LETTER TO THE EDITOR

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

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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 between 1-2 kG. Results from observations instead lead to contradictory results, indicating magnetic fields of only kG strength in some and including hG strengths in others.

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

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

Results. The distribution of 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 few kG. Field strengths in the hG range can result from observational effects, thus explaining the discrepancies presented in the literature. Our results also indicate that outcomes from spectro-polarimetric inversions with imposed unit filling-factor should be employed with great caution.

Key words. photosphere – magnetic field

1. Introduction

G-band Bright Points (BPs, hereafter) are roundish features, a few hundred kilometers in diameter, whose contrast with respect to quiet regions is high (usually 30% or more) when observed in Fraunhofer’s 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

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

Due 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 effects as has been showed by numerical models (e.g. Criscuoli & Rast 2009) and observations (e.g. Viticchié et al. 2010). We therefore want 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 on G-band images derived from 3D MHD simulations. The paper is organized as follows: in Sec. 2 we describe the simulations and their analysis; in Sec. 3 we present our results and in Sec. 4 we draw our conclusions.

2. MHD simulations and data analysis

We employed nine snapshots from a 3D MHD simulation covering an area of 6x6 Mm$^2$ of the solar photosphere obtained with the Copenhagen-Stagger code (Nordlund & Galsgaard [1995]), characterized by having 2hG average magnetic flux and spatial sampling of $\approx 0.03^\prime$/pixel in the horizontal direction (see Fabiani et al. [2010] and Fabiani et al. [2013] for a detailed description). Since properties of magnetic features are known to vary on the magnetic flux of their environment (Criscuoli [2013] and references therein), we also considered snapshots having 0.5 and 1 hG average magnetic flux. 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 of being between 6 and 11 minutes apart; this sampling ensured that the snapshots were independent from 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]).

Intensity images were then obtained by multiplying the spectra by a Lorentian-shape filter profile of Full Width at Half Maximum equal to 1 nm and centered at 430.5 nm. Note that we found that variations of up to 40% in the width of the filter do not produce significant variations of the results presented below. We also synthesized the intensity in the continuum at 630 nm.

Bright features were identified on each snapshot by considering all those 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 $IC = M + \alpha \ast \sigma$, where $M$ and $\sigma$ are the median and standard deviation of the contrast, respectively, within the snapshot and $\alpha$ is a free parameter that we let vary between 0.5 and 1.5. Each feature was then labeled with the IDL 'labelregion' routine. The number of features identified in this way in original data varied between 730 to 800, depending on the $\alpha$ 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 $\tau_{500} = 0.1$ (B0, 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 B0 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 B0 maps are good representations of results obtained from inversions.

In order to investigate the dependence of the distributions on spatial resolution, we convolved the intensity images, as well as B0 maps, with Point Spread Functions (PSFs, hereafter) of different shapes. Following Wedemeyer-Böhm (2008), we modeled the PSFs as the convolution between an Airy function, which is the PSF of 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, i.e., 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 will 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 Full Width at Half Maximum is 0.6° and whose wings 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. In order to investigate the effects due only to the spatial resolution, we kept the free parameters of the Voigt function equal to those derived for the 50cm PSFs. We also tested varying the wing amplitudes of the PSFs; obtained 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 B0 maps by shifting these data with respect to one another.

3. Results

Comparing G-band contrast and B0 maps we find, 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 find 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 in the left image of Fig.1. The solid blue lines also marked in the same panel represent pixels for which 1 hG < 1 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 associated

![Fig. 2. Statistical distribution of the average magnetic field strength in G-band bright points](image-url)
horizontal field only. On degraded images the area occupied by
positive-contrast hG pixels is larger (middle-left panel).

