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Solar Active Region Evolution: Comparing Models with Observations
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Solar Magnetic Elements: Models Compared with Observations

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Abstract. Models of solar magnetic flux concentrations based on numerical simulation of magnetic flux sheets are compared with spectropolarimetric observations. The diagnostics used provide mainly information about the deep photospheric layers. We find that moderately evacuated flux sheets (plasma beta about unity at optical depth unity) agree best with the observational data. The width of the sheets should be about 200 km in network and 300 km in plage regions.

1. Introduction

The major part of the magnetic flux observed at the solar surface is thought to exist in the form of concentrated structures ('magnetic elements') with kG fields and diameters of a few hundred km. Much work has been devoted to the derivation of the properties of these features on the basis of semi-empirical models (cf. reviews by Stenflo 1989, Solanki 1993). A more theoretical approach to this goal is the construction of consistent models by solving numerically the time-dependent MHD equations including the effects of radiative transfer. At present the success of this approach is limited by the available computing facilities so that simplifying assumptions need to be made. We have been working on the development of models of this kind for several years (Deinzer et al. 1984a, 1984b, Knölker and Schüssler 1988, Knölker et al. 1988, Grossmann-Doerth et al. 1989, Knölker et al. 1991. Here we briefly describe the results of a comparison of observational data with model predictions. A more extended discussion can be found in Grossmann-Doerth et al. (1994).

2. Models

The numerical code is based on an implicit version of the *Moving Finite Element* method (Gelinas et al. 1981) with a non-uniform and time-dependent distribution of node points. The following equations are solved:

- Momentum equation including inertial force, pressure force, gravity, magnetic (Lorentz) force, and viscous force

- Equation of continuity (compressible)
- Magnetic induction equation
- Energy equation, including advection and compression, radiation, turbulent entropy diffusion, and effects of partial ionization

The major simplifications still retained are:

- 2D Cartesian geometry which means that we treat *flux sheets* which extend indefinitely into one dimension
- 'Turbulent' values for the viscosity (in order to avoid numerical instability) resulting in hydrodynamic Reynolds numbers between 10^3 and 10^4
- Turbulent entropy diffusion by unresolved small-scale motions accounted for by a mixing length formalism outside of the flux sheet; the process is suppressed in the presence of a sufficiently strong magnetic field
- Wavelength-independent opacity ('grey approximation')
- No magnetic diffusivity for better control of the node point motion

The computations start with an initial flux sheet in temperature and horizontal pressure equilibrium with the undisturbed solar atmosphere, in which it is embedded. The parameters describing this initial state are α, the ratio of internal to external gas pressure, and w, the (full) width of the sheet at $\tau_c = 1$ of the external atmosphere. A model is specified by its values of α and w. The computations simulate the development of this configuration towards a stationary state with an oscillatory motion in the interior of the flux sheet and a strong downflow in its vicinity. For the purpose of illustration we show in Fig. 1 cross sections of model M350 ($\alpha = 0.5$, $w = 300$ km) after it has achieved its stationary state.

3. Comparison with observational data

We believe that in their deeper layers our present models are sufficiently accurate to warrant a comparison of their characteristics with observations. For this comparison we need quantities which can be derived unambiguously from both model and observational data. As a quantity of this kind we chose the Stokes V 'line ratio' which is the ratio of the Stokes V amplitudes of two spectral lines (Stenflo 1973, Solanki 1993). The line ratio is a very useful diagnostic tool because it is unaffected by the atmosphere outside of the flux sheet and it is independent of the the magnetic 'filling factor', i.e. the number density of flux tubes in the aperture of the observing instrument.

The observational data consist of sets of Stokes V profiles of three visible Fe I lines (5250.22 Å, 5250.65 Å and 5247.06 Å), two C I lines (5380.32 Å and 5052.15 Å), three Fe II lines (5132.66 Å, 5325.56 Å and 5414.07 Å) and the infrared Fe I line at 15648.52 Å, recorded near disc center, in both a network and a plage region. The data were taken with the McMath telescope of the National Solar Observatory/Kitt Peak. From these data we derived the line ratios of the six

