Spectropolarimetric Signatures of Convective Collapse

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Abstract. We present spectropolarimetric signatures of convective collapse and destruction of magnetic flux by an upward moving front in the quiet Sun. The observational data consist of a time series of the full Stokes vector of two infrared spectral lines. The amplitude of Stokes $V$ increases while the profiles are redshifted. It then decreases during a much shorter phase characterized by large blueshifts, due to the sudden appearance of a new, strongly displaced $V$ signal of the same polarity. An inversion code adopting the thin flux tube approximation has been applied to a subset of data (about 16 min) in order to derive the thermal, magnetic and dynamic structure of the atmosphere. The magnetic field strength increases moderately from 400 G to 600 G at $z = 0$ km, associated to strong downflows at the same height. After $\sim 13$ minutes, the Stokes $V$ profiles undergoes a strong blueshift and a decrease in amplitude, which is interpreted as the appearance of an upward propagating front, possibly caused by the bouncing of the material falling down inside the tube. The front moves with a velocity of 2.3 km s$^{-1}$ and has a downflow-to-upflow velocity difference of $\sim 6$ km s$^{-1}$. It strongly weakens the field strength and may be responsible for the destruction of the magnetic feature.

1. Introduction

Since the 1960s, a remarkable development in the theory and numerical modeling of the emergence of magnetic flux in the photosphere of the Sun and its amplification up to kG field strengths has taken place (see the review by Stenflo 1994). The kinematic mechanism of flux expulsion (see Parker 1963) explains how magnetic fields frozen in the photospheric plasma are swept into the boundaries of granular and supergranular cells by the horizontal motions. Only magnetic field up to equipartition values ($\sim 500$ G) can be reached by this process. The superadiabatic effect described by Parker (1978) drives the further intensification of magnetic field. According to Spruit & Zweibel (1978), flux tubes with field strengths below $\sim 1300$ G are convectively unstable. If the instability sets as a downflow, the superadiabatic effect amplifies the field. Spruit (1979) referred to the whole process of formation of stable magnetic structures with field strengths up to 1–2 kG as convective collapse. Numerical solutions of the MHD equations
for this process in the thin flux tube approximation have been obtained (see references in Steiner 1999). Time-dependent, 2D numerical solutions of the full set of MHD equations have been recently carried out by Grossmann-Doerth et al. (1998), and Gadun (2000), among others. The development of upward-propagating shocks within the tube, which destroys the flux tubes, has been found by Grossmann-Doerth et al. (1998) and Takeuchi (1999). These shocks originate by the rebouncing of the downflowing gas in the deeper layers when the internal downflows become very strong. They may lead to the dispersal of the magnetic flux concentration. The numerical simulations of Grossmann-Doerth et al. indicate that this process might happen for initial magnetic fields of the order of 400 G.

While theory has reached a significant degree of sophistication, there is no observational confirmation of the convective collapse and destruction of magnetic elements by upward propagating shock fronts. The reason could be the very short time intervals (of the order of minutes) in which these processes occur. Indirect evidence of convective collapse has been found by Lin & Rimmle (1999) and Sigwarth, Balasubramaniam, & Knölker (1999). Definitive conclusions could be drawn if precise measurements of the field strength and the line-of-sight velocity within the flux concentrations were obtained.

High temporal and spatial resolution spectropolarimetric data are required in order to identify observationally the processes of convective collapse and subsequent destruction of magnetic structures, provided the short time scales involved and the necessity of isolating individual magnetic elements.

In this work, we present the results of the inversion of a temporal series of the four Stokes parameters of two infrared FeI lines at 1.56 μm emerging from a quiet Sun region which shows network points in the CaII K band. Preliminary analyses of these data have been published by Khomenko et al. (1999).

2. Observations and data reduction

The observations were obtained at the German VTT of the Observatorio del Teide (Tenerife) in June 29, 1999, using the échelle spectrograph, the Tenerife Infrared Polarimeter (TIP), and the IAC/KIS Correlation Tracker. A description of these instruments can be found in Martínez Pillet et al. (1999), and Ballesteros et al. (1996), respectively. Spectra of the full Stokes vector of the FeI 15648.5 Å (g_{eff}=3) and 15652.9 Å (g_{eff}=1.53) were taken for about 1 hour, through a slit of 0″5×30″3 placed on a quiet region at the disk center. The observed wavelength range was 7.1 Å, the spectral sampling 29.1 mÅ, and the temporal sampling, 5.6 s.

