TACKLING THE CORONAL HEATING PROBLEM USING 3D MHD CORONAL SIMULATIONS WITH SPECTRAL SYNTHESIS

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Abstract

The lower corona and transition region of the Sun are highly structured and very dynamic. To account for both the structure and the dynamics one has to apply a time-dependent three-dimensional model description. Recently Gudiksen & Nordlund (2002) succeeded in constructing such a 3D MHD model for an active region with the heating being due to braiding of magnetic flux.

We have now calculated spectra of prominent EUV emission lines from such model calculations and compared them to observations. The main result from this study is that the flux-braiding heating is resulting in the right differential emission measure (DEM) curve, i.e. we can reproduce the increase of DEM for low temperatures, without any spurious assumptions. Furthermore the Doppler shifts of the synthesised lines match the observed Doppler shifts strikingly well.

To our knowledge this is the first model to reproduce the DEM and Doppler shift variations with temperature qualitatively and quantitatively. It also provides a unique tool to explore stellar coronae by changing the boundary conditions, in particular the photospheric magnetic field and velocity structure.

Key words: Sun: corona — stars: coronae — Sun: UV radiation — MHD

1. Introduction

In the late 1930s spectroscopic observations of the Sun and the identification of coronal lines as being from highly ionised species made it clear that the corona of the Sun is a million degree hot plasma (Grotrian 1933; Grotrian 1939; Edlén 1942. Shortly after that the first models for heating the corona have been suggested; e.g. Schwarzschild (1948) investigated the role of upward propagating acoustic waves resulting from the convection as seen in the photosphere. However, further research showed that acoustic waves are not sufficient to sustain a solar-type corona, but that the magnetic field has to play an important role. Much theoretical work has been devoted since then to understand the heating of stellar coronae; see e.g. the proceedings of Ulmschneider et al. (1991), the review by Narain & Ulmschneider (1996) or the upcoming proceedings of a SOHO workshop (Danesy 2004).

One major class of heating processes is based on the (stochastic) footpoint motions of the coronal magnetic field being rooted in the photosphere and was introduced by Parker (1972) — see also Sturrock & Uchida (1981); Parker (1983); van Ballegooijen (1986); Heyvaerts & Priest (1992). The footpoints are shuffled around in the photosphere by the convective granular motions leading to a braiding of the field lines. The resulting field gradients give rise to currents which are finally dissipated and heat the plasma. Recently several studies concentrated on the change of the photospheric magnetic field structures (e.g. Priest & Schrijver 1999; Priest et al. 2002) induced by the changing “magnetic carpet” (Schrijver et al. 1998). To investigate the details of the energy deposition due to field line braiding numerical experiments have been conducted (Hendrix et al. 1996; Galsgaard & Nordlund 1996). These efforts finally resulted in the first 3D MHD model for a small active region on the Sun based on the field braiding mechanism (Gudiksen & Nordlund 2002). The present paper will concentrate on the observational signatures as to be expected from this type of complex 3D models.

2. Heating and dynamics: what to observe?

In the light of the numerous suggestions for the coronal heating process the major question might not be how the corona is heated, but how to distinguish between different suggestions! As it was realized in solar and stellar wind theory very long ago, the process of plasma heating is very closely related to the acceleration of the wind — the acceleration and the heating cannot be treated separately. For investigations of magnetically closed coronal structures, which dominate the EUV and X-ray emission from solar and stellar coronae, this implies that the heating and the dynamics of the plasma have to be treated together. This is quite clear as any energy released on small scales (e.g. nanoflares in loops) or not exactly symmetric (asymmetric loop heating) will inevitably lead to plasma flows on all scales, ranging from flows as observed in explosive events (e.g. Innes et al. 1997) to large scale flows through a whole loop (e.g. Mariska 1988). So far most studies concentrate on the analysis of the intensities as observed from solar or stellar coronae. In the simplest case, which is widely used, the form of the differential emission measure is investi-
gated. This might provide information on how the plasma is distributed with respect to the different temperatures in the corona, e.g. how much emission originates from flare-type and quiet corona conditions. However, it does not provide information on the dynamics. For example Priest et al. (1998) compared the model temperature structure for different distributions of the heating (uniform, concentrated at loop top or foot) with inversions based on Yohkoh soft X-ray images. By concentrating on the energetics, however, they used only part of the information that can be acquired.

