SMALL-SCALE MOTIONS OVER CONCENTRATED MAGNETIC
REGIONS OF THE QUIET SUN

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Abstract. We have used a 5.5 min time-sequence of spectra in the Fe I lines $\lambda5576$ (magnetically insensitive), $\lambda6301.5$ and $\lambda6302.5$ (magnetically sensitive) to study the association of concentrated magnetic regions and velocity in the quiet Sun. After the elimination of photospheric oscillations we found downflows of 100–300 m s$^{-1}$, displaced by about 2" from the peaks of the magnetic field; this velocity is comparable to downflow velocity associated with the granulation and of the same order or smaller than the oscillation amplitude. Quasi-periodic time variations of the vertical component of the magnetic field up to $\pm$ 40% were also found with a period near 250 s, close to the values found for the velocity field. Finally we report a possible association of intensity maxima at the line center with peaks of the oscillation amplitude.

1. Introduction

High-intensity magnetic fields in the quiet solar network have been reported by Sheeley (1967) and Chapman and Sheeley (1968) who found field strengths of 600 G, often cospatial with the supergranulation cell boundaries. These concentrated magnetic regions correspond to bright features from the center of Ca II K to the continuum (Frazier, 1970; Gopasyuk and Tsap, 1971; Sheeley, 1967; Beckers and Schröter, 1968). Using simultaneous observations in two spectral lines with different Landé factors, Howard and Stenflo (1972) inferred that more than 90% of the magnetic flux (excluding sunspots) occurs in the form of small, unresolved flux tubes. The field lines spread out very rapidly with height. This result was confirmed by Frazier and Stenflo (1972), while Stenflo (1973) deduced a field strength of about 2000 G and a characteristic size of 100–300 km for individual flux tubes. These magnetic flux tubes are believed to be associated to small (0".25) network elements, the filigree, imbedded in the intergranular lanes although Koutchmy and Stellmacher (1978) pointed out that the photospheric magnetic flux is not confined in the filigree area but in an area of 1–3". Simon and Zirker (1974) reported similar results for a plage region.

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An important physical question raised by these observations is how the magnetic field is compressed and maintained to kG strengths, since the magnetic pressure inside the tube is comparable to the gas pressure in the surroundings. The widely held view is that convective motions sweep the diffuse magnetic field to the supergranule boundaries, forming flux tubes of moderate strength. According to Parker (1978), the field is further compressed as a result of the adiabatic cooling of the descending plasma which results in gravitational evacuation of the flux tube. Thus, mass motions, in particular downdrafts associated with magnetic structures, are believed to play an important role in the physics of intense flux tubes.

Downflows associated with chromospheric network elements were detected by Tanenbaum et al. (1969). Frazier (1970) computed average profiles across network elements from observations in the Fe 5250.2 line and found that they were associated with magnetic field peaks of \( \sim 50 \) G and downdrafts of \( \sim 90 \) m s\(^{-1}\). Stenflo (1973) estimated downward velocities of the order of 500 m s\(^{-1}\) at the boundaries of supergranules from line profiles of the same line, while Gopasyuk and Tsap (1971) reported no relation between line-of-sight velocity and \( B_{\parallel} \), and found zero velocity in regions of

\[ \text{KCa} \]

\[ \text{W.L.} \]

Fig. 1. Negative prints of slit-jaw pictures taken in white light (WL) and Ca II K, showing the position of the slit and hairline during the exposure of spectrum No. 9 (the location of the magnetic regions A and B is indicated).
maximum magnetic field. Giovanelli and Slaughter (1978) measuring the Doppler shift of Stokes V profile relative to the Stokes I profile – at the level where the photospheric lines 5247 and 5250 Å are formed – found a downdraft of 0.5 km s\(^{-1}\) relative to the quiet Sun. An increase of the downdraft velocity in lower layers of the photosphere was reported. Recently, Stenflo and Harvey (1985), using the same method of measurement reported downdrafts of only 0.1 km s\(^{-1}\), from FTS data and 0.3 km s\(^{-1}\) from grating spectrometer data, and a velocity decrease for large area factors. Taking into account a correction of 0.3 km s\(^{-1}\), due to the brightness-velocity correlation of the granulation, they concluded that the wavelength of zero \(V\) does not indicate any downdrafts within the fluxtubes, while the asymmetry of the Stokes V profile indicates vertical velocity gradients within the fluxtubes. Stenflo and Harvey pointed out that the absence of downflows in their study might be partly due to the different velocity reference (Stokes I profile).

