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Letter to the Editor

Infrared lines as probes of solar magnetic features

XII. Magnetic flux tubes: evidence of convective collapse?

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Abstract. The magnetic field in the solar photosphere is mainly composed of magnetic flux tubes. Their formation is not well understood, largely due to an absence of observational tests of theoretical predictions. Here we use infrared polarimetric data to test and confirm the prediction that whereas the field strength of large flux tubes is almost independent of their magnetic flux, small flux tubes show a strong dependence. Our work thus strengthens the case for convective collapse as the source of concentrated solar magnetic fields. We also present the first direct measurement of the intrinsic field strength of typical intranetwork elements. A significant fraction of them is in equipartition with the kinetic energy of convection. Nevertheless, our results suggest that as far as their internal structure is concerned intranetwork magnetic features are better described by flux tubes than by turbulent fields.

Key words: Sun: Magnetic fields – Sun: Infrared – Sun: Photosphere – Flux tubes

1. Introduction

At the solar surface the magnetic field is concentrated into discrete elements known as flux tubes (e.g. Stenflo 1989; Schüssler 1992; Solanki 1993). Typical flux tubes have intrinsic field strengths of 1000–1700 G and fluxes of 2×10^{17} Mx or more, with the field strength increasing slightly with increasing flux. For smaller fluxes. Tarbell et al. (1979) Martin (1988) and Keller et al. (1994) found indications that their field strengths may be lower. Lin (1995) first gave convincing evidence that such fields are intrinsically weak, typically 500 G.

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The process by which flux tubes are created is still partially unclear. The currently favoured theory is based on the onset of a thermally driven convective instability in a weak magnetic field leading to its concentration, a process referred to as convective collapse (Parker 1978; Webb and Roberts 1978; Spruit 1979; Spruit and Zweibel 1979; Venkatakrishnan 1985; Hasan 1985; Steiner 1996). This theory suffers, however, from a relative absence of observational evidence for or against it. In the present paper we present and discuss observations that address the interrelated questions of the origin of magnetic flux tubes and the intrinsic field strengths of the smallest known solar magnetic features.

Venkatakrishnan (1986) discovered that due to the efficient heating by the surrounding gas the convective instability is less efficient for smaller flux tubes, i.e. tubes with lower magnetic flux. More specifically, he predicted that if magnetic flux is concentrated by convective collapse then the final intrinsic field strength B at a given level in the solar atmosphere within a flux tube should increase rapidly with magnetic flux, Φ, per flux tube for small tubes ($\Phi \lesssim 10^{17}$ Mx), but should increase only very slowly with Φ for larger tubes. According to theory the field strength of flux tubes is bounded at its lower end by the equipartition field strength, $B_{\rm eq}$, at which the magnetic energy equals the kinetic energy of solar convective flows. $B_{\rm eq} = v\sqrt{4\pi\rho}$, where v and ρ are typical values of the velocity and density in the surrounding field-free gas. At the solar surface $B_{\rm eq} \approx$ 200–400 G.

2. Observations and analysis

In order to test the prediction made by Venkatakrishnan (1986) the possibly small intrinsic field strength of magnetic features with very small fluxes needs to be reliably determined. To achieve this aim we observed net linearly and circularly polarized spectra (i.e. the Stokes parameters Q, U, and V) from two $20 \times 40''$ pieces of very quiet sun near solar disk centre. The observations were carried out with the horizontal spectrograph and the Vertical Tower Telescope of the National Solar Observatory on Sacramento Peak. The observed wavelength range contains the neutral iron lines at 1.5648 μm (Landé factor, $g = 3$) and 1.5653 μm (effective Landé factor, $g_{\rm eff} = 1.53$) chosen for their extremely high Zeeman sensitivity, which is three times larger than in the visible. We need this additional sensitivity in order to measure intrinsic field strengths as low as $B_{\rm eq}$, i.e. 200 G (Solanki et al. 1992a). In addition, we also require low noise in order to detect small fluxes. In order to reduce noise we co-added 2×80 frames obtained at a single solar spatial location with a NICMOS 256×256 infrared array detector (see Lin, 1995, for details). Noise in the oversampled spectra was further reduced with the help of Fourier filtering, i.e. by nulling all frequencies above the spectral, respectively spatial Nyquist frequencies. The final noise level is approximately 2×10^{-4} per resolution element (in units of the continuum intensity I_c). The low noise level coupled with our best spatial resolution of 1–2″ allowed us to separate Stokes V profiles from the noise for magnetic features with fluxes as small as 2×10^{16} Mx. We compensated for instrumental cross-talk between the Stokes parameters by applying the technique of Kuhn et al. (1995) to sunspot Stokes-vector spectra obtained just prior to and after the quiet-sun observations.

