A FORMATION MECHANISM OF MAGNETIC ELEMENTS IN REGIONS OF MIXED POLARITY

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(Received 21 December 2000; accepted 27 June 2001)

Abstract. We present 2-D, fully compressible radiation-MHD simulations of the solar photospheric and subphotospheric layers that run for 2 hours of solar time starting from a magnetic configuration with mixed polarities. In the atmospheric layers the simulation reveals a correlation between field strength and inclination, with a nearly vertical strong-field magnetic component and a more horizontal weak-field component, in agreement with the observations. Our simulation also shows that magnetic flux is converted from one of these states to the other. In particular, magnetic flux sheets can also be formed when a new downflow lane starts due to granule fragmentation. The dynamics of the granulation and field-line reconnection are found to play a role in the initial stages of a magnetic element's formation. The simulation predicts that during or shortly after their formation magnetic elements could be associated with oppositely polarized flux at a small spatial scale.

1. Introduction

Magnetic elements with kG strengths are the dominant magnetic features in the network and in active region plages (Stenflo, 1973; Solanki, 1993). The most realistic theoretical description of these features is based on radiation-MHD simulations, which can be divided into static (Hasan, 1988; Steiner and Stenflo, 1990) stationary (e.g., Deinzer *et al.*, 1984; Knölker, Schüssler, and Weisshaar, 1988; Grossmann-Doerth *et al.*, 1994) and quasi- or non-stationary (Nordlund and Stein, 1989; Brandt and Gadun, 1995; Atroshchenko and Sheminova, 1996; Steiner *et al.*, 1996, 1998; Grossmann-Doerth, Schüssler, and Steiner, 1998). Here we present some specific results from a 2-D fully compressible, non-stationary radiation-MHD simulation of the layers around the solar surface. The present simulation differs from those previously published in two main aspects. (1) The simulation runs for 2 hours of solar time, allowing us to follow the birth, evolution and death of a number of magnetic flux sheets. (2) The simulation describes a region on the Sun with mixed magnetic polarity.

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Solar Physics **203:** 1–7, 2001.

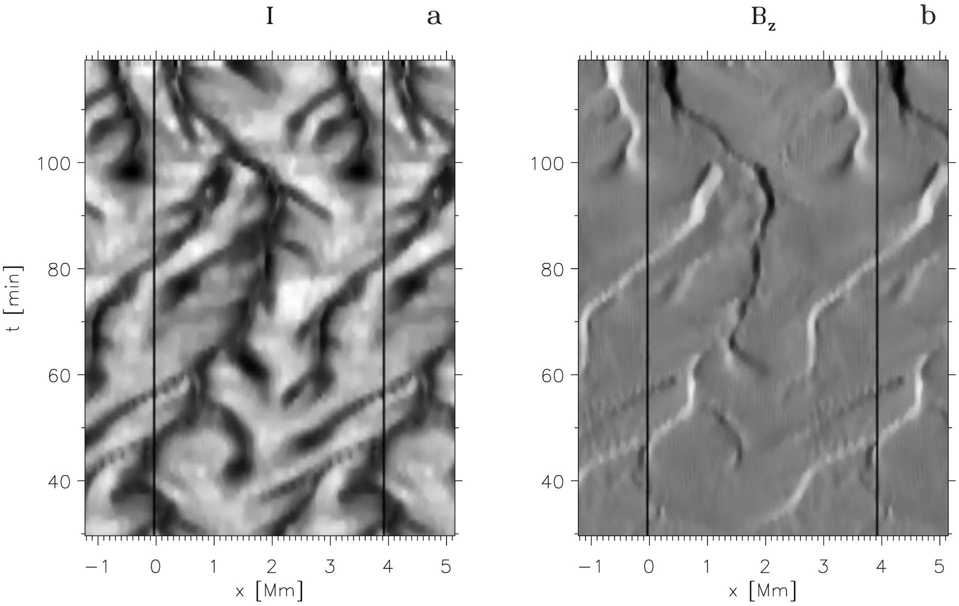

Figure 1. Time slices showing the evolution of (a) the continuum intensity, I, and (b) the vertical component of the magnetic field, B_z, at $z = -120$ km (where $z = 0$ corresponds to the solar surface). The horizontal axis indicates position on the Sun, while time increases upwards. The simulated region is enclosed by the *vertical black lines* and has been periodically extended on both sides. The *grey scale* in (a) is such that the lowest and highest plotted continuum intensities are 0.4 and 1.5 times the average intensity, respectively. In (b) *black* corresponds to −2180 G and *white* to 2120 G.

