ON THE MISALIGNMENT BETWEEN CHROMOSPHERIC FEATURES AND THE MAGNETIC FIELD ON THE SUN

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ABSTRACT

Observations of the upper chromosphere show an enormous amount of intricate fine structure. Much of this comes in the form of linear features, which are most often assumed to be well aligned with the direction of the magnetic field in the low plasma β regime that is thought to dominate the upper chromosphere. We use advanced radiative magnetohydrodynamic simulations, including the effects of ion-neutral interactions (using the generalized Ohm’s law) in the partially ionized chromosphere, to show that the magnetic field is often not well aligned with chromospheric features. This occurs where the ambipolar diffusion is large, i.e., ions and neutral populations decouple as the ion-neutral collision frequency drops, allowing the field to slip through the neutral population; where currents perpendicular to the field are strong; and where thermodynamic timescales are longer than or similar to those of ambipolar diffusion. We find this often happens in dynamic spicule or fibril-like features at the top of the chromosphere. This has important consequences for field extrapolation methods, which increasingly use such upper chromospheric features to help constrain the chromospheric magnetic field: our results invalidate the underlying assumption that these features are aligned with the field. In addition, our results cast doubt on results from 1D hydrodynamic models, which assume that plasma remains on the same field lines. Finally, our simulations show that ambipolar diffusion significantly alters the amount of free energy available in the coronal part of our simulated volume, which is likely to have consequences for studies of flare initiation.

Key words: magnetohydrodynamics (MHD) – methods: numerical – Sun: atmosphere – Sun: magnetic fields

1. INTRODUCTION

Optically thick chromospheric spectral lines such as Ca II 8542 Å and Hα are formed over a wide range of heights, from the photospheric line wings, to the middle or upper chromosphere line core. Observations in these lines show a dramatic transition from wing features that appear to be dominated by convective motions or acoustic waves in the high plasma β regime (gas pressure is larger than magnetic pressure), to more linear features in the cores of the lines that appear to trace magnetic field lines (e.g., Rouppe van der Voort et al. 2007; Cauzzi et al. 2008).

Because these linear features are most often assumed to reveal the direction of the magnetic field, chromospheric structuring is increasingly being used to help constrain magnetic field extrapolation codes (e.g., Wiegelmann et al. 2008; Jing et al. 2011; Aschwanden 2016; Aschwanden et al. 2016; Zhu et al. 2016). Such codes typically use nonlinear force-free field extrapolation methods based on photospheric magnetic field measurements. Since the boundary conditions are most readily measured in the photosphere but the field is not necessarily of a force-free nature at those heights, various methods are used to preprocess the magnetic field measurements (e.g., Régnier 2013) or to incorporate magnetic field information from a more force-free boundary region such as the upper chromosphere (Metcalf et al. 2008). The latter method is entirely dependent on the assumption that chromospheric features such as fibrils and spicules, which dominate the upper chromosphere, are well aligned with the magnetic field. For example, Aschwanden et al. (2016) extrapolated magnetic field lines using photospheric vector field measurements from the Helioseismic Magnetic Imager (Scherrer et al. 2012) on board the Solar Dynamic Observatory (SDO; Pesnell et al. 2012) using the Vertical-Current Approximation Nonlinear Force Free Field code (VAC-NLFFF code; Aschwanden 2016), which finds the best match of the extrapolated field lines with chromospheric and coronal features observed with the following imaging instruments: the Interferometric Bidimensional Spectrometer (Cavallini 2006), the Rapid Oscillation in the Solar Atmosphere instrument (Jess et al. 2010), the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014), and the Atmospheric Imager Assembly (AlA; Lemen et al. 2012) on board SDO.

