Letter to the Editor

Data-driven model of the solar corona above an active region

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ABSTRACT

Aims. In this study we aim to reproduce the structure of the corona above a solar active region as seen in the extreme ultraviolet (EUV) using a three-dimensional magnetohydrodynamic (3D MHD) model.

Methods. The 3D MHD data-driven model solves the induction equation and the mass, momentum and energy balance. To drive the system, we feed the observed evolution of the magnetic field in the photosphere of the active region AR12139 into the bottom boundary. This creates a hot corona above the cool photosphere in a self-consistent way. We synthesize the coronal EUV emission from the densities and temperatures in the model and compare this to the actual coronal observations.

Results. We are able to reproduce the overall appearance and key features of the corona in this active region on a qualitative level. The model shows long loops, fan loops, compact loops and diʃuse emission forming at the same locations at similar times as in the observation. Furthermore, the low intensity contrast of the model loops in EUV matches the observations.

Conclusions. In our model the energy input into the corona is similar as in the scenarios of fieldline-braiding or fluxtube tectonics, i.e. through the driving of the vertical magnetic field by horizontal photospheric motions. The success of our model shows the central role this process plays for the structure, dynamics and heating of the corona.

Key words. Magnetohydrodynamics (MHD) – Sun: magnetic fields – Sun: corona – methods: numerical

1. Introduction

When observed in the extreme UV, the corona of the Sun above an active region is dominated by plasma loops over a range of temperatures from just below one Million to several Million Kelvin. In the corona, the magnetic field channels the plasma and guides the energy flux. A one-dimensional model can capture the distribution and variation of intensities and flows along a loop, at least if correct variation of the energy input is prescribed. Still, it cannot account for the spatial complexity of the real corona, of course.

A three-dimensional (3D) model can account not only for the complex interaction of the various magnetic features, but it can also self-consistently provide the spatial and temporal distribution of the energy input (with all its limitations; Peter 2015). The first of these 3D models (Gudiksen & Nordlund 2002, 2005b,a) created a loop-dominated corona confirming the field-line braiding (Parker 1988) or fluxtube tectonics scenarios (Priest et al. 2002). One main question was then, and still is now: Can such a model recreate the actual observed corona, if driven by the observed changing magnetic field in the photosphere.

So far such models have been compared to observations in a generic sense and with good success. For example, results have been compared with respect to average quantities such as emission line Doppler shifts (Peter et al. 2004, 2006; Hansteen et al. 2010). Or individual features in the models have been picked out that resemble actual observed structures. This gave interesting matches in terms of the width of coronal loops (Peter & Bingert 2012) or transient extreme UV bursts (Hansteen et al. 2017).

In these models the driving of the magnetic field in the photosphere is prescribed by a photospheric velocity driver which mimics the solar granulation (Bingert & Peter 2011, 2013) or using models of magneto-convection directly included in the model (Gudiksen et al. 2011; Rempel 2017) or fed in through the boundary condition (Chen et al. 2014). Using a flux emergence model motivated by observations for the photospheric input, Cheung et al. (2018) were able to reproduce the emission signature of an C-class flare. Bourdin et al. (2013, 2014) used an observed magnetogram to drive the coronal evolution, but this was limited to a small active region just slightly larger than an X-ray bright point.

Magneto-frictional models have been used to recreate the corona driven by the changing observed photospheric magnetic field, but by design such models do not provide information on temperature and density (Cheung & DeRosa 2012). Instead they can only derive proxies for the coronal emission to be expected. Furthermore, in these models essential the currents are close to (anti-) parallel to the magnetic field, an assumption, which is not fully valid above active regions (Peter et al. 2015; Warnecke et al. 2017).

Here we use a data-driven 3D magneto-hydrodynamic (MHD) model that uses the observed (variable) magnetic field of an active region in the photosphere as a lower boundary condition. Most importantly, the model allows to synthesize the coronal emission. Consequently a direct comparison can be made between the model and the observed coronal emission from exactly the time of the driving magnetogram.

2. Data-driven 3D MHD model

We numerically solve the 3D resistive MHD equations, i.e. the induction equation together with the mass, momentum and energy balance, from the surface of the Sun into the corona. For
this we use the Pencil Code\textsuperscript{1} with its special module to account for the physics of the corona (Bingert & Peter 2011, 2013). This solves for the vector potential $A$, the velocity $u$, the density $\rho$ and the temperature $T$ in a fully self-consistent and time-dependent way.