Since we modulate the polarization at a frequency of only 4.5 Hz, typical of infrared polarimetry, seeing may induce apparent changes in the observed solar feature in the time between the recording of two opposite polarizations, and thus distort the net polarization signal due to cross-talk from Stokes I (intensity spectrum). Such distortions were reduced by averaging over 80 modulation cycles. In addition, we selected only those Stokes V signals for further analysis which were larger than any Stokes V shaped signals in Stokes Q and Stokes U. The latter may be considered to be an upper limit to the seeing-induced cross-talk from Stokes I into Stokes V, since some of the signals in the Stokes Q and U spectra having the spectral shape of Stokes V profiles are probably residuals of the instrumental cross-talk from Stokes V into Stokes Q and U. Statistically none of the analysed Stokes V profiles is expected to be purely a result of seeing induced cross-talk. Nevertheless, we expect that some of the profiles passing the above test are distorted by such cross-talk. Such distortions, however, produce ratios between the Stokes V amplitudes and splittings of the two lines which are incompatible with the expectations of Zeeman splitting (e.g. Lin 1995), so that they are in general easily recognised and eliminated.

Next we took care to identify by eye the Stokes V profiles belonging to an individual, distinct magnetic feature and fit the profile averaged over the whole feature. The magnetic features in our data could almost always be easily separated. We then applied an inversion code (Solanki et al. 1992b, 1994) to the data. It is based on automated least-squares fitting of observed Stokes profiles by solutions of the radiative transfer equations for polarized light. The code returns a set of parameters describing the physical conditions within the magnetic features. Among these parameters the field strength, B, at a reference height $z = 0$, the height of 0.5 μm continuum formation in the average quiet sun, is of immediate concern.

3. Results and conclusions

For 73 of the 103 analysed magnetic features we obtained field strengths significant at the 1-σ level. For the remaining 30 features the combination of weak intrinsic field ($B \lesssim 500$ G) and small S/N ratio (due to their generally small Φ) did not allow a reliable measurement of B. By adding together all these 30 Stokes V profiles (after correcting for relative Doppler shifts and magnetic polarity) we obtained the Stokes V profile plotted in Fig. 1, which exhibits a noise level around 4×10^{-5} in units of I_c (dotted). The solid curves are the synthetic best-fit profiles and yield a field strength of 280 G $\pm$ 160 G, which is in good agreement with theoretical predictions of the equipartition field strength. Based on the line fit error there is, however, a 15% chance that a $B \leq 100$ G could describe the data. For these weak fields the average flux per magnetic feature is 6×10^{16} Mx.

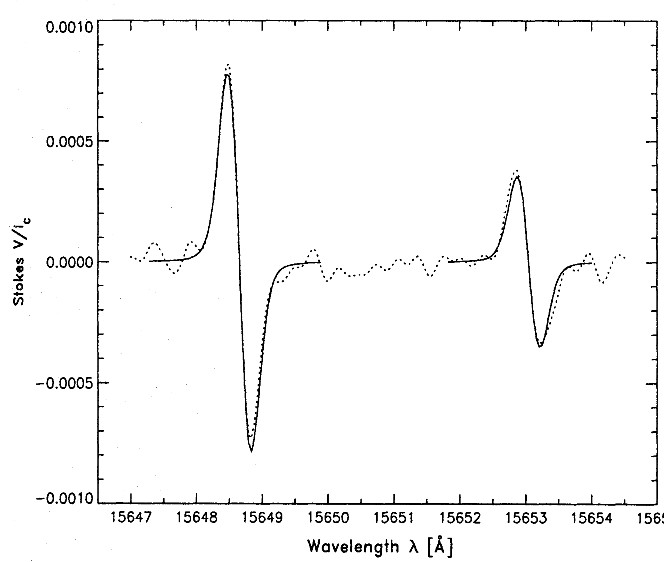

Fig. 1. Stokes V profiles of two Fe I lines. The dotted curve represents the average of the profiles of 30 magnetic features with low magnetic flux and field strength. Solid curves are best fit synthetic profiles

