Temporal variations in solar magnetic bright points intensity and plasma parameters

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Abstract. Magnetic bright points are one of the finest magnetic structures observed in the solar atmosphere. They possibly represent single flux tubes in quiet Sun regions. Their formation is described by the convective collapse model, while the decay phase of these structures is not well characterized yet. We attempt to follow the evolution of a few selected examples of MBPs and to study their changes in brightness and also the variations of plasma parameters during their lifetime. We use data from the Hinode satellite and the Sunrise mission. The G-band observations taken with a cadence of 30 seconds by the Hinode Solar Optical Telescope (SOT) show very fast changes of the maximum intensity of these structures. The complementary spectropolarimetric data, which are used to estimate the plasma parameters, were taken with a cadence of approximately two minutes. The variations of plasma parameters cannot be matched one to one to the changes in intensity due to the different temporal resolution. However, the slow changes of intensity with large amplitude are matched with variations of magnetic field strength and line-of-sight (LOS) velocity. The Sunrise/IMaX data have a temporal resolution of 32 seconds and show fast variations in the line wing intensity. These variations are associated with changes in the magnetic field strength and LOS velocity.

1. Introduction
Magnetic bright points (MBPs) are structures with field strengths exceeding the equipartition field strength in the photosphere. The formation mechanism called convective collapse (superadiabatic effect) was suggested first by Parker [1] and further studied by e.g. Spruit [2]. According to theory, the intensification of magnetic field takes place simultaneously with fast downflows. This behaviour was observationally confirmed during the formation of flux tubes with strong magnetic fields by e.g. Bellot Rubio [3] and Nagata [4].

The decay phase of MBPs is not yet understood well. Bellot Rubio [3] found that the convective collapse does not lead to a stable kilogauss magnetic element, but the magnetic field decreases again below equipartition field strength in the late phase when upflows prevail in the flux tube. This is in agreement with the study by Takeuchi [5] who found that flux tubes resulting from the collapse of weak magnetic fields in large structures are destroyed by upward-moving shocks. However, there are some discrepancies between the maximum field strengths found in observations by Bellot Rubio (600 G) and reached in simulations by Takeuchi (over 1000 G).
Figure 1. Maps of G-band intensities and plasma parameters corresponding to the MBP observed by the Hinode/SOT. From top to bottom: G-band filtergram images, SP continuum intensity, temperature, magnetic field strength, and line-of-sight velocity. The maps of plasma parameters are displayed at $\log(\tau) = -1$. Seconds shown in the G-band filtergram images correspond to the time between the first detection of the MBP and the given frame. The first two and last two columns show the situation before and after the MBP could be identified. The white (black) cross-hair mark the position of maximum G-band intensity of the MBP.

We follow the evolution of several MPBs identified in the datasets obtained by the Hinode satellite and the balloon-borne Sunrise observatory. The first results presented here show how the intensity changes correspond to the changes of plasma parameters during the lifetime of the studied magnetic structures.

2. Observations and data analysis

We use data from the Hinode Solar Optical Telescope [6, 7]. The data were taken on January 20, 2007 at 8 UT. From the broad-band filtergram imager we have G-band images taken with a cadence of 30 seconds and a pixel sampling of 0.11″. The diffraction-limited spatial resolution due to the 0.5 m primary telescope aperture is 0.22″. From the Hinode spectropolarimeter (SP) we have full Stokes profiles of the Fe I lines around 630.2 nm. Scans of a narrow solar surface region, comprising 25 slit positions, were taken with a cadence of approximately two minutes. The resulting spatial resolution of the SP data is 0.32″. The data were calibrated with standard routines available within the Hinode SolarSoft package.

We also use data taken by the Sunrise/IMaX instrument [8] on June 9, 2009 at 2 UT. IMaX is an imaging spectropolarimeter based on Fabry-Perot etalon. It scanned all Stokes profiles of the Fe I line at 525.02 nm at four wavelength positions within the line and one in the continuum. The pixel sampling of this instrument corresponds to 0.055″, which results into diffraction limited spatial resolution of 0.16″. The IMaX data have been corrected for instrumental effects by performing dark-current subtraction, flat-field correction, and cross-talk removal.

The MBPs were identified manually in the Hinode G-band images and automatically in the Sunrise/IMaX data using the intensities in the blue wing of the scanned line (at 524.98 nm) and the code developed by Utz [9]. The plasma parameters were computed from the observed Stokes
Figure 2. Temporal evolution of maximum G-band intensity (black + symbols) of the MBP shown in Fig. 1. The values of magnetic field strength (blue + symbols), temperature (green + symbols), and LOS velocity (red + symbols) are taken at the same position as the maximum G-band intensity (marked in Fig. 1) at log(\(\tau\)) = -1. The Δ symbols correspond to the plasma parameters at the position of the strongest magnetic field strength in the MBP region. Spline functions are used to connect the + and Δ symbols. The dashed lines mark the lifetime of the MBP.

profiles using the inversion code SIR [10]. To analyze the Hinode SP data, we assumed plasma parameters changing linearly with height except for temperature, which has a more complex stratification. In the case of the Sunrise/IMaX data, we used plasma parameters constant with height (except for temperature), as the number of wavelength points does not allow a more complex atmospheric model.

