LETTER TO THE EDITOR

The statistical distribution of the magnetic-field strength in G-band bright points

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Received 24 October 2013 / Accepted 4 December 2013

ABSTRACT

Context. G-band bright points are small-sized features characterized by high photometric contrast. Theoretical investigations indicate that these features have associated magnetic-field strengths of 1 to 2 kG. Results from observations, however, lead to contradictory results, indicating magnetic fields of only kG strength in some and including hG strengths in others.

Aims. To understand the differences between measurements reported in the literature, and to reconcile them with results from theory, we analyzed the distribution of the magnetic-field strength of G-band bright features identified in synthetic images of the solar photosphere and its sensitivity to observational and methodological effects.

Methods. We investigated the dependence of magnetic-field strength distributions of G-band bright points identified in 3D magneto-hydrodynamic simulations on feature selection method, data sampling, alignment, and spatial resolution.

Results. The distribution of the magnetic-field strength of G-band bright features shows two peaks, one at about 1.5 kG and one below 1 hG. The former corresponds to magnetic features, the second mostly to bright granules. Peaks at several hG are obtained only on spatially degraded or misaligned data.

Conclusions. Simulations show that magnetic G-band bright points have typically associated field strengths of a few kG. Field strengths in the hG range can result from observational effects, which explains the discrepancies presented in the literature. Our results also indicate that results from spectro-polarimetric inversions with an imposed unit filling-factor should be employed with great caution.

Key words. magnetohydrodynamics (MHD) – magnetic fields – Sun: photosphere – Sun: magnetic fields

1. Introduction

G-band bright points (BPs) are roundish features of a few hundred kilometers in diameter, whose contrast with respect to quiet regions is high (usually 30% or more) when observed in the Fraunhofer G-band (the spectral range of about 1 nm around 430.5 nm). Co-temporal and co-spatial observations with magnetograms show that some BPs have associated magnetic-flux concentrations, while others correspond to bright granules (Keller 1992; Berger & Title 2001; de Wijn et al. 2009 for a review); the two populations also present different spectral characteristics in the G-band (Langhans et al. 2002).

Theoretical studies have shown that the brightening of magnetic features in the G-band is caused by the weakening of CH molecule lines (which are conspicuous in this Fraunhofer band), which results from the lower temperature and reduced pressure and density within magnetic structures with respect to the surrounding quiet regions (e.g. Schüssler et al. 2003; Uitenbroek & Tritschler 2006). Results obtained by Schüssler et al. (2003) and Shelyag et al. (2004) from the analysis of magnetohydrodynamic (MHD) simulations indicate that these conditions are satisfied only in kG structures.

Some observations confirm the kG nature of G-band BPs. For instance, Ishikawa et al. (2007), who analyzed data from the Swedish Solar Telescope (SST), retrieved an average magnetic flux of ≈ 1.5 kG. Vitićhić et al. (2010) also found a field strength of 1.5 kG by inverting spectro-polarimetric data acquired at the Dunn Solar Telescope (DST). However, from

spectro-polarimetric inversions of data acquired at the Vacuum Tower Telescope (VTT) and simultaneous G-band observations from the Dutch Open Telescope (DOT), Beck et al. (2007) deduced a rather flat field strength distribution ranging between ≈ 0.5 kG and 1.5 kG. More recently, from analyzing Hinode/BFI G-band data and spectro-polarimetric inversions of Hinode/SP data, Utz et al. (2013) found that the magnetic-field distribution of BPs can be described by the superposition of four log-normal functions, of which two peak in the kG, and two in the hG range. These authors concluded that features in the kG range correspond to “collapsed fields” (subdivided into a “weak collapsed field”, with a peak at ≈ 1.1 kG, and a “strong collapsed field”, with a peak at ≈ 1.3 kG); features whose field distribution peaks at ≈ 7 hG correspond to a “pre- and post-collapsed” magnetic field; and features whose field distribution peaks at ≈ 3 hG correspond to a “background” field related to solar dynamo processes. It is worth noting that while Utz et al. (2013) employed results from spectro-polarimetric inversion with an imposed unit filling-factor, Beck et al. (2007) and Vitićhić et al. (2010) assumed two component atmospheres, one magnetic and one quiet, so that the filling factor was a free parameter.