Their results are in conflict with those of Wiehr (1985) who found, from the study of Stokes V and I profiles in isolated Ca II K features, downdrafts of \(\leq 2\) km s\(^{-1}\) inside the tubes with respect to their non-magnetic surroundings.

In a previous paper (Dara-Papamargarit and Koutchmy, 1983, hereafter called Paper I), we studied a typical quiet Sun magnetic network element with size of 1" by 3" and found field strength of the order of 1000 G. The study of the velocity field in the region could not give reliable results since it was influenced by the 5 min oscillations. In this paper we study the mass motions in the same magnetic region (region A, see Figure 1) as well as in another one in its vicinity (region B). A time series of spectra taken at the same position was used, thus we could eliminate the effect of oscillations and determine the velocity field inside, as well as around the magnetic fluxtubes.

2. Observations and Data Reduction

A time series of spectra of three iron lines, Fe 5576 Å (magnetically insensitive line), Fe 6301.5 Å (\(g = 1.5\)), and Fe 6302.5 Å (\(g = 2.5\)) with circular polarization analysis, were observed simultaneously with the SPO tower telescope in a region near the center of the disk where no pores and faculae or other activity manifestations were detected on 8 June, 1976. The spectra were obtained with a moving slit in order to follow the differential solar rotation (in steps of 0.1 arc sec), therefore, exactly the same region was observed all the time. The effect of differential refraction due to the atmosphere of the earth was also minimized. Slit jaw pictures (Figure 1) were obtained as well as filtergrams before and after the spectrographic observations (see Paper I). The width of the slit was 0".75 while the spatial resolution along the slit was estimated to be near 0".75, from the narrowest continuum streaks, and 0".95 from the minimum distance of two streaks; the exposure time was 1 s. The instrumental half-width profile measured in the telluric lines near the Fe 6302.5 Å and 6301.5 Å lines was 39.2 mÅ. The spectra were taken on Kodak film type S0392 which provided a very high signal to noise ratio, even for microphotometric scans taken with a 0.4 arc sec slit.
We should point out that the magnetic regions A and B correspond to bright regions of the CaII K network which have a different morphology, while in the continuum there seems to be no evident difference (Figure 1). Region A corresponds to the edge of a rosette of the Hα chromospheric network (see Paper I), while region B is centered to a much smaller bright region. For the present analysis, we selected ten spectra with the best resolution, uniformly distributed in a time period of 5.5 min (Table I). The spectra of all three lines were processed with the video-system of the Paris Institut d’Astrophysique which gives a set of coded isophotes with arbitrary colors on a TV monitor. The isophotes were used to determine the location of the line center in each of the five simultaneous spectra (one for the magnetically insensitive line and two, in opposite circular polarizations, for the magnetically sensitive lines). The measurements were made every 0''71 along the slit.

The value of the longitudinal magnetic field was determined from the comparison of the position of the line center in the left- and right-hand polarized spectra, assuming zero magnetic field far from the magnetic regions, as described by Semel (1985). The measurements of the Doppler shifts in the three lines give the longitudinal (in our case also the vertical) component of the velocity inside and in the vicinity of the magnetic regions. In one spectrum we also measured the velocity from the Doppler shift of the $V$ profile zero crossing; this gave values within 10% of those obtained from the position of the line center. We should note that the magnetically sensitive lines are formed at about the same layers as the magnetically insensitive line (an assumption supported by the fact that all three lines have the same excitation potential). The error in the measurements of $B_\parallel$ is of the order of $\pm 50$ G, while for the velocity it is of the order of $\pm 0.05$ km s$^{-1}$.

Each spectrum of the 5576 Å line was also scanned with a digital microphotometer of the Institut d’Astrophysique, in order to deduce the intensity fluctuations at the center of the line, as well as in the nearby continuum.
3. Results

The measurements of the magnetic field strength in the two regions in both lines give similar results. Figure 2 shows the relation between measurements of $B_\parallel$ in the 6301.5 Å line and in the 6302.5 Å lines. Measurements at 6301.5 Å give higher values but this difference seems to be minimized as the field strength increases. The time-averaged field strength in region A is of the order of 500 G, while in region B it is 400 G. The results given in Figure 2 represent directly measured values including scattered light and smearing effects; therefore, these values are smaller than the real field strength value, which from Figure 2 seems to be around $10^3$ G where measurements in both lines would agree.