After applying a standard reduction procedure to the data, they were carefully corrected for instrumental polarization, by using frames taken through calibration optics. Residual crosstalk from Stokes I to Q, U, and V were also removed, by imposing no polarization in the continuum. The resulting S/N ratio in I was about 500 in units of the continuum intensity. In order to improve the insufficient S/N ratio in Stokes V, 5 successive spectra corresponding to 2 adjacent spatial points were averaged, thus leading to an effective temporal and spatial sampling of 28 s and 0″8, respectively. No linear polarization signal was present above the noise level.
Figure 1. Left panel: temporal sequence of Stokes I (top) and unsigned V (bottom), integrated over the whole wavelength range. The vertical direction corresponds to spatial points along the slit; the horizontal direction is time. The circular polarization image has been saturated to emphasize the weak fields. The white rectangles enclose the region and time interval of interest; the arrow marks the spatial point analyzed. Right panel: temporal evolution of the Stokes I and V profiles corresponding to this spatial point. Here, time goes from bottom to top, and the horizontal direction is wavelength, centered around the FeI 15648 Å line.

The left panel of Fig. 1 shows a fragment of the temporal evolution of Stokes I and unsigned V, integrated over the wavelength range. The white box indicates the time interval of interest. In this work, we have analyzed the spectra corresponding to the spatial point marked by the arrow, whose temporal evolution is shown in the right panel. There is no significant magnetic signal at the beginning of the series; later, it notably increases, associated with a strong redshift either in I and V; in the last fourth of the time interval, a sudden blueshift appears and the circular polarization signal weakens very quickly.

In order to see this behavior more clearly, the spectral profiles of Stokes I and V are displayed versus time (in the vertical direction; time step= 28 s) in the left panel of Fig. 2. The dashed lines connect the intensity minima and the V zero-crossing wavelengths. The position of the Stokes I minimum shows the well known 5 min oscillation for the most part of the sequence. According to the behavior of the circular polarization spectra, the whole time interval can be divided into three different phases: the first one, up to ~9 min, is characterized by moderate redshifts associated to a magnetic field amplification; in the second one, lasting for about 3 min (spectra plotted in dotted line), strong redshifts are apparent, with a notable increase of the magnetic signal; the spectra plotted in thick line constitute the last phase, of ~2 min, and show a sudden strong blueshift together with the practical disappearance of the V signal. Several pa-
Figure 2. Left panel: temporal sequence (time goes from bottom to top) of Stokes I and V spectra, separated by a time step of 28 s. The dashed lines connect the intensity minima and V zero-crossing wavelengths. The three different phases mentioned in the text are distinguished with thin solid line, dotted line, and thick line, respectively. Some more spectra in thin line are also plotted at the end of the series. Right panel: several parameters (see labels in the plots) characterizing the I and V profiles are plotted versus time. The three phases are separated by vertical dotted lines.

Parameters describing the behavior of the profiles have been evaluated and are plotted versus time in the right panel of Fig. 2. The vertical dotted lines divide the temporal sequence into the three phases mentioned above. The most significant feature in the upper plot is the strong redshift shown by the V zero-crossing shift during the second phase, followed by a sharp reversal to blueshift in the third one. The same behavior, but much less steep, is shown by the shifts of intensity minima. The mean amplitude of the circular polarization signal and the intensity of the line core, normalized to the continuum intensity, are displayed in the middle plot. Since the V signal is extremely weak in the first 3 min, we are not very confident of the results derived from these spectra, which will not be analyzed later. After a sharp increase of the V mean amplitude, it keeps almost constant during the first and second phases, while the line strengthens. In the third phase, the magnetic signal decreases strongly, coupled with a weakening
of the line. Asymmetries of the $V$ profiles, either in amplitude and area, are plotted in the bottom panel.

All these parameters are related with velocities, field strength and temperature, and velocity and magnetic field gradients. In order to infer the actual evolution of the field and the thermodynamical variables, an inversion technique has been applied to the data. The results are shown in the next section.

3. Inversion of data

Precise values of the field strength and line-of-sight velocity are needed to undoubtedly identify the elusive processes of magnetic flux amplification and destruction. Other thermodynamical parameters, as temperature, can also show the signature of such processes. An adequate model for the structure of the magnetic elements is required to guarantee the reliability of the inferred parameters.

The inversion code developed by Bellot Rubio, Ruiz Cobo & Collados (2000a), which retrieves the relevant physical quantities of the magnetic elements in the thin flux tube approximation, has been applied to the observed Stokes $I$ and $V$ profiles. Flux tubes are axisymmetric structures made up of two different atmospheres, one for the magnetized interior, and another one for the adjacent non-magnetized environment. Spreading out of flux tubes with height is required by magnetic flux conservation. The free parameters of the model are the stratification with height of temperature and line-of-sight velocity in the two atmospheres, the magnetic field strength at the base of the tube, the gas pressure of the nonmagnetic surroundings at that height, the same height-independent macroturbulence, and the percentage of stray light. All the parameters in the internal and external atmospheres are assumed horizontally constant. The stratification of magnetic field is determined from hydrostatic equilibrium. An example of application can be found in Bellot Rubio et al. (2000b).