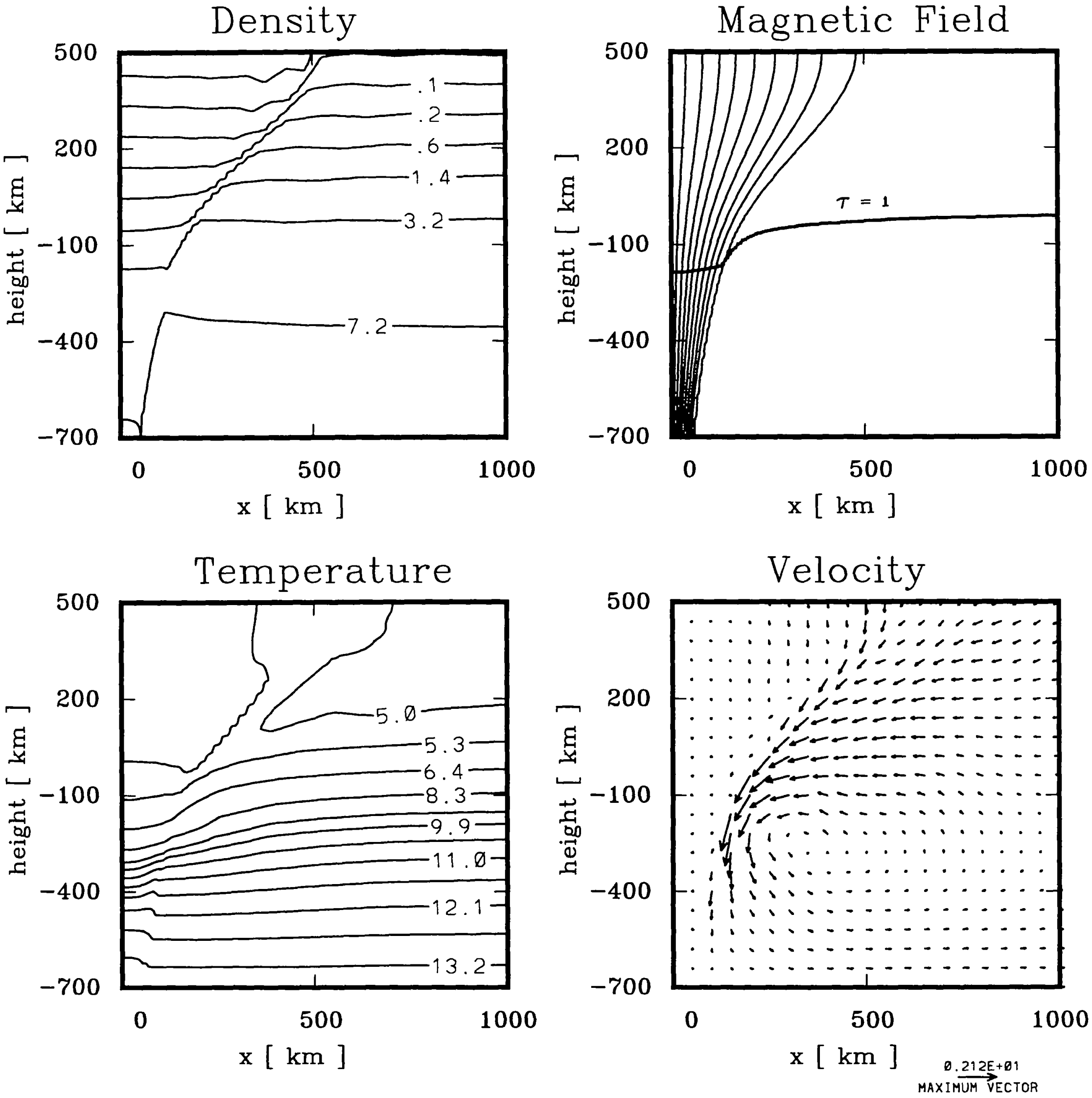

Figure 1. Properties of the flux sheet model M350. Only half of the symmetric structure is shown; the sheet extends infinitely in the direction perpendicular to the plane of the figure. Densities are in units of 10^{-7} g·cm^{-3}, temperatures in 1000 K. The level at which the continuum optical depth at 5000 Å is unity is indicated in the magnetic field plot. The velocity arrows scale with the modulus of the velocity; the maximum velocity in the downflow jet adjacent to the flux sheet is about 4 km·s^{-1}. The temperature structure in the upper levels of the flux sheet (above $\sim$ 100 km) varies strongly in the course of the internal oscillation; however, the layers around $\tau_c = 1$ are hardly affected.

C I/Fe II combinations which are sensitive to the temperature around $\tau_c = 1$ and depend only weakly on the magnetic field strength. As a diagnostic tool for the latter we used both the line ratio Fe I 5250.2/Fe I 5247 and the Zeeman splitting of the infrared line. Additionally, we have determined the Fe I 5250.6/Fe I 5247 'thermal' line ratio which is sensitive to the temperature around $\tau_c = 0.1$.

The purpose of the present analysis is to find the models, specified by α and w, whose values of temperature (T_0) and magnetic field strength (B_0) around $\tau_c = 1$ agree best with the observations. Fortunately, B_0 and T_0 depend in different ways on the model parameters α and w. For a given value of α the temperature T_0 *decreases* with growing width since the flux sheet becomes more opaque and, therefore, is less efficiently heated by radiation from the side. At the same time, the field strength B_0 *increases* since the surface $\tau_c = 1$ in the flux sheet moves downward due to the temperature sensitivity of the continuum opacity. On the other hand, for a given width both temperature and field strength decrease for increasing values of α (larger internal density) since the surface $\tau_c = 1$ moves upward. Hence a unique determination of the pair parameters (α, w) should be possible on the basis of the diagnostics chosen by us.