Are these chromospheric structures really aligned with magnetic field lines? In the single-fluid magnetohydrodynamics (MHD) framework, the assumptions that the upper chromosphere in the vicinity of a network or plage is in the low plasma β regime, and that the observed features are thus aligned with the magnetic field, seem reasonable. However, there are observational clues that this may not always be the case. For example, de la Cruz Rodríguez & Socas-Navarro (2011) show that in some cases chromospheric fibrils do not necessarily follow the magnetic field structures. They used Stokes profile observations of Ca II 8542 Å from the Spectro-polarimeter for INfrared and Optical Regions (Socas-Navarro et al. 2006) at the Dunn Solar Telescope and CRisp Imaging Spectro-polarimeter (Scharmer 2006) in full Stokes mode at the Swedish 1 m Solar Telescope (Scharmer et al. 2003) and found that the misalignment of some fibrils with the magnetic field lines can be larger than 45°.

What causes such a large deviation from the magnetic field direction? It is already known that, in principle, the neutral population in the partially ionized chromosphere can have an impact on the force-free nature of the chromospheric field (Arber et al. 2009). Is it possible that neutrals can also lead to
magnetic field?

In order to better understand this misalignment of the magnetic field lines with upper chromospheric features, we performed 2D advanced radiative MHD simulations using the Bifrost code (Gudiksen et al. 2011). We included the effects of the interaction between ions and neutrals in the magnetized and partially ionized gas of the middle to upper chromosphere by including ambipolar diffusion in the induction equation (the so-called generalized Ohm’s law) of our MHD code. Our simulations show that while neutrals are mostly coupled to the magnetic field through collisions with ions, under certain conditions the collisional frequency between neutrals and ions is low enough that the ions can become somewhat decoupled from the magnetic field, thereby allowing the magnetic field to diffuse and magnetic energy to be dissipated into thermal energy (see, among others, Cowling 1957; Braginskii 1965; Parker 2007). We find that our simulation naturally produces misalignment of the magnetic field and spicules and explains why some of the observations show field lines that are misaligned with chromospheric features.

2. MODEL DESCRIPTION

The Bifrost code solves the full MHD equations with non-gray, non-local thermodynamic equilibrium (LTE) radiative transfer (Hayek et al. 2010; Carlsson & Leenaarts 2012) and thermal conduction along the magnetic field. The code is described in detail in Gudiksen et al. (2011). In addition, we have also included ion-neutral interaction effects, adding two new terms to the induction equation, i.e., the Hall term and the ambipolar diffusion:

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[ \mathbf{u} \times \mathbf{B} - \eta \mathbf{J} - \eta_{\text{Hall}} \frac{\mathbf{J} \times \mathbf{B}}{|\mathbf{B}|} + \frac{\eta_{\text{amb}}}{B^2} (\mathbf{J} \times \mathbf{B}) \times \mathbf{B} \right] - \frac{\nabla \cdot \mathbf{B}}{\rho},
\]

where \( \mathbf{B}, \mathbf{J}, \mathbf{u}, \) and \( \eta, \eta_{\text{Hall}}, \eta_{\text{amb}} \) are the magnetic field, the current density, velocity field, the ohmic diffusion, the Hall term, and the ambipolar diffusion, respectively (see Cowling 1957; Braginskii 1965, for the derivation of this equation). J. Martínez-Sykora et al. (2016, in preparation) describes the details of the implementation of the Hall term and ambipolar diffusion in the Bifrost code and extensive tests of this code are described by Martínez-Sykora et al. (2012). The collision cross-sections used here are the measurements and calculations listed by Vranjes & Krtič (2013).