A plot of intrinsic field strength B vs. spatially averaged, unsigned longitudinal field $\langle |B \cos\delta| \rangle$ of all 103 features is quite revealing. Here $\langle\,\rangle$ signifies averaging over the spatial resolution element and δ is the angle between the magnetic vector and the solar surface normal. Consider first the inset to Fig. 2. It shows B vs. $\langle|B\cos\delta|\rangle$ for our data, each magnetic feature being represented by a small symbol: circles for B values larger than the fit uncertainties, crosses for the uncertain B values. The solid diamond represents the fit to the average profile shown in Fig. 1. It is averaged over all the profiles represented by crosses. In order to accentuate trends, we merge together the data points within $\langle|B\cos\delta|\rangle$ bins of 4 G width. The binned values are represented by large squares. Only the binned data from the inset are plotted in the outer part of Fig. 2 (squares). In addition, Fig. 2 shows an extension of the relationship between B and $\langle|B\cos\delta|\rangle$ to larger fluxes using data from an active region plage (circles) analysed and described earlier by Rüedi et al. (1992). We only employ the results they obtained from Stokes V profiles arising from single magnetic components. For these, their derived B values are more reliable than for multi-component profiles (see Rüedi et al. 1992 for details). We have averaged all plage data points within bins of 100 G width. In spite of the broader bins there are considerably fewer points per bin than in our quiet-sun data set. This shortcoming is offset by the extremely low uncertainty of the B values (20–25 G for most data points).

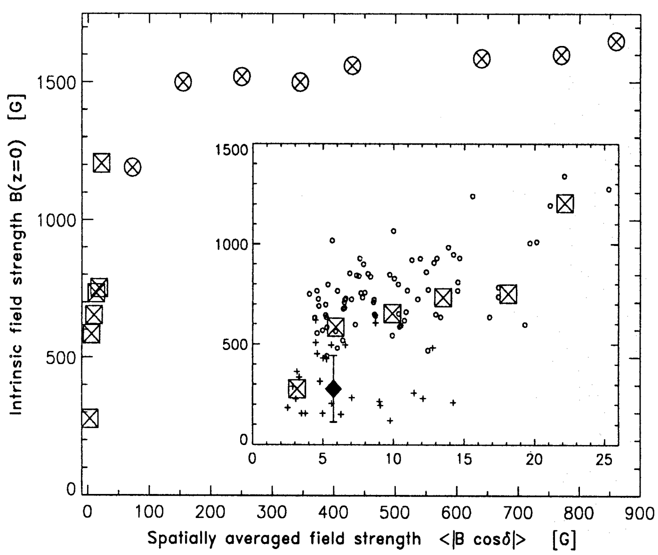

Fig. 2. Intrinsic magnetic field strength at the solar surface $B(z=0)$ vs. the unsigned, spatially averaged longitudinal field strength $\langle|B\cos\delta|\rangle$. Plotted are binned values resulting from our quiet-sun observations (squares) and earlier plage observations (circles; Rüedi et al. 1992). The inset shows only the leftmost part of the main figure, with the squares being identical to those in the main figure. The small circles/crosses represent values that lie above/below the uncertainties, respectively. The errors on $\langle|B\cos\delta|\rangle$ are considerably smaller than on B, and these values are significant in every case. The diamond denotes the B derived from the profile averaged over all the magnetic features denoted by crosses. Its errors are indicated. If instead we average directly over the B values marked by the crosses we obtain a very similar result

Since the geometrical size of the flux tubes we observe in the quiet sun is an order of magnitude smaller than the spatial resolution element of the observations (values of the magnetic filling factor $\alpha(z=0)$ range from 1 to 4%), and since the features appear to be well separated, $\langle|B\cos\delta|\rangle$ is in general a reasonable, but not exact measure of the magnetic flux per magnetic feature. Given this interpretation the relationship exhibited by the data in Fig. 2 is in good agreement with the predictions of Venkatakrishnan (1986), with an initial steep rise of B with magnetic flux per feature and a much more gradual rise at larger fluxes. Figure 2 is also very similar to Fig. 9 of Lin (1995).

A more direct estimate of the flux of a magnetic feature can be determined by multiplying its spatially averaged field strength $\langle|B\cos\delta|\rangle$ with the apparent area it covers, which is obtained from its size along the slit by assuming that the point spread function is isotropic. Here, we are essentially assuming that there is only one flux tube in each patch of magnetic flux.