Owing to their small size, which is still at the limit of the spatial resolution of modern instrumentation, the estimation of properties of BPs is prone to observational effect as has been shown by numerical models (e.g. Criscuoli & Rast 2009) and observations (e.g. Vitićhić et al. 2010). We therefore aim to qualitatively investigate whether the discrepancy of results presented

in the literature can be attributed to differences in the quality of the data and in the tools employed for their analysis. With this aim we investigated the effects of image degradation, image-thresholding, pixelization, and misalignment between G-band and magnetograms of magnetic-field distributions of bright features identified in G-band images derived from 3D MHD simulations. The paper is organized as follows: in Sect. 2 we describe the simulations and the data analysis; in Sect. 3 we present our results, and in Sect. 4 we draw our conclusions.

2. MHD simulations and data analysis

We employed nine snapshots from a 3D MHD simulation covering an area of $6 \times 6 \text{ Mm}^2$ of the solar photosphere obtained with the Copenhagen stagger code (Nordlund & Galsgaard 1996), characterized by having average magnetic flux of 2 hG and a spatial sampling of $\approx 0.03''/\text{pixel}$ in the horizontal direction (see Fabbian et al. 2010, 2012 for a detailed description). Since properties of magnetic features are known to vary depending on the magnetic flux of their environment (Criscuoli 2013 and references therein), we also considered snapshots with average magnetic flux of 0.5 and 1 hG. Nevertheless, since results obtained from these latter simulations are similar to those obtained from 2 hG simulations, but present lower statistics, in the following we show only results obtained from the 2 hG simulations. The snapshots were randomly selected with the constraint that they needed to be between 6 and 11 min apart; this sampling ensured that the snapshots were independent of each other, and also reduced effects introduced by p-modes. Each snapshot was spatially resampled in the vertical dimension, as described in Criscuoli (2013), and the G-band spectrum was synthesized in the vertical direction with the RH code (Uitenbroek 2002, 2003), as described in Uitenbroek et al. (2007). Intensity images were then obtained by multiplying the spectra by a Lorentzian-shape filter profile with full width at half maximum (FWHM) equal to 1 nm and centered on 430.5 nm. Note that we found that variations of up to 40% in the width of the filter do not produce significant variations in the results presented below. We also synthesized the intensity in the continuum at 630 nm.

Bright features were identified in each snapshot by considering all pixels whose G-band intensity contrast IC (defined as the ratio between the G-band intensity of the pixels and the median intensity in each snapshot) satisfied the relation $IC \geq M + \alpha * \sigma$, where M and σ are the median and standard deviation of the contrast within the snapshot and α is a free parameter that we let vary between 0.5 and 1.5. Each feature was then labeled with the IDL label_region routine. The number of features identified in this way in the original data varied between 730 to 800, depending on the α values, and varied between 300 and 350 in spatially degraded data (see text below). We then produced maps of the magnetic-field strength at optical depth $\tau_{500} = 0.1$ (B_0 , hereafter) and for each identified feature we considered their average field strength and their field strength at the pixel corresponding to the G-band intensity barycenter over the B_0 maps. Since we obtained similar distributions and trends with the two methods, in the following we only present results obtained for average magnetic-field strengths. Note that Orozco Suárez et al. (2010) showed that Milne Eddington inversions statistically provide reliable estimates of magnetic-field properties at $\tau_{500} = 0.1$, therefore the magnetic-field strength values computed over B_0 maps are good representations of results obtained from inversions.

To investigate the dependence of the distributions on spatial resolution, we convolved the intensity images and the B_0 maps, with point spread functions (PSFs) of different shapes.

Following Wedemeyer-Böhm (2008), we modeled the PSFs as the convolution between an Airy function, which is the PSF of the telescope aperture, and a Voigt function, which takes scattered light into account. The free parameters of the PSF model were varied to represent five different cases. Two were obtained assuming a telescope aperture of 50 cm and wavelengths of 630 nm and 430 nm, respectively, which determine the parameters of the Airy functions. We set the parameters for the Voigt function to reproduce an average rms contrast over the snapshots similar to those derived from Hinode BFI and SP measurements, that is 0.11% for the G-band (Mathew et al. 2009) and 7% for the 630 nm images (Danilovic et al. 2008). In the following we refer to these functions as PSF_50cm_430 and PSF_50cm_630. They approximately represent the PSFs of Hinode BFI and SP. Following results obtained by Beck et al. (2013), to represent the PSF of SP we also constructed a third function whose FWHM is $0.6''$ and whose wing amplitude is similar to that obtained by Beck et al. (2013; PSF_50cm_06, hereafter); the average rms contrast in our snapshots using this PSF is about 6% at 630 nm. Two other PSFs, representing a telescope aperture of 70 cm at 630 nm and 430 nm were also calculated (PSF_70cm_630 and PSF_70cm_430, hereafter); these approximately represent the PSFs of the VTT and the DST. To investigate the effects caused only by the spatial resolution, we kept the free parameters of the Voigt functions equal to those derived for the 50 cm PSFs. We also tested varying the wing amplitudes of the PSFs; the results are briefly discussed below.