Using spectroscopy one has access not only to the intensities, but also to the line shifts and widths. These two quantities provide vital information on the large scale (Doppler shift) and small scale flows (non-thermal line width), the latter including non-resolved motions, like turbulence. Any decent model for coronal heating makes predictions on the plasma dynamics, i.e. on the large and small scale flows, and thus an investigation on the Doppler shifts and line widths is of vital importance to understand the relevant physics of the corona.

On the quiet Sun the Doppler shifts show a characteristic variation with line formation temperature: from 10000 to about 200000 K the average Doppler shifts rise from zero to some 15 km/s to the red. Above that temperature the redshifts decrease again and turn into blueshifts into the corona (cf. thick dashed line in Fig. 4). It also has to be noted that the spatial scatter of the Doppler shifts on the Sun is quite enormous (larger than the mean line shift, see Peter 1999). The same holds for the temporal variability (e.g. Brković et al. 2003). Stars show a similar behaviour of the line shift over a range of activity levels (e.g. Pagano et al. 2004). Many models have been suggested to understand the Doppler shifts, but most do not really match the observations. And as all these models are 1D models (at best) they cannot account for the complex spatial structure of the low corona. The implications of the Doppler shift observations and a discussion of some models can be found in Peter & Judge (1999) and Peter (2004).

The line widths can provide vital information on the small scale not-resolved motions. These can either be due to small scale mass flows, turbulence or wave action. In the quiet Sun the non-thermal velocity rises from a bit more than 10 km/s in the low transition region to almost 30 km/s around 300000 K. It then drops again towards the corona (cf. thick dashed line in Fig. 5 and Chae et al. 1998). Line width observation above the limb contain information on the wave action (Hassler et al. 1990) as well as ion temperatures (Tu et al. 1998).

Finally the differential emission measure derived from the line intensities provides information on the distribution of the plasma with temperature. On the quiet Sun it reaches a minimum around 200000 K and steeply rises towards lower and higher temperatures (cf. thick dashed line Fig. 6). At temperatures well above a couple of million K the emission measure of the quiet Sun finally drops. For other stars with more active corona this high temperature maximum is shifted to higher temperatures and often shows multiple peaks. The models for the transition region and low corona so far failed to give a solid explanation for the increase at low temperatures. Models based on classical heat conduction and a relatively simple stratified structure of the transition region (e.g. Gabriel 1976) pro-

Figure 1. Spatial maps synthesised from a single time step of the 3D MHD model. Shown are maps in Doppler shift and line intensity for S(1533 Å) from the low transition formed below 200000 K. The left panel shows the Doppler shift map from the synthesised spectra as seen from straight above, the middle panel shows the same for line intensity. This corresponds to the appearance near disk center. The two panels to the right show side views of the computational box along the x and y axis in line intensity. The intensities I are scaled with respect to the average intensity ⟨I⟩ of the respective map. The resolution of the spatial maps is about 400 km, i.e. about twice as good as current solar instrumentation.
duce a monotonic drop of emission measure from 200 000 K towards the chromosphere. This is because the heat conduction scales with \( T^{5/2} \partial T/ \partial T \): at lower temperatures the gradient has to become extremely steep to make up for the inefficient conductivity there and thus the source region for lines originating from the low transition region cover an extremely small volume resulting in a very small emission measure. Many proposals have been made to overcome this problem, the most "natural" of them being that the low corona hosts also of a multitude of low-lying cool structures that give rise to the increasing emission measure at low temperatures (Dowdy et al. 1986). There is also some spectroscopic evidence for such a multi-structured corona consisting of coronal funnels, large scale loops and cool small loops (Peter 2000; Peter 2001). However, the main problem with such a multi-structure scenario is that basically it is an ad-hoc assumption.

A decent model for the structure, dynamics and heating of the corona has to provide some information on the above observations of average line shifts, widths and intensities (or rather emission measures). A model that only gives a good explanation of the heating, but fails to account for the dynamics, i.e. the Doppler shifts, cannot be considered a good model.

3. FORWARD MODEL APPROACH

To account for the complex structure of the corona as proposed e.g. by Dowdy et al. (1986) and to describe the heating and dynamics of the corona we use a forward model that consists of the 3D MHD model and a code to compute the resulting emission line spectra.

