the relative sunspot number (taken from the SIDC). The bottom panel displays the nominal exposure time (dashed line) and the actual exposure time (crosses) of the images taken with the G-band filter.
Figure 4: Scatter plot of the 2nd order fit parameter and the 4th order fit parameter of the CLV of MBP intensity. The applied linear fit is also plotted, giving a linear correlation coefficient of $-0.95$.

this can be rewritten as:

$$I_n(x) = 1 + d \cdot x^4 + A(t) \cdot (x^2 + k \cdot x^4)$$

Inserting the derived values for the y-intercept and the slope we finally obtain:

$$I_n(x) = 1 - 0.6 \cdot x^4 + A(t) \cdot (x^2 - 1.24 \cdot x^4).$$

$I_n(x)$ is the intensity normalized to the disc centre MBP intensity depending on the position normalized to the solar radii ($x=0$ equals to the disc centre, $x=1$ equals to the solar limb). $A_1$ was replaced by $A(t)$ as it is the sole free parameter after fixing $A_2$. Furthermore, we consider the parameter as time dependent and have in mind that it can vary with the solar cycle. In the following we want to investigate the behaviour of the $A(t)$ parameter and study the evolution of the parameter within the frame of the analysed data sets. In Figure 5 we see the obtained fit parameter for the CLV of the mean MBP intensity. A weak increase during the period under study can be seen. This is also verified by the correlation coefficient between observation time and the parameter itself which gives us a value of 0.30. A linear fit applied to the scatter yields $-0.59$ for the $y$ intercept and a slope of 0.016 per year.
Figure 5: The normalized CLV fit parameter as described in Equation 4 versus time. The correlation between the parameter and time amounts to 0.3. A linear fit, showing a slight increase, is given in full line.

Figure 6 shows the range of the obtained CLVs of mean MBP intensities during the observation period. The left panel gives the minimum, median and maximum parameter variant of CLVs. The right panel shows the difference between the maximum and the minimum variant. During the 3 years of analysed data it turns out that the CLV changes within a boundary of about +5 to −7% of the disc centre intensity.

5. Discussion

The most striking possibility for a varying CLV of the mean MBP intensity is a dependence on the solar activity cycle. To cross check this assumption, we took the relative sunspot number (a proxy for solar activity) as provided by the SIDC (http://sidc.oma.be/sunspot-data/) and correlated this time series with the series of derived fit parameters. In order to correlate the two time series, we interpolated the relative sunspot number to the same time basis as given by the north south scan data sets. It is important to have in mind that this may reduce the correlation between both data sets when compared with data that already originally has the same basis. Af-
Figure 6: Left panel: minimum, median and maximum CLV of the mean MBP intensity as given by the fit parameter $A(t)$ are shown together. Right panel: difference between the minimum and maximum CLV variants.

ter interpolating the relative sunspot number to the same time instances as given by the used data sets the correlation coefficient between the two quantities amounts to 0.17, representing at least a weak correlation. Nevertheless we think it is too early to give a final statement as the new solar cycle just started and the significant time span is thus rather short. Figure 7 shows the scatter plot of the two parameters. One can see that larger relative sunspot numbers go in general along with higher values of the CLV fit parameter. Two of the measurement points look like outliers. Excluding these points (encircled in the figure) the correlation rises to a value of 0.34. Most of the current measurements and accessible data were unfortunately still taken during the solar minimum. Hence measurement points are concentrating on the left hand side of the figure and hinders to derive stricter conclusions. The linear fit applied to the scatter plot of Figure 5 shows a slight increase with time (0.016 per year). Up to now the interpretation of the changing CLV of MBP intensities with time is unclear.

6. Summary and Conclusions

The current study is one out of a series (see also Utz et al., 2011) which will deal with the derivation of characteristics of MBPs with longitude, latitude and changes of these characteristics over the solar cycle. The present study deals with the CLV of mean intensities of MBPs. We showed that the CLV can be fitted in a good approximation with a 4th order polynomial. Due to instrumental concerns we symmetrized the data and hence the 4th order
polynomial (after normalization to the centre intensity) was left with only 2 free fitting parameters. We derived a relationship between these 2 parameters and finally got an equation for the CLV, which is only dependent on one parameter. We assumed that this parameter is time dependent (on the solar cycle) and studied the variation of the parameter with solar activity for the rising phase of cycle 25 during 10/2008 to 10/2011. This yielded a slight correlation which has to be studied more thoroughly in the future. The next step will be a study of the number of detected MBPs with longitude, latitude and cycle dependence. This has to be done very carefully as a changing image contrast (instrumental instabilities) can have a strong impact on the resulting measurements.

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