FORMATION AND DESTRUCTION OF A WEAK MAGNETIC FEATURE IN THE SOLAR PHOTOSPHERE

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ABSTRACT

A time series of intensity and circular polarisation profiles obtained with TIP (Tenerife Infrared Polarimeter) in a quiet region at solar disk centre is analysed. The evolution of the profiles reveals a first amplification of the magnetic field, a further amplification of the field coinciding with an increasing downdraft as indicated by the red shift of the $V$-zero crossing wavelength (convective collapse), and a fast decrease of the magnetic field strength (related to the presence of distinct upflows).

Key words: Solar photosphere; magnetic fields; quiet sun.

1. INTRODUCTION

It is widely believed that photospheric solar magnetic fields outside sunspots appear in the form of spatially unresolved magnetic elements. Processes that lead to the concentration of weak magnetic elements into flux tubes of 1-2 kG strength in the lower photosphere have been well investigated theoretically. In the solar atmosphere the magnetic field is “frozen” in the photospheric plasma. As there are strong convective flows, magnetic field is swept by them to the boundaries of granular and supergranular cells. However, this mechanism alone is unable to produce magnetic field strengths larger than about 500 G (Parker, 1978). Further intensification is driven by thermal effects. The magnetic field inside a forming flux tube suppresses convective motions and therefore convective heat transport. Gas inside the tube becomes cooler than the surroundings and accelerates downwards due to its larger density. Horizontal mechanical balance is maintained by an increase of the magnetic field in the collapsing region. According to Steiner (1999) the maximum value of the field strength in this case may reach 1800 G at unity optical depth of the non-magnetised atmosphere. This process, known as convective collapse, has been studied with the help of MHD equations by, among others, Webb & Roberts (1978), Spruit & Zweibel (1979), Unno & Ando (1979), and Takeuchi (1999), who came to the conclusion that the described convective instability takes place if the ratio between the gas and magnetic pressure exceeds a value of about 2. The last stages of this instability were computed by Spruit (1979).

Stokes profiles with well-defined shapes must appear in regions of formation of new magnetic elements. In particular, a weak magnetic field at the beginning of the process produces a small signal in Stokes $V$. Then, enhanced downflows at the region of new flux tube formation give rise to an increasing asymmetry of Stokes $V$, whose red lobe becomes very extended. This is accompanied by a redshift of the corresponding Stokes profiles. At the last stage, the magnetic field grows rapidly, as does the amplitude of the $V$ profile and the splitting between the lobes (see Steiner, 1999).

Since magnetic flux tubes have diameters smaller than the resolution capabilities of modern telescopes, it is difficult to test theoretical predictions of convective collapse. Different attempts were made recently. Lin (1995) carried out Zeeman splitting measurements of intranetwork magnetic fields and concluded that solar magnetic fields outside sunspots are composed of a strong and a weak component of different origin. The weak component might be generated by turbulent velocity fields. Solanki et al. (1996) found indirect evidence that the concentration of solar magnetic field may be caused by convective collapse. Lin & Rimmeele (1999) used high-precision infrared polarimetric data together with high-resolution imaging and concluded that the evolution of weak magnetic features is mainly caused by the evolution of the granular velocity field. They found one example in their observations where a strong kilogauss magnetic feature appeared simultaneously with the formation of an intergranular lane. This process might be interpreted as convective collapse.

To study the evolution of weak magnetic elements, observations with high spatial resolution and large sensitivity to magnetic fields are required. In this case, polarimetric measurements in the infrared are most appropriate. For weak fields, the amplitude of polarised light is proportional to Zeeman splitting. As Zeeman splitting depends on wavelength as $\lambda^2$, for infrared observations it is possible to detect smaller magnetic signals, as the medium-strong field regime is reached at lower magnetic field strength values. In the following investigation we use observations from...

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Figure 1. Sequence of the Fe i 15648 Å I and V profiles analysed in this work. The temporal direction goes from bottom to top. The time interval between every two successive profiles is 28 seconds. The dashed lines correspond to the evolution of the line minimum and Stokes V zero-crossing wavelength. Wavelengths are referred to the average wavelength of the minimum of the intensity profiles.

the Tenerife Infrared Polarimeter (TIP). The main goal of our analysis is to detect the signatures of convective collapse.

2. OBSERVATIONS AND DATA REDUCTION

The observations analysed here were made with TIP at the German VTT in Teide Observatory on 1999 June 29. Details about the telescope and TIP can be found in Sotau (1987) and Martinez Pillet et al. (1999). The spectrograph slit was placed on a quiet region at disk center, far away from any activity center, and included two CaII K bright points. The width of the slit was 100 µm (0.5 arcsec × 36.4 mÅ), and its length covered 30.3 arcsec in the spatial direction. TIP was used to measure the four Stokes parameters of the Fe i lines at 15648.5 (g_{eff} = 3) and 15652.9 Å (g_{eff} = 1.53) along the slit. The observed wavelength range spanned 7.1 Å with a spectral sampling of 29.1 mÅ.

The observations consist of a time series lasting about one hour. Four alternate linear combinations of the Stokes parameters were produced at a frequency of 2 Hz. The actual integration time for each of these images was 50 ms. All images corresponding to the same linear combination were added in real time over 10 modulation cycles and saved to disk at a mean cadence of 3.6 s. During the observing interval, the seeing conditions were excellent, with an image blurring of ∼0.5 arcsec. To stabilise the image, the IAC/KIS correlation tracker (Ballesteros et al. 1996) was used. Possibly, the spatial resolution of these observations is the highest ever obtained with TIP. The measurements were corrected for flatfield and dark current following standard procedures and treating separately each step of the modulation scheme. The noise level in Stokes Q, U, and V is of the order of 10^{-3} in units of the continuum intensity.