The 3D MHD model includes the atmosphere from the photosphere to the lower corona in a 60×60 Mm horizontal times 37 Mm vertical box and is described in more detail in Gudiksen & Nordlund (2004b) and Gudiksen & Nordlund (2004a). It solves the mass, momentum and energy balance, the latter one including classical heat conduction (Spitzer 1956) and optically thin radiative losses as piecewise power laws. The temperature of the chromosphere is kept near a prescribed profile by Newtonian cooling. Initially the magnetic field is given by a potential field extrapolation with the lower boundary as observed by MDI/SOHO for an active region. Further on in the simulation the field evolves self-consistently and becomes non-potential, of course. The system is driven by horizontal motions at the lower boundary. The flow field is constructed using a Voronoi-tessellation technique (Okabe et al. 1992) and reproduces the typical pattern of the granular motions of the Sun (Schrijver et al. 1997). Through this the power spectra of the velocity and the vorticity are also reproduced.

This procedure leads to a heating of the corona just in the way Parker described (see Introduction). The field line braiding gives high coronal temperatures of a million K and a system of hot loops is forming, connecting the magnetic concentrations of the active region. Furthermore the system reaches some sort of quasi-stationary state, with large fluctuations in time and space, or in other words, the system is quite dynamic. The detailed discussion of the MHD results can be found in Gudiksen & Nordlund (2004b) and Gudiksen & Nordlund (2004a).

The main question now is if the spatial structure and dynamics of the MHD model result in the observed patterns of the spectroscopic properties as discussed in the preceding section. Therefore we computed the emission line spectra which are to be expected from the model calculation.

Using the density and temperature from the MHD model we calculated the emissivity for a number of EUV emission lines using the atomic data package CHIANTI (Dere et al. 1997; Young et al. 2003). The lines have been selected in order to allow for a good comparison with the

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**Figure 2.** Same as Fig. 1, but for C IV (1548 Å) formed in the middle transition region at about 100 000 K.
SUMER spectrograph on SOHO providing high quality solar data, but any other set of lines can be evaluated. The main assumption in this procedure is ionisation equilibrium. To check this critical point, we compared the ionisation times with the dynamic time scale, i.e. the time to cross the line formation region, which typically covers 0.15 dex in temperature. We found that for the present model the assumption of ionisation equilibrium is sufficient. Nevertheless, for future models including a higher level of activity the inclusion of non-equilibrium ionisation effects is very important.

Now having the emissivity at each grid point and time step we can use the velocity from the MHD model to calculate the spectrum at each grid point, assuming a Gaussian profile with a thermal width. Finally we integrate along the line-of-sight, which gives us maps of spectra, just in the way SUMER or CDS on SOHO provide raster maps. Calculating the moments of the line profiles results in maps of line intensity, shift and width. Figs. 1–3 show such Doppler maps (left panels) and intensity maps (middle panels) for a vertical line of sight, which represents the situation at disk center. The right panels show the respective intensity maps for horizontal lines-of-sight (along x- and y-axis), representing the situation at the limb. Further details on the emission line processing and its assumption will be available in Peter et al. (2005).

4. Spatial structures: Doppler & intensity maps

The appearance in the three lines shown in Figs. 1–3 is quite different. In the coronal line (Fig. 3) we see relatively smooth structures in line intensity that form large loops connecting the magnetic concentrations in the photosphere. In contrast, the variations in Doppler shift are remarkable. This illustrates what we would see if an instrument would be available to obtain Dopplergrams of the solar corona!

The intensity structures in the transition region are much sharper than in the corona, which is because of the less efficient heat conduction. In the middle transition region we also see a very highly structured Dopplergram (Fig. 2), sometimes with large jumps from blue to red over a very small distance, as it is known from observations. Also the scatter is considerable in the C IV Doppler image, with values ranging from 20 km/s to the blue to 20 km/s to the red, similar to what is found with observations (Peter 1999). In the low transition region (Fig. 1) the appearance is similar to the middle transition region, but now with much smaller amplitudes in Doppler shifts.
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In the lines formed below 200 000 K numerous small low lying loops can be seen, which do not coincide with the loops seen in higher temperature lines (compare the right panels of Figs. 1 and 2 to the coronal line in Fig. 3). This clearly supports the scenario for the lower corona as proposed by previous studies (e.g. Dowdy et al. 1986, Peter 2001).

Overall the spatial structures we see in the synthesised spatial maps roughly resemble what we see in the real solar corona. Of course, here we do not see the structures of the super-granular network, as this is not included in the MHD model. However, one can expect to find the chromospheric network, when we are able to increase the spatial resolution of the numerical model in order to incorporate the magnetic fields of the chromospheric network together with the active region structures.