Finally, we analyzed the dependence of the results on spatial sampling, rebinning the data to one- and two-thirds of their original sizes, and on the misalignment between the G-band images and B_0 maps by shifting these data with respect to one another.

3. Results

Comparing G-band contrast and B_0 maps we found in general that hG fields mostly occur in intergranular lanes, while kG fields preferentially appear at vertexes between granules with some presence in lanes. However, we also found that only the kG features are bright in the G-band. The contours of the two classes of features are marked in dotted blue and solid red lines in the left image of Fig. 1. The solid blue lines also marked in the same panel represent pixels for which $1 \text{ hG} < B_0 < 1 \text{ kG}$ and $IC > 1$; these are few and are mostly located at the borders of larger magnetic regions. Inspection of data shows that they result mostly from the expansion of the field with height, while a small fraction has only associated a horizontal field. In degraded images the area occupied by positive-contrast hG pixels is larger (middle left panel).

Middle right and right panels of Fig. 1 show examples of contours of features identified assuming $\alpha = 1.5$ in original and spatially degraded data, superimposed on B_0 maps, and B_0 maps degraded with PSF_50cm_630. Clearly, two types of features are identified in both types of data: bright granules (whose field strength is $< 1 \text{ hG}$) and kG features. Only few features identified in nondegraded data have an hG field strength (for instance, in the middle right image only one such feature is identified); these typically encompass bright granules adjacent to small-sized magnetic patches. In spatially degraded data, more identified features have hG field strength. These correspond in part to bright granules close to features that in the original images had kG field, and correspond in part to small-sized features that had an associated kG field in the original data, whose average field decreased as an effect of the spatial degradation.

Fig. 1. *Left:* G-band contrast IC of one of the MHD snapshots, saturated at 1.5. Dotted blue lines: borders of regions where $1 \text{ hG} < B_0 < 1 \text{ kG}$. Solid blue lines: regions where $1 \text{ hG} < B_0 < 1 \text{ kG}$ and $\text{IC} \geq 1$. Solid red lines: regions where $B_0 \geq 1 \text{ kG}$. *Middle left:* same as *left panel*, but image degraded with a PSF_50cm_430. *Middle Right:* B_0 corresponding to *left panel*. *Right:* B_0 convolved with a PSF_50cm_06. Dotted green lines denote contours of features identified in images in the *left* and *middle-left panels*, respectively, assuming $\alpha = 1.5$; solid green lines denote borders of a subset of identified features whose average field value is between 1 hG and 1 kG.

Fig. 2. Statistical distribution of the average magnetic field of features identified assuming $\alpha = 1.5$ in G-band and B_0 images (black symbols), both degraded (blue symbols), and when only G-band images are degraded (red symbols). Bin size = 100 G. The PSFs employed to degrade the data are indicated.

Magnetic-field distributions of the identified features are illustrated in Fig. 2. The black symbols represent the distribution of features identified in the original G-band intensity images. We note a peak at $\approx 1.5 \text{ kG}$, with values up to 2 kG ; the weak tail at hG field strengths confirms that features identified in nondegraded images with an average field-strength of some hG are statistically irrelevant. The blue symbols denote the distribution of features identified in G-band images degraded with a PSF_50cm_430 and the corresponding B_0 degraded with a PSF_50cm_06; in this case the distribution covers a wider range of average field-strength values, and the peak occurs at $\approx 7 \text{ hG}$. The red symbols show the distribution of features identified on the G-band snapshots degraded with a PSF_50cm_430, but B_0 nondegraded. This latter case simulates results obtained from a perfect spectro-polarimetric inversion performed with the filling-factor as a free parameter, that can return the real magnetic-field strength value (these cases are denoted with the suffix *_Str.* hereafter); indeed, the distribution in this case is more similar to that obtained from the original snapshots, because the peak occurs at $\approx 1.5 \text{ kG}$. In all distributions, the highest peak occurs at $B_0 < 1 \text{ hG}$; these correspond to bright granules or to granules adjacent to magnetic features that are identified as a single feature, as discussed above.