Table 1. Parameters and properties of the set of investigated flux sheet models. $\langle I_c \rangle / I_0$ is the continuum intensity at 5000 Å averaged over the magnetic structure in units of the disc center value for the undisturbed atmosphere.

Model	w (km)	α	T_0 (K)	B_0 (G)	$\langle I_c \rangle / I_0$
M130	100	0.3	7100	2300	1.70
M150	100	0.5	6580	1800	1.12
M230	200	0.3	6880	2550	1.50
M250	200	0.5	6230	1940	1.01
M350	300	0.5	6060	1980	0.94
M430	400	0.3	6480	2730	1.19
M450	400	0.5	5930	2270	0.86
M460	400	0.6	5680	1940	0.70
M850	800	0.5	5720	2200	0.78

For a set of models whose properties are shown in Table 1 we computed the values of our diagnostic quantities and compared them with the observed values. The result is shown in Table 2. To express quantitatively the degree of similarity between model and real Sun we computed χ^2, the sum of the squared differences between calculated and measured values for the six C I/Fe II line ratios, normalized to the minimum value. For the other line ratios and the Zeeman splitting of the infrared line the table shows directly measured and computed values.

4. Discussion and Conclusions

From the pronounced minima of χ^2 calculated from the C I/Fe II line ratios in Table 2 we conclude that models M250 (for the network) and M350 (for the plage) are in much better agreement with the data than any other model. In particular, models with low α values, i.e. models with greater temperature and

Table 2. Observed and computed values of the line ratios Fe I 5250.2/Fe I 5247 and Fe I 5250.6/Fe I 5247 (columns 4 and 5) and of the Zeeman splitting $\Delta\lambda$ of Fe I 15648 (column 6). Column 2 and 3 show the sums of the squared differences between observed and computed values of the six C I/Fe II line ratios.

	χ^2 (C I/Fe II) (Network)	χ^2 (C I/Fe II) (Plage)	5250.2/ 5247	5250.6/ 5247	$\Delta\lambda$ (Å)
Network			.74	1.7	0.98
Plage			.74	1.5	1.10
M130	105.7	99.0	.58	1.50	1.30
M150	5.1	13.4	.68	1.24	0.92
M230	20.7	29.3	.61	1.99	1.50
M250	1.0	3.7	.67	1.04	1.00
M350	13.5	1.0	.72	0.98	0.95
M430	12.9	22.1	.66	1.50	1.55
M450	14.6	1.0	.68	1.21	1.33
M460	40.0	8.6	.70	1.12	1.12
M850	35.3	6.7	.70	1.11	1.20

magnetic field strength, appear to be ruled out. We attribute the stringency of this result to the small height range of formation of the C I lines (Grossmann-Doerth 1994). The lines Fe I 5250.6 and Fe I 5247 are formed in a much wider height interval and their their line ratio is sensitive to the temperature in somewhat higher layers (around $\tau_c = 0.1$). We see that the models which best fit the C I/Fe II line ratios are too cool there; consequently, some form of mechanical heating which is not described by our models must be present even in such relatively deep layers.

As far as the magnetic field diagnostic is concerned, the Zeeman splitting data of the infrared line are in essential agreement with the C I/Fe II data due to the fact that the Fe I 15648 line is also formed deep in the atmosphere although the range of its formation height is considerably larger than that of the C I lines. The Fe I 5250.2/Fe I 5247 data, however, are not very conclusive - perhaps because of the large range of their height of formation.

As can be seen from Table 1 the continuum contrast of model M250 is about unity and that of M350 amounts to 0.94. The latter value is in agreement with results of Solanki & Brigljević (1992); in the network, however, the same authors found the contrast value to be somewhat larger than unity.

Our analysis is based upon the tacit assumption that all magnetic flux tubes on the Sun are identical. Although there is evidence to suggest that there is not a large variety of small magnetic features we must admit the possible existence of flux tubes with properties different from those of M250 and M350. Therefore we do not think that our results contradict the existence of magnetic 'bright points' with continuum contrasts far in excess of unity as reported, for example, by Keller (1992). However, according to our results, such structures should contain only a minor fraction of the observed magnetic flux.

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Group Discussion

Stein: How do you determine the vertical and the horizontal temperature structure?

Knoelker: The temperature structure of the magnetic part matches the Spruit convection zone model and the HSRA atmosphere. This is the temperature structure that is prescribed at time t=0 in the whole computation.

Pillet: Does your model predict both area and amplitude asymmetries of the observed Stokes V profiles

Knoelker: Yes, but there has to be an additional line broadening by microturbulence.