In Fig. 3 we plot the histogram of the magnetic flux per magnetic feature as a function of field strength. Clearly, the average flux decreases with decreasing B, consistent with the conclusion drawn from Fig. 2. In addition we see that the average flux per magnetic feature changes only slightly for $B \lesssim 1000$ G, but increases rapidly with B above that. Note that the binned plage data (not plotted in this histogram) all have $1200\text{ G} \lesssim B \lesssim 1700$ G. In addition they correspond to large flux values lying well off-scale ($\Phi > 10^{18}$ Mx), reinforcing the above conclusion. Our observations are thus in remarkable agreement with the predictions of Venkatakrishnan (1986) and consequently enhance the case for convective collapse as the mechanism responsible for concentrating solar magnetic fields of equipartition strength into kG flux tubes. We distinguish between three domains: the equipartition fields ($B \lesssim 500$ G), the intermediate strength fields between 500 and 1000 G that may have undergone a weak convective collapse and strong fields with $B > 1000$ G.

We identify most of our magnetic features (at least those with $\Phi \lesssim 3\times10^{17}$ Mx, or almost equivalently $B < 1000$ G) with intranetwork features. This is firstly based on their random spatial distribution on scales well below the supergranulation scale. In addition, for $B < 500$ G the average flux per feature is around 7×10^{16} Mx, almost identical with the peak of the intranetwork flux distribution (Wang et al. 1995, cf. Livingston & Harvey 1975; Martin 1984). Finally, the flux distribution of the magnetic features, i.e. the number of features per flux interval is also similar. In spite of the poor statistics a power law fit to the weak fields gave an exponent of -1.5 ± 0.3, which is compatible with the value of -1.68 found by Wang et al. (1995) for intranetwork fields.

Our work shows that the intranetwork fields we could detect are composed of concentrated field elements, i.e. flux tubes or close relatives thereof. Some of them appear

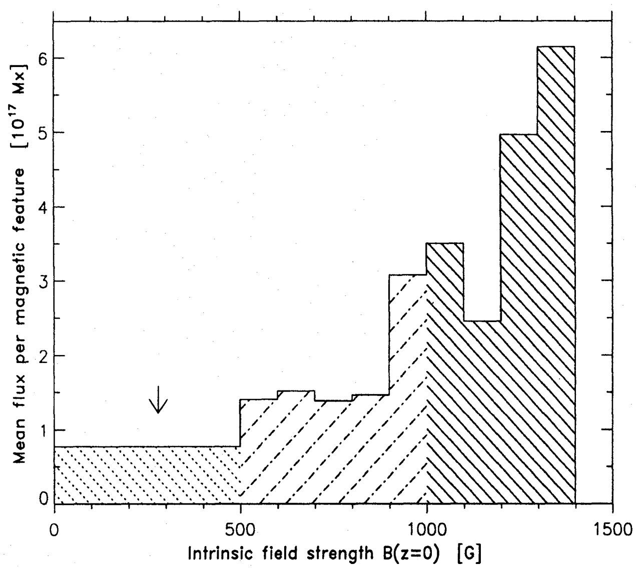

Fig. 3. Histogram of the flux per magnetic element as a function of B. Features with $B < 500$ G have been put into a single bin. The mean B of these features is indicated by an arrow

to have undergone a (weak) convective collapse. At least in their internal structure they do not appear to correspond to turbulent magnetic fields.

The support for the convective collapse model provided by our data suggests that the intrinsic field strength of a magnetic feature is determined primarily by its magnetic flux and not, e.g., by its origin. According to this picture network fields are intrinsically stronger than intranetwork fields mainly because they (network fields) have a larger flux per magnetic element. Of course, convective collapse cannot explain the large-scale organization of the strong-field component (or equivalently the component with a large flux per feature) into the magnetic network.

The relative flux distribution in weak- and strong-field form is of considerable interest. We find that roughly 80% of the magnetic flux in our quiet-sun data is in the form of relatively weak field, i.e. field with $B < 1000$ G, with 60% of the flux having 500 G $< B \leq 1000$ G and 20% having $B \leq 500$ G. This result suffers from the small solar surface area we sampled, which corresponds only to roughly a single supergranular cell, so that it may not be representative of the quiet sun as a whole. Nevertheless, it suggests that a significant portion of the total flux is in weak-field form. This is in basic agreement with the conclusions of Tarbell et al. (1979), which were based on indirect arguments, and the measurements of Lin (1995). The observations of Wang et al. (1995), on the other hand, indirectly suggest that averaged over a much larger surface area only 20% of the magnetic flux is intrinsically weak. Magnetic features that have escaped detection due to a small flux per feature are unlikely to tip the balance in favour of intrinsically strong fields, since according to Fig. 2 and Venkatakrishnan (1986) magnetic features with very small flux are expected to have weak fields.

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