For this work, it is relevant to reformulate expression (1) as follows:

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[ \mathbf{u} \times \mathbf{B} - \eta \mathbf{J} - \mathbf{u}_H \times \mathbf{B} + \mathbf{u}_A \times \mathbf{B} \right],
\]

where the Hall velocity is \( \mathbf{u}_H = (\eta_{\text{Hall}} \mathbf{J})/|\mathbf{B}| \) and the ambipolar velocity is \( \mathbf{u}_A = (\eta_{\text{amb}} \mathbf{J} \times \mathbf{B})/B^2 \) (see also Cheung & Cameron 2012; J. Martínez-Sykora et al. 2016, in preparation). The ambipolar velocity can be understood as the velocity drift between ions and neutrals, i.e., the magnetic field lines are attached only to the ions. To gain a better intuitive grasp of how these effects (and velocities) act on the magnetic field, let us imagine a curved magnetic “field line” contained in a plane. Since the Hall velocity is a function of \( \mathbf{J} \), the Hall velocity moves the magnetic field line out of the plane. Because the ambipolar diffusion is a function of \( \mathbf{J} \times \mathbf{B} \), the ambipolar velocity will be perpendicular to the field line but contained within the plane. Therefore, the ambipolar diffusion relaxes the magnetic tension of the field line.

3. MODELS AND INITIAL CONDITIONS

The simulation used here is the so-called GOL (Generalized Ohm’s Law) simulation in J. Martínez-Sykora et al. (2016, in preparation), i.e., it is a 2.5D model that spans from the upper layers of the convection zone (2.5 Mm below the photosphere) to the corona (40 Mm above the photosphere). Convective motions perform work on the magnetic field and introduce magnetic field stresses in the corona. This energy is dissipated and creates the corona self-consistently as the energy deposited by magnetic and kinetic energy dissipation are spread through thermal conduction (Gudiksen & Nordlund 2002) and the temperature reaches up to two million degrees (top panel, Figure 1). The horizontal domain spans 96 Mm. The spatial resolution is uniform along the horizontal axis (14 km) and non-uniform in the vertical axis, allowing a smaller grid size where needed, i.e., in locations such as the photosphere and the transition region (TR; \( \sim 12 \) km). With this resolution, the ambipolar diffusion is larger than the artificial diffusion (by 3–5 orders of magnitude) in extended regions in the chromosphere, including the regions with large misalignment (J. Martínez-Sykora et al. 2016, in preparation).

The initial magnetic field has two plage regions of opposite polarity that are connected and form loops that are up to \( \sim 50 \) Mm long (Figure 1). The mean unsigned field strength at the photosphere is \( \sim 190 \) G. The initial magnetic field is a potential field. First we run this setup for roughly 1.5 hr. After transients have passed through the domain, we continue the simulation for another half hour of solar time (see J. Martínez-Sykora et al. 2016, in preparation, for a detailed description of the setup of the model).

4. RESULTS

The ion-neutral interaction effects implemented through the generalized Ohm’s law strongly influence the state of the simulated chromosphere (J. Martínez-Sykora et al. 2016, in preparation). Here we focus on misalignment of the magnetic field direction from the chromospheric thermodynamic features.

Generally, the ion-neutral interaction effects impact the magnetic field distribution and configuration. Figure 2 compares the magnetic free energy from the model that includes ion-neutral interaction effects with the free energy in an equivalent model that has been run without ion-neutral interaction effects. The ambipolar diffusion helps to accumulate a bit of extra magnetic free energy in the middle-upper chromosphere and transition region but reduces it in the photosphere (\( \sim 10\% \)) and in the corona (by a factor between 1.5 and 4). The magnetic free energy is reduced in the photosphere because a small portion of the accumulated magnetic field in the photosphere is sporadically diffused into the chromosphere in regions where the ambipolar diffusion is large enough at low enough heights (J. Martínez-Sykora et al. 2016, in preparation). Ion-neutral interaction effects prevent magnetic free energy...
from reaching the corona because it is largely dissipated in the chromosphere due to the ambipolar diffusion.