2. 2-D Radiation MHD

A complete description of the equations and the method of their solution is given elsewhere (Gadun, Sheminova, and Solanki, 1999; Ploner *et al.*, 2001a, 2001b). Here we restrict ourselves to a brief summary. We solve the full set of 2-D radiation-MHD equations describing a compressible, gravitationally stratified medium under conditions representative of those present near the solar surface. The employed code is an extension of the radiation-hydrodynamic code described in detail by Gadun, Solanki, and Johannesson (1999). In contrast to simulations described in that paper, however, we treat the radiative transfer in the grey approximation.

The simulation is run for 2 hours, starting from a fully relaxed radiation hydrodynamic simulation of solar granulation (Gadun, Solanki, and Johannesson, 1999). On to this we superimpose a magnetic field corresponding to two loop-like structures with a strong vertical stratification of the field strength. The computational domain is 3920 km wide and 1820 km high. The spatial step size is 35 km. The chosen grid size is obviously too large to resolve the boundary current sheet of these magnetic flux sheets. On the other hand, this coarse spatial resolution, in combination with the grey treatment of the radiative transfer, allows us to compute a time series of sufficient length to follow the birth, evolution and death of a number of magnetic flux sheets. The lateral boundaries are periodic while the upper and lower boundaries are open. We impose $B_x = 0$ and $\mathrm{d}B_z/\mathrm{d}z = 0$ at the upper and lower boundaries, where B_x is the horizontal and B_z the vertical component of the magnetic field. Allowing half an hour of real time for the magnetic field and the hydrodynamic structure to attain consistency we analyze here the remaining 1.5 hours of the simulation.

3. Results

In Figure 1 we show time slices of the continuum intensity I (Figure 1(a)) and B_z (Figure 1(b)) at approximately the height of the solar surface. For purposes of illustration the figure can be thought of as showing the evolution of I and B_z (corresponding roughly to magnetograms) along a slit placed across the solar surface[1]. In Figure 1(a) the evolution of the granules (bright areas) and the associated intergranular lanes (dark areas) can be followed. Of relevance for the current investigation is that granules end either by dissolving (visible as the merging of two intergranular lanes) or by fragmenting (corresponding to the formation of a new lane, see, e.g., Ploner, Solanki, and Gadun, 1999).

In Figure 1(b) the magnetic elements are visible as dark (negative polarity) or light (positive polarity) lines located in intergranular lanes (compare with Figure 1(a). A further comparison between the two frames reveals a connection between magnetic elements and the lanes harbouring them. Not only are at least some magnetic elements born soon after the birth of the corresponding lane, but magnetic elements also die close to the time when two lanes merge. In other words, magnetic element formation is related to granule fragmentation while magnetic element destruction is linked with granule dissolution, at least for a mixed polarity magnetic field in 2 spatial dimensions. In the following we investigate this interaction in greater detail, but concentrate on the process responsible for the formation of magnetic elements.

Our simulation confirms the efficiency of the flux expulsion process (Parker, 1963; Weiss, 1966; Stein and Nordlund, 1989). In the solar atmosphere the dominant horizontal flows very quickly concentrate any vertical field into the intergranular lanes and do not allow such field, once there, to escape. Horizontal field can, however, survive over granules for as long as the granular flow field continues. Our simulation also reveals, that there is a clear relation between magnetic inclination and field strength (Figure 2). Here, the inclination and field strength have been determined from Stokes profiles of Fe I 15648 Å to allow a better comparison with observations. Our result is in qualitative agreement with the observational findings of Lites, Skumanich, and Martinez Pillet (1998) and Sigwarth *et al.* (1999), see also

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[1] In reality, magnetic elements can also move perpendicular to the spectrograph, so that relative to Figure 1(b) the picture is complicated by magnetic flux sheets moving in and out of the field of view.