We then compared distributions obtained from data convolved with the different PSFs described in Sect. 2. The left panel in Fig. 3 shows the results obtained from convolving both G-band and B_0 images. We note that the peaks of the distributions shift toward lower values, being $\approx 9 \text{ hG}$ for a telescope

of 70 cm diameter and $\approx 7 \text{ hG}$ for a 50 cm telescope. Similarly, the widths of the distributions increase with the decrease of the spatial resolution. Similar results were obtained when only the G-band images were degraded (not shown).

The middle panel in Fig. 3 shows the effects on magnetic-field distributions of image thresholding in the case of B_0 and G-band images degraded with a PSF_50cm_06 and a PSF_50cm_430, respectively. We notice that peaks shift toward lower values and distributions broaden with the decrease of the threshold value. Results obtained degrading only G-band images show qualitatively the same trends (not shown), with the distributions resulting from $\alpha = 0.5$ being rather flat. Note that we found that increasing the amount of scattered-light has qualitatively the same effect as decreasing the threshold value.

We also investigated the effects of pixel sampling on the shapes of the magnetic field distributions. With this aim, we compared distributions obtained at the original pixel scale of $0.03''$ with images resampled at approximately $0.05''$ and $0.1''$. We found that for both original and degraded images, rescaling does not affect the shape of the distributions, as is shown for instance by comparison of the distribution obtained from $0.03''$ pixel scale data (represented with blue symbols in Fig. 2), and the distribution obtained from $0.1''$ pixel scale data (represented with black symbols in Fig. 3).

Finally, we investigated the effects of misalignment between the G-band images and B_0 . We found that with increasing of misalignment the distribution peaks shift toward lower values and their widths increase. Nevertheless, distribution shapes are significantly altered only for misalignments comparable to or larger than the spatial resolution of the data (i.e., the amount of spatial degradation), therefore, original data distributions are more affected by misalignment than distributions obtained from degraded data. The plot in the right panel of Fig. 3 represents an intermediate case, because it shows results obtained when only G-band images were degraded with a PSF_50cm_430. Note that the plot shows results obtained in data whose pixel scale is $0.1''$. Here, we also note that even for the intermediate case in which only G-band images were degraded, a subpixel shift leads to significant modification of the distribution shapes.

4. Conclusions

We implemented an automatic method to select bright features in synthesized G-band intensity images obtained from 3D MHD simulations. We found that most of the bright features identified

Fig. 3. Dependence of distributions on observational and methodological effects. *Left:* distribution of the average field of features identified assuming $\alpha = 1.5$ in G-band images and B_0 degraded with different PSFs (see legend). *Middle:* distribution of the average field of features identified assuming different α values (see legend) in both G-band and B_0 images degraded with the indicated PSFs. *Right:* distribution of the average magnetic field of features identified assuming $\alpha = 1.5$ in G-band images of $0.1''$ spatial sampling degraded assuming the indicated PSF, and B_0 shifted in the x -direction (see legend).

in nondegraded images correspond to either kG features or to granules. As a result, the distribution of the average magnetic field of the identified bright features presents two populations. One spans the range 1–2 kG and has a peak at about 1.5 kG, the other spans the range 0–2 hG. Because we obtained similar results from snapshots characterized by different amounts of magnetic flux, we conclude that G-band BPs harbor kG magnetic fields regardless of the region (quiet or active) they are embedded in. We then investigated the sensitivity of the distribution shape on the data quality and the employed feature-selection method. We found that the distributions widen and shift toward lower magnetic-field values when images are spatially degraded, when the threshold value employed for identification is lowered, and when the misalignment between G-band images and magnetic-field data is increased. On the other hand, distributions are rather insensitive to the spatial sampling, as long as this is good enough to resolve the BPs.