We also find that under certain chromospheric conditions, thermodynamic structures may decouple from the magnetic field lines due to the ambipolar velocity. As a result of this, misalignments are seen in most of the simulated spicules (we see a dozen spicules in 30 minutes), and in TR loops (a few of them achieve rather strong misalignment within 30 minutes). Figure 3 shows temperature maps of the evolution of several spicules, with magnetic field lines overplotted as white lines. At the early stages of spicule evolution, they follow the magnetic field lines. However, as the spicules evolve in time, field lines start to decouple from the apparent spicular structure. This figure shows misalignment angles of up to \( \sim 25^\circ \), and this simulation shows features that can reach a misalignment with field lines of up to \( 40^\circ \) in the most extreme cases. As a result, sometimes the magnetic field lines do not follow the thermal structures in the upper chromosphere and TR.

This also impacts the evolution of the features. Toward the end of the evolution of these spicules, they become wider and their footpoints drift from left to right.

The thermodynamic chromospheric features do not follow the magnetic field lines when the following conditions are met: (1) ambipolar diffusion, magnetic field strength, and the current perpendicular to the magnetic field are high enough; (2) the timescales of the thermodynamic processes are longer than, or of the same order as, the ambipolar timescales. In other words, the misalignment does not depend on the fluid velocity. Instead, it depends on the length and lifetime of the features, the ambipolar velocity, and the surrounding magnetic field.

This often occurs in upper chromospheric spicules for several reasons. Since the density drops drastically as a function of height and also as a function of time (because of the expansion of the spicule), the ambipolar diffusion increases drastically (panel C, Figure 4). This is a result of low temperature and low ion-neutral collision frequency.
One component of the magnetic field advection comes from the ambipolar velocity (Panel (B)), which differs from the advection flows and the direction of the spicule and separates the magnetic field lines from the spicule. Consequently, the field lines along the spicule have two velocity components: (1) one from the advection that is the same as the plasma motion (Equation (2)), i.e., this flow will move the field lines and the chromospheric features in the same direction (see the flow velocity in Panel (A) in Figure 4), and (2) a second component that is completely detached from the plasma motion and is perpendicular to the field lines (see the ambipolar velocity in Panel (B) in Figure 4). The latter component is the one that leads to a misalignment of the field lines with the spicules. This misalignment is large as long as the displacement of the field lines due to the ambipolar velocity is large enough during the lifetime of the spicule.

Figure 4. An absolute velocity map with velocity fields as white vectors is shown in panel (A); an absolute ambipolar velocity map with ambipolar velocity fields as white vectors is shown in panel (B); and the ambipolar diffusion in logarithmic scale is shown in panel (C). Magnetic field lines are shown as thin white lines and the temperature contour at 105 K is shown as a thick white line.

5. DISCUSSION

Our 2.5D radiative MHD simulation includes ion-neutral interaction effects and produces some examples of chromospheric features that are decoupled from the magnetic field direction. This is a result of ion-neutral interaction effects in the chromosphere and can occur when the ambipolar diffusion and the current perpendicular to the magnetic field lines are large, and the thermodynamic timescales are at least of the same order as the ambipolar velocity timescales, whereas the simulation without ambipolar diffusion does not show any appreciable misalignment. The simulated features that become misaligned from the magnetic field have lifetimes of the order of a few minutes. The timescale becomes shorter in regions with large currents that are perpendicular to the magnetic field lines and with large ambipolar diffusion due to low values of the temperature, ion-neutral collision frequency, and/or ionization degree. Under these conditions the magnetic field may undergo evolution that is different from that of the thermodynamic structures. For example, decaying spicules may change their connectivity with “different” field lines crossing the spicule. In such a case, the spicules may show a horizontal displacement at the same time as they disappear (toward the end of their lifetime). This process can provide a natural explanation for the observations of de la Cruz Rodríguez & Socas-Navarro (2011) where fibrils or spicule-like features do not necessarily follow the magnetic field direction.

Our model shows that the misalignment is not uniform in space or time, with some structures being less affected. In addition, dynamic features appear to be typically more misaligned toward the end of their lifetimes. This occurs in particular in regions with enough current perpendicular to the magnetic field, i.e., where there is large magnetic tension. Such conditions can also be expected in active regions with strong currents, such as in newly emerging active regions. However, it is a priori not clear how one can determine from the observations alone which features are likely not well aligned with the magnetic field. Future work will be needed to investigate how misalignment can be estimated based on observational clues, such as the temporal behavior of the structures or the presence of currents.