Middle-right and right panels show examples of contours of
features identified assuming $\alpha=1.5$ on original and spatially
degraded data, super imposed on B0 maps, and B0 maps de-
graded with PSF$_{50\text{cm, 630}}$, respectively. Clearly, two types of
features are identified on both types of data: bright granules (for
which the field strength is $< 1$ hG) and kG features. Only a small
amount of features identified on non-degraded data have hG field
strength (for instance, on the middle right image only one of such
features is identified); these usually encompass bright granules
adjacent to small-size magnetic patches. On spatially-degraded
data, the number of identified features having hG field strength
is larger. These in part correspond to bright granules close to
features that, on the original images, had kG field, and in part
correspond to small-size features that had associated kG field in
the original data, and whose average field decreased as an effect
of the spatial degradation.

Magnetic field distributions of the identified features are ill-
ustrated in Fig. 2. The black symbols represent the distribu-
tion of features identified on the original G-band intensity im-
ages. We notice a peak at $\approx 1.5$ kG, with values up to 2 kG;
the small tail at hG field strengths confirms that features identi-
fied on non-degraded images whose average field strength is of
some hG are statistically irrelevant. The blue symbols denote the
distribution of features identified on G-band images degraded
with PSF$_{50\text{cm, 430}}$ and the corresponding B0 degraded with
PSF$_{50\text{cm, 06}}$; in this case the distribution covers a wider range
of average field strength values, and the peak occurs at $\approx 7$hG.
The red symbols show the distribution of features identified on
the G-band snapshots degraded with ‘PSF$_{50\text{cm, 430}}$', but B0
non-degraded. This latter case would simulate results obtained
from a ‘perfect’ spectro-polarimetric inversion performed with
filling-factor as free parameter, capable of returning 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 the one obtained from the original snapshots,
as the peak occurs at $\approx 1.5$kG. In all distributions, the highest
peak occurs at B0$=1$ hG; these correspond to bright granules or
to granules adjacent to magnetic features identified as a single
feature, as discussed above.

We then compared distributions obtained from data con-
volved with the different PSFs described in Sec. 2. Left panel
in Fig. 3 shows results obtained convolving both G-band images
and B0. We notice that the peaks of the distributions shift to-
ward lower values, being $\approx 9$hG in the case of a telescope of
70 cm diameter and $\approx 7$hG in the case of a 50 cm. 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 B0 and G-
band images degraded with PSF$_{50\text{cm, 06}}$ and PSF$_{50\text{cm, 430}}$,
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 qualita-
tively the same trends (not shown), with the distributions result-
ning from $\alpha=0.5$ being rather flat. Note that we found that in-
creasing 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, rescal-
ing 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 the blue symbols in Fig. 2),
and the distribution obtained from 0.1" pixel scale data (repre-
sented with the black symbols in Fig. 3).

Finally, we investigated the effects of misalignment be-
tween the G-band images and B0. We found that with the increase
of the amount of misalignment the peaks of the distributions shift
toward lower values and their widths increase. Nevertheless,
shapes of distributions are significantly altered only for mis-
alignments 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 right
panel of Fig. 3 represents an intermediate case, as it shows
results obtained when only G-band images are degraded with
PSF$_{50\text{cm, 430}}$. Note that the plot shows results obtained on data
whose pixel scale is 0.1". Here, it is also worth to note that even
for the intermediate case in which only G-band images are de-
graded, a sub-pixel shift leads to a non-negligible modification
of the shapes of distributions.
Our results therefore suggest that the different shapes of distributions presented in the literature mostly result from the different identification methods employed to select features and the quality of the data analyzed. In particular, we speculate that the broad distribution obtained by Beck et al. (2007) could be the result of residual temporal and spatial misalignment between the data. Results by Utz et al. (2013), obtained employing spectropolarimetric inversions with unit filling factor, are most likely affected by image degradation. In particular, it is likely that the kG component they found results from larger magnetic structures, which are less affected by spatial degradation, on which the inversion could retrieve reliable estimates of the field intensity. The population peaking at 7 hG that they found, instead, results from smaller-size 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 turns to be of 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) like the ones that we employed. It is also worth to 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 unit filling factor is more likely to return 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 do not find a clear indication of two populations of bright features in the kG range. In fact, the distribution obtained on 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 unit filling factor (see also Orozco Suárez et al. 2007).

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