The polarimeter was calibrated by means of known polarisation optics located at an appropriate position in the optical beam. This calibration optics allows to remove most of the instrumental crosstalk between the Stokes parameters which, in the infrared, is less severe than in the visible (Collados 1999). Residual instrumental polarisation I → Q, U, V due to the telescope coelostat was also taken into account. The correction was derived from the continuum level of Stokes Q, U, and V. Furthermore, we note that the spatial points considered in this work do not have Q
and $U$ signal above the noise level.

3. DATA ANALYSIS AND RESULTS

For the present study, we have selected a region from our observations which is interesting in the sense that a magnetic field signal appears, evolves rapidly, and finally disappears. The whole process of magnification and disappearance of the magnetic field takes place in about 10 minutes.

To have a better signal-to-noise ratio in the spectral profiles, we averaged two adjacent pixels in the spatial direction and five successive pixels in the temporal direction, leading to a temporal resolution of 28 seconds. The sequence of $I$ and $V$ profiles of the Fe 15648 Å line is plotted in Fig. 1. The scale of the profiles has been arbitrarily modified to better show the temporal evolution. Time goes from bottom to top. The dashed lines represent the position of the intensity minimum (left) and Stokes $V$ zero-crossing wavelength (right) in each one of the selected profiles.

The zero wavelength position has been taken to be the average position of the intensity minima.

Several characteristics of Fig. 1 deserve further discussion. As can be seen, the amplitude of the polarisation signal is very small at the beginning, increasing more or less monotonically, reaching the maximum with the highest redshift of the Stokes $V$ zero-crossing wavelength. Simultaneously, the position of the intensity minimum follows a similar temporal evolution. The intensity profiles become markedly asymmetric, coinciding with the highest redshifts. The turning from red to blueshift in Stokes $V$ occurs very rapidly, in a time interval of a few minutes. These profiles have very special shapes, as will be shown below. From there on, the Stokes $V$ zero-crossing wavelength and intensity minimum approach the zero position, while the amplitude of $V$ decreases rapidly.

Fig. 2 shows the profiles involved in the sharp transition from the redshift to the blueshift. Time goes in the figure from left to right and from top to bottom. The first profile is the most redshifted, with its Stokes $V$ zero-crossing wavelength at about 2.3 km/s. The blue peak is very prominent, while the red one
As a first attempt to interpret the data, we have carried out a preliminary analysis of our Stokes V spectra to estimate velocities and magnetic field strengths. For simplicity, we fit each observed V profile of the two spectral lines with two gaussians (using a procedure similar to that described by Lin, 1995). The free parameters of the fit were velocity (with respect to the average position of the intensity profiles), magnetic field strength, and V amplitude of both spectral lines. The halfwidths of the gaussians were kept fixed at 120 mÅ and 90 mÅ for the 15648 Å and 15653 Å lines, respectively. Despite the profiles are at some moments very asymmetric, the fitted curves were strictly anti-asymmetric with respect to the corresponding Stokes V zero-crossing point. For this reason, the values obtained should be regarded with caution, especially during the fast transition shown in Fig. 1.

The upper panel in Fig. 3 shows the temporal evolution of the velocity derived from the fit, \( v_V \). The behaviour of the Stokes V zero-crossing wavelength leads to very similar velocities (curve labelled \( v_{zero} \)). For comparison, the variation of the intensity minimum is also plotted (curve labelled \( v_I \)). It is apparent that, during the whole process, the V profiles are redshifted by about 1-2 km/s.

The lower plot shows the evolution of the magnetic field strength determined from the gaussian fit. There is a sudden increase at the beginning (from very small values to about 500 G) and a subsequent slow decrease, down to about 300 G. Then, the downflow velocity suffers a sudden increase (from 0.75 to nearly 3 km/s), while, at the same time, the magnetic field strength varies from 300 to 500 G. Preliminary inversions of the profiles with the help of the code developed by Bellot Rubio, Ruiz Cobo & Collados (1999) result in somewhat larger field strength values. More specifically, the magnetic field strength at \( z = 0 \) km is found to increase from \( \sim 200 \) G at the beginning of the series to values of the order of 1000 G, after which it rapidly decreases to values of some 100 G. The differences between the results obtained from the gaussian fit and the inversions are quantitative, but not qualitative.

This process may be interpreted as the onset of a thermal instability, leading to a downflow of the material inside the magnetic feature, while compressing the field to keep horizontal pressure equilibrium. At some moment, the downflowing material bounces off because of the high density existing in the lower layers, and produces an upward moving front while some material is still falling. A first estimate of the relative velocity between both fronts may be obtained from the distance between the two blue peaks shown in Fig. 1. This value is about 6 km/s. Our results suggest that an upward propagating shock wave may be produced, leading to the destruction of the magnetic feature in a very short time interval (2 minutes).

4. CONCLUSIONS

We provide observational evidence for strong flows associated with the evolution of magnetic features in the quiet Sun. Initially, the magnetic field is very small. We then observe a distinct redshift of the...
minimum of Stokes \( I \) and the Stokes \( V \) zero-crossing wavelength. Simultaneously, the magnetic field increases. This process takes place in about 8 minutes. Once the maximum field strength is reached, Stokes \( V \) becomes blueshifted, with distinct abnormal shapes. This is accompanied by a strong decrease of the magnetic field.

We interpret this as being the signature of convective collapse followed by the destruction of the magnetic element due to upward flows. Numerical simulations indicate that, under certain conditions, convective collapse does not produce stable kG flux tubes (Grossman-Doerth et al. 1998, Steiner 1999, Takeuchi 1999). Our observations seem to confirm the basic results of these simulations.

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