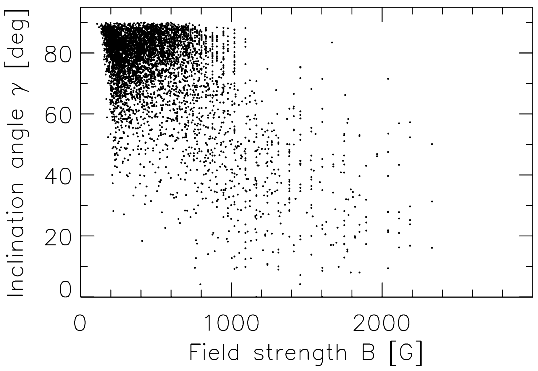

Figure 2. Scatter plot of the magnetic field inclination measured from the vertical, γ, versus magnetic field strength, B.

Schüssler (1998). More details of the line calculations will be given in a subsequent paper (cf., Sheminova and Gadun, 1999; Ploner *et al.*, 2001c).

To provide insight into the process leading to the formation of a magnetic element we display in Figure 3 six snapshots of the simulation. They are separated by 5.5 min (frame (a) to (b)) respectively 2 min (remaining frames). Frame (a) corresponds to a time of 93.5 min (compare with Figure 1). Plotted are the magnetic field lines (thick solid lines), velocity vectors (arrows) and the temperature (color). Comparatively slowly (i.e., over 5 min) weak horizontal field of some 200 G strength (frame (a)) is intensified up to 1100 G (frame (b)) as the granule begins to fragment. These field strengths refer to the solar surface ($z = 0$). Once the granule fragmentation, i.e., the birth of a new downflow lane, starts the intensification of the field proceeds more rapidly. The downflowing gas, first clearly seen in frame (c), drags the entrapped, originally horizontal field with it. A downward-directed plume or finger of field with closely packed field lines of opposite polarity is formed along which magnetic reconnection takes place and a magnetic 'island' can be formed (frame (d)). The surface peak field-strength is 1700 G. Two minutes later most of the vertical field of the left part of the magnetic plume has been reconnected (frame (e)) and a magnetic flux sheet with one dominant polarity with a peak strength of 1800 G remains (frame (f)). In the illustrated case many of the field lines belonging to the newly formed flux tube were originally part of the subsurface field, which surfaced during this process. In summary, our simulation reveals a new two-step process of formation of magnetic flux sheets. First the new downflow converts the weak horizontal field into relatively strong vertical field (peak strength of 1700 G in frame (d)) by stretching it as the flow drags it down. At this point the vertical finger of field is bipolar. Note that it would hardly show up at all except in the highest resolution magnetograms. Koutchmy and Stellmacher (1978) present an example of a bipolar structure with very close footpoints. In the second step magnetic reconnection, mainly below the solar surface finally leads to