In this work, flux tube model atmospheres have been determined in a spatial grid from $z = -100$ to $z = 250$ km. We will show the atmospheric parameters at two representative heights in the atmosphere: $z = 0$ (where the optical depth of the continuum at 5000 Å is unity for the quiet Sun) and $z = 100$ km, because the infrared lines observed provide reliable values at those layers. The atomic parameters have been taken from Bellot Rubio, Ruiz Cobo, & Collados (2000c).

Most of the observed spectra do not present abnormal features, but the profiles of the third phase show anomalous shapes thus being rather difficult to fit. They seem to be composed of two different signals of the same polarity, one of them strongly blueshifted. A smooth velocity run has shown to be unable to reproduce such profiles. A sharp step in the internal velocity stratification, separating downflows in the upper layers and upflows in the lower layers (as suggested by the numerical simulations by Grossman-Doerth et al. 1998) seem to be adequate to fit the anomalous profiles: therefore, such a velocity run with depth has been assumed, allowing as free parameters the position in the atmosphere ($z_{\text{disc}}$) and the amplitude ($\Delta v$) of the velocity discontinuity in the inversion of the spectra corresponding to the third phase.

An example is given in Fig. 3, where the internal velocities derived from the inversion of the profiles at $t = 13.07$ min are plotted in the upper panel. The
Figure 3. Top: example of the internal velocity stratification for one anomalous spectrum of the third phase. The jump separates downflows in the upper layers from upflows in the lower ones. Bottom: temporal evolution of the position and amplitude of the discontinuity, with linear and parabolic fits (dashed lines).

The evolution of $Z_{\text{disc}}$ and $\Delta v$ is plotted in the two lower panels. A linear increase with time of $Z_{\text{disc}}$ can be seen, with a propagation velocity of 2.3 km s$^{-1}$. $\Delta v$ varies smoothly from 7 to 4 km s$^{-1}$ as the discontinuity moves upwards. These results are compatible with an upward propagating front which travels about 250 km in only two minutes. Although we do not claim that this solution is unique, let us remark that it is able to provide a reasonably good fit to the data.

In Fig. 4, the internal and external velocities, the internal temperature, and the field strength at $z = 0$ km (solid lines) and $z = 100$ km (dashed lines) determined from the inversion are plotted versus time. During the first phase, motions in the magnetized atmosphere are downflows with approximately constant velocities of 4 km s$^{-1}$ at $z = 0$ km, coinciding with upflows of $\sim 1$ km s$^{-1}$ in the non-magnetic surroundings; the temperature varies slightly, and the field strength at $z = 0$ km increases slowly from values of $\sim 400$ G. The second phase is characterized by enhanced internal downflows, the appearance of strong external downflows of up to 6 km s$^{-1}$, and cooling of the magnetic atmosphere by about 500 K in the deeper layers.

In the third phase, strong internal upflows of up to 6 km s$^{-1}$ propagates from bottom to top (note the temporal lag of the internal velocities at $z = 100$ km as compared to those at $z = 0$ km), the magnetic field strength decreases
Figure 4. Results of the inversion: from left to right and top to bottom, temporal evolution of the internal and external velocities, internal temperature, and field strength at two atmospheric heights. The vertical dotted lines separate the three phases of the process.

significantly from \(\sim 600\) to 200 G at \(z = 0\) km, and there is a huge temperature increase of 1500 K within the tube. The decrease of the field strength and the reversal of the external downflows into upflows occur simultaneously, about 0.5-1 min (a small, but non negligible time lag) after the appearance of the strong upflows in the magnetic interior.

4. Conclusions

Our results, derived from the inversion of spectropolarimetric data, strongly suggest that we have been witnesses of a process of magnetic flux intensification by the mechanism of convective collapse. The most characteristic signature of convective collapse is extremely large redshifts coupled with an amplification of the magnetic field. This is what we have observed in the analyzed temporal sequence. Nevertheless, it seems that further amplification to kG fields has been prevented by the development of an upward front within the magnetic structure, characterized by a downflow-to-upflow difference of 6 km s\(^{-1}\), and propagating at 2.3 km s\(^{-1}\) towards higher layers. The observed behavior is in general agreement with theoretical expectations of convective collapse, as well
as with the development of shocks within the tubes, which may lead to the complete destruction of the magnetic structure.

Several sets of similar data have been obtained during the observing campaigns of 1999 and 2000. After a first inspection, no obvious example of field amplification up to kG strengths has been found.

References

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