Our results suggest that ion-neutral interaction effects may have a significant impact on magnetic field extrapolation methods. Within the chromosphere, the ambipolar diffusion shows strong variations in both space and time. In regions where the ambipolar diffusion is strong the magnetic field will be more potential. However, at the boundaries between regions of strong and weak ambipolar diffusion, the magnetic field lines may have strong changes in the connectivity. These variations in space and time of the ambipolar diffusion impact the magnetothermodynamic processes in the chromosphere (J. Martínez-Sykora et al. 2016, in preparation). This was missing in previous numerical models (Carlsson et al. 2016). It is unclear how such spatial and temporal complexity can be captured in field extrapolation methods that are based on photospheric vector magnetograms.

Magnetic field extrapolation codes that attempt to use the direction of chromospheric features in order to find the best match with the field lines may provide field configurations that are incorrect. This is because the magnetic field may not be well aligned with the chromospheric features, due to the presence of ambipolar diffusion. As a result of this, measurements of the misalignment between features and magnetic field
extrapolation using these methods may be incorrect and in general may be underestimated (Aschwanden et al. 2016). Future studies of these extrapolation codes should investigate this issue further by trying the method on synthetic data from these types of radiative MHD models that include ion-neutral interaction effects, and comparing with the actual magnetic field.

Many studies of the solar atmosphere, in particular the corona, are undertaken using 1D hydrodynamic loop models (e.g., Klimchuk & Bradshaw 2014). Such models are based on the assumption that thermodynamic evolution occurs along magnetic field lines or tubes (1D). However, our results indicate that the decoupling of the field lines from plasma frequently occurs in the chromosphere. This will change the connectivity of each element along the 1D models. In addition, ambipolar diffusion fundamentally undermines the assumption that the plasma is tied to the field on timescales of many minutes. As we have shown, this is not always the case. Therefore, these 1D models cannot capture or mimic the physics of the processes that connect the corona to the chromosphere and TR.

Leake & Arber (2006) performed 2D simulations of flux emergence with ambipolar diffusion. They also noticed that the magnetic field is more potential in the atmosphere, due to the ambipolar dissipation. However, they achieve currents that are several orders of magnitude smaller for the case with ambipolar diffusion than those for the case without ambipolar diffusion, whereas we achieve currents that are from 1.5 to 4 times smaller in the case for ambipolar diffusion than those without ambipolar diffusion. This is most likely due to the highly simplified setup of the ambipolar diffusion in their model chromosphere and also due to them missing many of the chromospheric processes that are driven by the convective motion.

Our results also have a potential impact on more advanced 3D radiative MHD models. This is because the magnetic field energy deposition in the corona in radiative MHD models will change as soon as ion-neutral interaction effects are introduced. For example, Peter (2015) noticed that larger domains show stronger flows and Doppler shifts for TR EUV profiles (similar to observations), compared to smaller simulated domains (Hansteen et al. 2010, 2015). Ion-neutral interaction effects will impact these results and deeper investigations that include ion-neutral effects must be performed for computational domains of various sizes.

Our simulation suffers from several limitations that need to be addressed. Our simulation does not include time-dependent ionization, which would impact the spatial and temporal distributions of ambipolar diffusion in the chromosphere (Leenaarts et al. 2007; Golding et al. 2014). The process described above is also strongly constrained to the two dimensions of the model, therefore an expansion of these models into three dimensions is needed. Finally, the Generalized Ohm’s law is valid as long as the timescales are much larger than the ion-neutral collision frequencies, but in the TR this may not always be fulfilled and ions may decouple from neutrals (Martínez-Sykora et al. 2012). This can potentially alter these results.

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