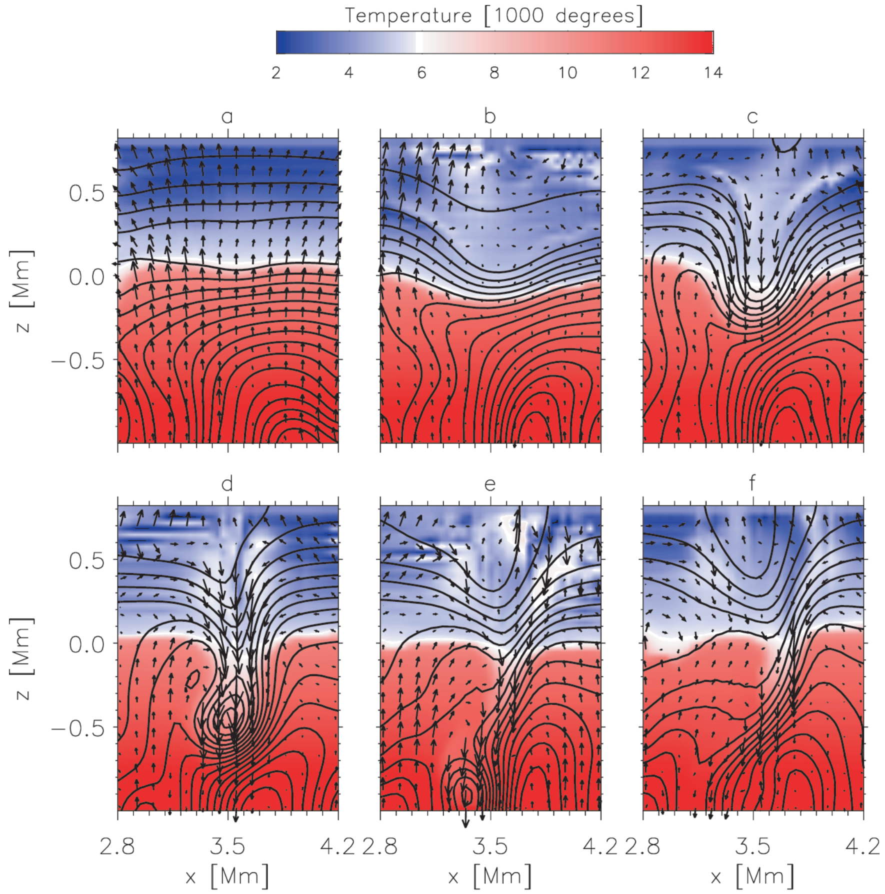

Figure 3. Six snapshots of simulated flows (*arrows*), magnetic field lines (*solid curves*), and temperature (*color scale*). Illustrated is the formation of a new magnetic element. Height relative to the mean solar surface increases along the vertical axis, while the horizontal axis represents horizontal location on the Sun. Frame (a) corresponds to a time of 93.5 min, the time step between frame (a) and (b) is 5.5 min, while between the remaining frames it is 2 min.

the annihilation of one of the polarizations, leaving a dominantly unipolar magnetic flux sheet.

There are three points of crucial importance for the second step, i.e., converting this bipolar finger of field, with no net magnetic flux, into a magnetic flux sheet with a single or at least a dominant polarity. Firstly, the subsurface layers into which the downflow plume plunges are far from field-free as can be seen from Figure 3. The strength of the ambient field increases strongly with depth (as expected from equipartition with the granular flow). Secondly, the ambient subsurface field is in general not strictly horizontal (e.g., Figure 3(b–d); i.e., there is a net vertical magnetic flux below most granules. Thirdly, the flow pattern in the immediate surroundings of the new downflow finger is in general not symmetric with respect to it. Usually, the two granules on either side of the newly-formed lane have different sizes and hence also horizontal flows of different strengths relative to the downflow lanes (see Ploner, Solanki, and Gadun, 1999). The combination of these three points is responsible for the fact that a single magnetic polarity with enhanced field strength finally remains in most cases.

The final evacuation and strengthening of the field of the magnetic flux sheet happens in the presence of a downflow and an inward directed flow from the sides. This is consistent with the convective collapse mechanism (Spruit, 1979). However, our study reveals the importance of other physical processes for the formation of at least some flux sheets. Thus we find that magnetic reconnection plays a major role, as does the fragmentation of granules. This may have to do with the fact that we start from a mixed polarity configuration, while earlier studies considered only isolated magnetic elements or an initially unipolar field.

4. Conclusions

We have presented results of a 2-D radiation MHD simulation of the layers close to the solar surface. In contrast to earlier such simulations we start with a mixed polarity initial magnetic field configuration. A predominantly horizontal and comparatively weaker field is found in the photospheric layers of granules (associated with the strong horizontal flows), while the downflowing intergranular lanes harbour the strong, nearly vertical field associated with magnetic elements. The output of our simulation agrees with the observed relationship between field strength and inclination.

When both magnetic polarities are allowed to be present then the field can be transformed from one of these states into another by changes in the associated granulation: From the weak horizontal to the strong vertical state when a granule fragments, and in the opposite direction when a granule dissolves. In 3-D further possibilities are present. Since the downflow lanes form a connected network, magnetic elements can in principle avoid destruction together with the dissolution of a neighbouring granule by moving along the downflow.

In our simulation we find cases when the formation of a magnetic flux sheet is associated with the formation of a new downflow lane, which creates a nearly vertical finger of field, and with magnetic reconnection, which leads to a dominance of one magnetic polarity. We propose that at least for some cases the usual convective collapse process needs to be extended by these features in order to provide a more complete and realistic picture of the formation of magnetic flux sheets. To judge just how common such a process is, however, more extensive simulations are needed. We are also aware of the need to test (1) the influence of small, so far unresolved scales on our result by increasing the spatial resolution and (2) whether such a process is also present in 3-D or not, and, if it is, the rate of its occurrence.

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