5. AVERAGE FLOWS: RESOLVED AND NOT RESOLVED

The average Doppler shifts from the spatial maps are displayed as a function of line formation temperature in Fig. 4 for two different time steps together with the observed trend (thick dashed). The overall match is very good, especially the peak at around 200 000 K. Only at the high temperatures the observed blueshifts are not reproduced (even though some time steps come quite close). The reason for this could be, e.g. a not appropriate treatment of the upper boundary or some missing processes, like acceleration on open field lines, which would give rise to blueshifts.

Nevertheless it should be stressed, that for the first time this model provides an overall match to the line shifts observed in the transition region without any fine-tuning or special assumptions on the geometry of the relevant coronal structures.

As for the non-thermal broadening, we get a close match for the low transition region and the low corona, but we miss the pronounced peak in the middle transition region, where we underestimate the non-thermal broadening (Fig. 5). As probably the spatial resolution is not high enough to resolve all the transition region line structures, we should not be surprised about this result. Future models with increased spatial resolution will have to show if the flux braiding mechanism predicts the right behaviour of the non-thermal line broadening.

6. DIFFERENTIAL EMISSION MEASURE

Using the synthesised spectral lines we performed a standard emission measure inversion, again using CHIANTI. The results are plotted as a thin solid line in Fig. 6. For the comparison with observations we have used line radii-ances from exactly the same lines (thick dashed; full disk observations with SUMER, Wilhelm et al. 1998).

The remarkable result is that the emission measure matches the observations very closely (we have scaled the observation by a factor of two to account for the difference between active regions and quiet Sun). We would like to emphasise especially that this work correctly predicts the emission measures below 200 000 K, i.e. the increase towards lower temperatures.

This shows that the scenario as proposed by Dowdy et al. (1986) is correct and that the low corona consists of a multitude of cool low structures under and next to larger loop systems. It is important to note that the cool structures are not simply the low-temperature ends of the hotter loops, which becomes clear when investigating the spatial maps (cf. Sect. 4). The area below the footpoints of the hot loops in the forward model covers about 2% of the (model) photosphere. And only about 10 to 15% of the emission from a typical transition region lines comes from those footprint areas. Thus the transition region emission is enhanced at the footpoints of hot loops, but the vast majority come from regions outside the hot loop system. Thus the cool structures exist independently of the hot structures and actually, they are not stationary, but highly intermittent. Nevertheless they dominate the emission at low temperatures and lead to the increasing emission measure at low temperatures.

7. DISCUSSION AND CONCLUSIONS

This forward modeling approach shows that the flux-braiding mechanism is a prime candidate for the coronal heating process. The spectra derived from a complex 3D MHD model show properties very similar to those observed with the Sun and solar-like stars. Especially the Doppler shifts and the emission measure as a function of temperature are matching the observations very well. For the first time this match was achieved without any fine tuning or special assumptions. The model shows that the whole corona is very intermittent with large fluctuations in time and...
Figure 6. Differential emission measure (DEM) as following from the MHD model compared to observations. The solid line shows the fit from the DEM inversion based on the lines displayed as bars, which have been synthesised from the MHD model. The dotted-dashed line displays the DEM curve as following directly from the MHD results. The thick dashed line is based on a DEM inversion using observed quiet Sun disk center line radiances observed with SUMER (Wilhelm et al. 1998) scaled by a factor of two.

space. A further discussion of the model results can be found in Peter et al. (2004).

This type of forward modeling is also of vital interest to understand stellar coronae. As to be found in these proceedings, other stars exhibit a quite different structure of the photospheric magnetic fields (e.g. Donati et al. 1999) and of convection patterns (e.g. Freytag et al. 2002). This type of forward model is a valuable tool to study the relevant processes in these coronae in detail and to compare the results for the spectral lines synthesised from the model directly to stellar observations. Further progress in numerical forward modeling will open a new path to study stellar coronae.

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References

Dere K. P., Landi E., Mason H. E., Monsignori Fossi B. C., Young P. R. 1997, A&AS, 125, 149

Edlén B. 1942, ZAp, 22, 30
Grotian W. 1933, ZAp, 7, 26
Grotian W. 1939, Naturwiss., 27, 214
Spitzer L. 1956, Physics of fully ionized gases, Interscience, New York