The longitudinal component of the magnetic field shows time variations which are not correlated to the seeing (Dara-Papamargariti and Koutchmy, 1985), so they are presumably of solar origin. As a measure of these variations we used the parameter $\int B_\parallel \, dl$, the integral of the profile of $B_\parallel$ along the structure, which is less sensitive to
errors, especially when seeing effects are present. We find time variations of this parameter up to ±40% (Figure 3). A periodicity of 250 s is evident in region B.

The velocity measurements for each of the 10 spectra used were corrected for a spatial linear trend; Figure 4 gives the velocity variation in time and space in the vicinity of the magnetic elements for all three lines. In general, measurements of the velocity in the magnetic and non-magnetic lines give similar values within ±100 m s⁻¹; this is not surprising since they are formed at approximately the same level. There are, however, occasional differences of up to 400 m s⁻¹, both near and far from the magnetic regions; such differences also exist between the two magnetic lines. In the subsequent analysis we will use primarily the magnetically insensitive line, which shows an intermediate behaviour between that of the two magnetic lines.

An inspection of the velocity maps of Figure 4 reveals nothing peculiar at the location of magnetic regions A and B. Indeed, there is no way to distinguish the magnetic regions from their surroundings on the basis of the velocity field alone: they are not associated with prominent downflows or upflows. The dominant feature in the velocity maps is the
Fig. 4a–c. Variation of the vertical velocity as a function of position along the slit and time for the three observed lines. Solid lines correspond to ascending and dashed lines to descending material; the position of the two magnetic regions is also indicated (a): for the magnetically non-sensitive line; (b) and (c): for the magnetically sensitive lines; note that the scale of velocity amplitudes is the same as shown in (a).

oscillation with a period of about 250 s. The lifetime of the magnetic elements is much longer; therefore, we should look for velocity patterns with larger time-scale. In order to correct for the effect of oscillations, we averaged the velocity measurements in each spatial point over the 258 s time-interval of spectra Nos. 2 through 8 (see Figure 5(e)); averaged velocity measurements for the 10 spectra gave similar results. We also computed the corresponding r.m.s. values for each of the 131 points of measurements along the slit (Figure 5(d)), which are related to the oscillation amplitude.
Fig. 5a–i. Spatial variation of the average line center intensity for 5576 Å (a) and the average continuum intensity (b). Magnetic field strength in regions A and B (c). The RMS value of the velocity (d) and the corresponding average velocity for 5576 Å (e). Parameters of the velocity fit: amplitude $V$ (f), constant velocity $v_0$ (g), period $T$ (h), and phase parameter $t_0$ (i) of the oscillatory component.
In order to have more elaborate results for the velocity field and to be sure that we have eliminated the oscillations, we made a least-square fit of the time variation of the velocity at every point. The observed velocity was fitted to a function with a constant term, a linear term and an oscillatory term:

\[ v(t) = V_0 + at + V \cos \left( \frac{2\pi}{T} (t - t_0) \right), \]

where \( V_0 \) is the constant term, \( a \) the coefficient of the linear term, \( V \) the amplitude of the oscillatory term, \( T \) the period of oscillation, and \( t_0 \) the parameter defining the phase. Before the fitting, the values were smoothed with a 60 s wide triangular function; the only parameter that had to be corrected for the smoothing was the amplitude.

The average velocity (excluding the oscillatory term), the oscillation amplitude as well as its period and phase are shown in Figures 5(f–i). The quality of the fit was in general good (\( x^2 \approx 0.01 \)), however, regions where the fit was not satisfactory were not drawn.

A comparison of Figures 5(d–e) and 5(f–g) shows that computed values of the constant component are very similar to the average values of the eight spectra, while the ratio of the computed amplitude to the r.m.s. value of the velocity is close to \( \sqrt{2} \), as expected for a sinusoidal variation. This shows that the oscillatory component has been efficiently suppressed by the averaging; moreover the fit gives a more reliable estimate of the period of oscillation and its phase. In the same Figure 5 we give the intensity variation at the line center (5576 Å) and in the continuum as well as the time-average of the magnetic field in the two magnetic regions.

A comparison of the average velocity curve with that of the continuum intensity shows that, in general, intensity maxima correspond to upflows and intensity minima to downflows; thus most of the velocity features are manifestations of convective motions associated with the photospheric granulation. However, at the location of the magnetic regions A and B, this correlation breaks down: downflows which are not associated with intensity minima are observed in their vicinity.