3. Results
In Fig. 1, we show one of the MBPs manually identified in the Hinode dataset. In this case, the MBP lasted for approximately 14 minutes as it was detected on 28 consecutive G-band filtergrams. The first two columns in Fig. 1 show the G-band intensity images and maps based on SP data before the formation of the MBP, while the last two columns illustrate the situation after its disappearance. The maximum brightness of the MBP was reached 5 minutes after its formation (270 sec), then it became fainter (570 sec), followed by another brightness peak around 690 sec. As can be seen in the second row of Fig. 1, the MBP cannot be identified in the continuum map obtained from the SP scans. This is probably due to insufficient spatial resolution and lower contrast of MBPs in continuum intensities. The MBP is however visible as a bright structure in the temperature maps at log(\(\tau\)) = -1, which are proportional to the intensity of the line wings. In the magnetic field strength maps (fourth row), an intensification of the magnetic field can be clearly seen around the MBP during the initial phase. Also the downflow velocity (LOS velocity maps are shown in the fifth row) is increasing during this phase. This is in agreement with previous studies [3, 4] and the convective collapse scenario.

In Fig. 2, we show the evolution of MBP maximum G-band intensity and the plasma
Figure 3. Analogous to Fig. 1 but showing the MBP automatically identified in the IMaX data. In the top row, the line-wing intensities are shown. The white (black) cross-hair mark the position of barycentre of the MBP.

parameters. As the pixel with the maximum G-band intensity is not necessarily co-spatial with the pixel where the maximum field strength can be found, we display the evolution of plasma parameters for both of these pixels. It is clear that the G-band intensity is rapidly changing and that the temporal resolution of SP measurements is insufficient to follow these fast fluctuations. However, we selected this MBP as there is a second peak of G-band intensity, which can be temporarily resolved also in the SP data. It is clear that each of these MBP intensity brightenings is accompanied by an intensification of the magnetic field strength and a higher downflow velocity.

In Fig. 4, we show the evolution of plasma parameters and intensities of the MBP shown in Fig. 3. Again one can observe fast changes of intensity, now matching with fast changes of plasma parameters. In most cases, local maximum in intensity is accompanied by local maximum of magnetic field strength and LOS velocity. Contrary to the results based on Hinode SP, the maximum values of magnetic field strength and LOS velocity at the MBP barycentre (Δ symbols and dashed lines in Fig. 4) are not co-temporal with the maximum of the line-wing intensity. The peak value of intensity corresponds only to the peak value of LOS velocity in the $5 \times 5$ pixels.
Figure 4. Analogous to Fig. 2 but showing the temporal evolution of the maximum line-wing intensity (black + symbols) of the MBP shown in Fig. 3. The + symbols represent averaged values from 5 × 5 pixels region around the barycentre of the MBP. The Δ symbols are the values of plasma parameters at the barycentre.

4. Discussion
The main problem arising in our analysis comes from the uncertainties caused by the inversion. We have satisfactory spectral resolution from the Hinode SP, but these data have still insufficient spatial resolution. As we used only an one-component atmospheric model with a fixed amount of stray-light, it results into underestimation of magnetic field strength, i.e., a maximum of only 400 G in the presented MBP. Also, the supposed atmospheric model is not complex enough to fit the highly asymmetric Stokes V profiles observed in the MBPs. To fit such profiles, it is necessary to use complex atmospheric models like Bellot Rubio [3] did.

Another problem is the temporal resolution of the Hinode SP measurements. We have to select a long lasting MBP with multiple brightenings to be able to compare it to the evolution of plasma parameters. In most cases, the MBPs have shorter lifetimes (comparable to the example selected from the Sunrise/IMaX dataset) and better temporal resolution is necessary.

The modest spectral resolution of the Sunrise/IMaX data and the fact that only one line is scanned does not allow for complex atmospheric models even for these data. However, the spatial resolution is high enough to provide more reliable values of magnetic field strength than those obtained from the simplified inversions of Hinode SP data.

5. Conclusions
In agreement with [3, 4], we confirmed observationally the convective collapse as the mechanism responsible for formation of MBPs. In the presented examples, the magnetic field strength does not reach the values predicted by the theory of the convective collapse, but it might be due to an oversimplified inversion setup. However, the resulting flux tube is not stable as the theory
claims and dissolves rapidly, i.e., the convective collapse of the flux tube can be possibly stopped by some mechanism even before a stable kilogauss field concentration is reached.

In the presented MBP observed by Hinode, there is a relation between G-band intensity and magnetic field strength, i.e., the brighter the structure is, the stronger is the magnetic field. This does not seem to be true if we compare different MBPs. Some of the other MBPs identified in the Hinode data have higher G-band intensities than the presented one, but lower magnetic field strengths.

The Sunrise/IMaX data cannot be used to derive more complex atmospheric models as there is not enough information contained in the four measured wavelength points within the spectral line. The Hinode SP data can provide us with more accurate atmospheric models, if specially designed inversion codes are used, e.g. following the analysis of Bellot Rubio [3]. However, the insufficient spatial resolution must be kept in mind.

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References
[1] Parker E N 1978 ApJ 221 368–377
[2] Spruit H C 1979 Sol. Phys. 61 363–378
[3] Bellot Rubio L R, Rodríguez Hidalgo I, Collados M, Khomenko E and Ruiz Cobo B 2001 ApJ 560 1010–1019
[4] Nagata S e a 2008 ApJ 677 L145–L147
[5] Takeuchi A 1999 ApJ 522 518–523
[6] Kosugi T e a 2007 Sol. Phys. 243 3–17
[7] Tsuneta S e a 2008 Sol. Phys. 249 167–196 (Preprint arXiv:0711.1715)
[8] Barthol P e a 2011 Sol. Phys. 268 1–34 (Preprint 1009.2689)
[9] Utz D, Hanslmeier A, Möstl C, Muller R, Veronig A and Muthsam H 2009 A&A 498 289–293
[10] Ruiz Cobo B and del Toro Iniesta J C 1992 ApJ 398 375–385