Our results therefore suggest that the different distribution shape presented in the literature mostly result from the different identification methods employed to select features and the quality of the data. In particular, we speculate that the broad distribution obtained by Beck et al. (2007) might be the result of residual temporal and spatial misalignment between the data. Results by Utz et al. (2013), obtained by employing spectropolarimetric inversions with unit filling-factor, are most likely affected by image degradation. In particular, it is very likely that the kG component they found results from larger magnetic structures, which are less affected by spatial degradation, on which the inversion was able to retrieve reliable estimates of the field intensity. The population peaking at 7 hG that they found instead results from smaller-sized elements, for which the inversion returned the magnetic flux, not the field strength. Finally, the population that peaks at about 3 hG most likely encompasses bright granules adjacent to magnetic concentrations, whose flux therefore is a few hG, and patches of horizontal field, whose number is known to be underestimated in MHD simulations without local dynamo (e.g. Danilovic et al. 2010) such as those we employed. We also note that the identification method employed by Utz et al. (2013) selects structures that are bright with respect to the local background. As a result, features such as umbral dots or penumbral and light-bridge features are also selected (see their Fig. 4). These features are embedded in the canopy of the pore or sunspot they belong to, so that an inversion performed with a unit filling-factor is more likely to return a kG magnetic-field strength. This explains the remarkable difference that these

authors found between distributions obtained in quiet areas and around a pore. Finally, in our simulations we did not find a clear indication of two populations of bright features in the kG range. In fact, the distribution obtained from the original data reported in Fig. 2 might suggest two peaks at about 1.4 kG and at 1.7 kG, but inspection of simulations did not reveal any relevant physical difference between the two populations.

Our results therefore suggest that great care should be taken when employing results from inversions performed with a unit filling-factor (see also Orozco Suárez et al. 2007).

Acknowledgements. The snapshots of magnetoconvection simulations were calculated using the computing resources of the MareNostrum (BSC/CNS, Spain) and DEISA/HLRS (Germany) supercomputer installations.

References

- Beck, C., Bellot Rubio, L. R., Schlichenmaier, R., & Sütterlin, P. 2007, *ApJ*, 472, 607
- Beck, C., Fabbian, D., Moreno-Insertis, F., Puschmann, K. G., & Rezaei, R. 2013, *A&A*, 557, A109
- Berger, T., & Title, A. M. 2001, *ApJ*, 553, 449
- Criscuolo, S. 2013, *ApJ*, 778, 27
- Criscuolo, S., & Rast, M. P. 2009, *A&A*, 495, 621
- Danilovic, S., Gandorfer, A., Lagg, A., et al. 2008, *A&A*, 484, L17
- Danilovic, S., Schüssler, M., & Solanki, S. K. 2010, *A&A*, 513, A1
- de Wijn, A. G., Stenflo, J. O., Solanki, S. K., & Tsuneta, S. 2009, *Space Sci. Rev.*, 144, 275
- Fabbian, D., Khomenko, E., Moreno-Insertis, F., & Nordlund, Å. 2010, *ApJ*, 724, 1536
- Fabbian, D., Moreno-Insertis, F., Khomenko, E., & Nordlund, Å. 2012, *A&A*, 548, A35
- Garlsgaard, K., & Nordlund, Å. 1996, *J. Geophys. Res.*, 1011, 1344
- Ishikawa, R., Tsuneta, S., Kitakoshi, Y., et al. 2007, *A&A*, 472, 911
- Keller, C. U. 1992, *Nature*, 359, 307
- Langhans, K., Schmidt, W., & Tritschler, A. 2002, *A&A*, 394, 1069
- Mathew, S. K., Zakharov, V., & Solanki, S. K. 2009, *A&A*, 501, L19
- Orozco Suárez, D., Bellot Rubio, L. R., Del Toro Iniesta, J. C., et al. 2007, *PASJ*, 59, 837
- Orozco Suárez, D., Bellot Rubio, L. R., Vögler, A., & Del Toro Iniesta, J. C. 2010, *A&A*, 518, A2
- Schüssler, M., Shelyag, S., Berdyugina, S., Vögler, A., & Solanki, S. K. 2003, *ApJ*, 597, L173
- Shelyag, S., Schüssler, M., Solanki, S. K., Berdyugina, S. V., & Vögler, A. 2004, *A&A*, 427, 335
- Uitenbroek, H. 2002, *ApJ*, 565, 1312
- Uitenbroek, H. 2003, *ApJ*, 592, 1225
- Uitenbroek, H., & Tritschler, A. 2006, *ApJ*, 639, 525
- Uitenbroek, H., Tritschler, A., & Rimmele, T. 2007, *ApJ*, 668, 586
- Utz, D., Jurčák, J., Hanslemeier, A., et al. 2013, *A&A*, 554, A65
- Viticchié, B., Del Moro, D., Criscuolo, S., & Berrilli, F. 2010, *ApJ*, 723, 787
- Wedemeyer Böhm, S. 2008, *A&A*, 487, 399