A closer look at the velocity data in the magnetic regions shows that at the peak of region A the average velocity is very close to zero, with an oscillation amplitude of \( \sim 300 \) m s\(^{-1}\); near its boundaries there are two velocity extrema, one with downflows of \( \sim 110 \) m s\(^{-1}\) and another with upflows of \( \sim 260 \) m s\(^{-1}\) (Figure 5(e)). At the peak of region B the velocity is downward with a value of \( \sim 200 \) m s\(^{-1}\), while the extrema near its edge correspond to upflows of \( \sim 160 \) m s\(^{-1}\) and downflows of \( \sim 280 \) m s\(^{-1}\). The average velocity curves for the magnetically sensitive lines are similar to that of Figure 5(e). At the peak of region A the average velocity in \( \lambda 6302.5 \) is \(-40\) m s\(^{-1}\) and \(-80\) m s\(^{-1}\) in \( \lambda 6301.5 \), while that of region B is \(-440\) m s\(^{-1}\) and \(-80\) m s\(^{-1}\), respectively, with a mean of \(-260\) m s\(^{-1}\). Both A and B are regions of intermediate velocity amplitude; moreover, the period of oscillations as well as their phase do not show any extrema or discontinuities in their vicinity.

The intensity at the center of the 5576 Å line is poorly correlated with that of the continuum, consequently at the center of the line we observe features associated with the chromospheric network rather than with the granulation. It is interesting to note that
most peaks of the central intensity are associated with peaks of the velocity r.m.s., in particular peaks to the left of region B, which are not affected by strong magnetic field. This indicates a possible relation between the heating of the transition region between the photosphere and the chromosphere and the amplitude of photospheric oscillations. We believe that this question warrants further investigation which is beyond the scope of this paper.

4. Discussion and Conclusions

The main result of this analysis, as it is evident from the study of Figure 5, is that we find very small downflows, 100 to 300 m s\(^{-1}\), in the vicinity of regions where we identify concentrated magnetic fields; however the velocity peaks are displaced with respect to the peak of the magnetic field by about 2\(^{\prime}\) which is comparable to the width of the features. Moreover, similar downflows are observed in regions without any evident magnetic field; the only difference is that the latter are associated with minima in the continuum intensity, which is not the case with magnetic regions A and B, where the granulation is probably distorted by the presence of bright features. Karpinsky (1985) gives also an explanation for low correlation of line-of-sight velocity and photospheric fine structure, since he finds varying correlation coefficients depending on the size of the structure.

Another interesting point that comes out of the present analysis is that the photospheric oscillations must be eliminated in the study of velocity fields associated with magnetic regions. Indeed, the amplitude of the oscillations is of the same order or larger than the average velocity; thus, for example, if we had used the spectrum 144 alone, we would have found a downflow of 700 m s\(^{-1}\) associated with region B (Figure 4), more than a factor of 2 larger than the average value.

On the basis of the above results, i.e., the small value of the downflow velocity, the presence of oscillations of comparable amplitude and the displacement between the velocity and magnetic field peaks, we cannot infer that downflows play a fundamental role in the confinement of small-scale magnetic fields.

Most of the modelling of the motions within a fluxtube was made to be in agreement with the early observations of downflows (Deubner, 1976; Spruit, 1979; Unno and Ribes, 1979). In a recent paper, Ribes et al. (1985), favor a model of moderate field strength within the flux tube and a downdraft decelerating with depth; their 'best model' predicts downflows of the order of 1.5 km s\(^{-1}\), a factor of five above our values. Stenflo and Harvey's (1985) recent observations indicating almost no downdrafts within the fluxtubes have stimulated new modelling of the tubes. Hasan (1985) proposed a new model for fluxtubes which results in a field strength in the kG range, and an oscillating flow with an amplitude between 1–2 km s\(^{-1}\), an average value which is approximately zero and a period of the order of 20 min; our measurements give considerably lower values for the velocity, but we can only observe much smaller time-scales.

In addition to the velocity oscillations, our observations confirmed the existence of flux variations of an oscillatory character. Flux changes (Figure 3) in small magnetic
regions have also been reported by Wilson and Sinion (1983). Recently, Wiehr (1985) found that the $V$-profile participates in the photospheric 5-min oscillation. This point should be further investigated. Further investigation is also necessary on the possible association of bright features at the line center with maxima of the amplitude of the velocity oscillations, which was reported in Section 3.

Our values of the downflow velocity are lower than those quoted in the early literature (see Section 1), but they are in the same range as the more recent values of Stenflo and Harvey (1985). High-resolution observations, such as those of this paper, seem to lead to conclusions that can be different from those of low-resolution observations. Even with our resolution we have the feeling that smearing effects mask a part of the physical phenomena. We, therefore, believe that the effort for higher resolution should be continued.

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