One key element of a coronal model is the inclusion of (Spitzer) heat conductivity along the magnetic field that depends on temperature as $T^{5/2}$. For this we make use of non-Fourier heat flux evolution and semi-relativistic Boris correction (e.g. Boris 1970; Rempel 2017), both newly implemented into the Pencil Code to speed up the simulation significantly (see Chatterjee 2013; Warnecke & Bingert 2018, for details). The plasma is cooled by optically thin radiative cooling calculated from a prescribed radiative loss function. The details of the model are presented in (Bingert & Peter 2011, 2013; Warnecke & Bingert 2018) and will not be repeated here. We use a magnetic diffusivity of $\eta=5\times10^9$ m$^2$s$^{-1}$, ensuring a mesh Reynolds number of around unity, and a viscosity of $\nu=10^{10}$ m$^2$s$^{-1}$, similar to the Spitzer value at coronal temperatures and densities.

Our computational domain is a Cartesian box with $1024 \times 1024 \times 512$ grid points, representing $374 \times 374 \times 80$ Mm\textsuperscript{3} on the Sun, big enough to host a typical active region. We use periodic boundary conditions in the horizontal $x$ and $y$ directions. At the top boundary, the box is closed for all thermodynamic quantities and we apply a potential field condition for the magnetic field. At the bottom boundary ($z=0$), representing the solar surface, the temperature and density are fixed. Here, we prescribe the photospheric velocities using a granulation driver, which mimics the distribution of flows in time and space comparable to observed motions, following the original description by Gudiksen & Nordlund (2005b).

The central ingredient of our model is the implementation of the bottom boundary for the magnetic field. Here, we feed a time series of observed values for the (vertical) magnetic field and thus drive the evolution of the magnetic field in the photosphere matching the observed evolution. Because the time cadence of the magnetograms is much slower than the time step of the simulation, we interpolate between the magnetograms closest in time for every time-step of the numerical model. Photospheric velocities also act on the magnetic field at the bottom boundary and alter it. To keep the magnetic field at the bottom boundary evolving according to the observations, we employ a relaxation scheme. This smoothly forces the field at the bottom boundary to follow as prescribed by observations. We choose a time scale of 10 mins for this relaxation, motivated by the general time scale time the granular magnetic fields. This approach allows to generate upward directed Poynting flux and be close to the observed state at the same time (see Bingert & Peter 2011, 2013; Warnecke & Bingert 2018, for details).

To feed the simulation, we use a time series of line-of-sight magnetic field measurements of active region AR 12139 from the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) starting on 16. Aug. 2014 starting at 23:14:53 UT having a cadence of 45 s (Fig. 1). The region is very close to disk center and we therefore use the line-of-sight magnetic field for the vertical component in our simulation. The grid spacing of the model (366 km) is the same as the plate scale of the HMI observation (0.5”/pixel). We adjust the edges of the magnetograms to ensure they fulfill the horizontally periodic boundary conditions. We first run the simulation with the magnetic field from the first snapshot of the time series to let the temperature and density reach a quasi-stationary state which took around four solar hours. We then start feeding the time series of the changing magnetic field into the bottom boundary driving the evolution in the computational domain. The simulation then evolves for another half hour and in the following we focus our analysis on the snapshot at 16.5 mins.

3. Comparison with observations

The main goal of this study is the comparison of real observations to the coronal emission synthesized from our 3D MHD active region model driven by a time series of actually observed magnetograms. For this we derive extreme UV emission as it would be observed by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012). Based on the temperature and the density in the model, we use the temperature response kernel (Boerner et al. 2012)\textsuperscript{2} of the 171 Å channel that is dominated by emission from Fe$^{x}$ originating from just below 1 MK.

Overall, the numerical model does reproduce the dipole-like structure of the active region. In Fig. 2 we show the comparison of the model as viewed from straight above (left) and the observations near disk center (right) at the same time, i.e. the model has been evolved using the time-dependent observed magnetograms to the the same time as the observations shown here (16.5 mins). The peak emission from the observations and the simulation differ by a factor of less than six corresponding to differences in density of less than a factor of 2.5, see Sect. 5 for a detailed discussion. Having this in mind, we find an overall qualitative agreement, in particular for the following four features (numbers as in Fig. 2).

(1) **Long loops.** We find loops with lengths of 100 Mm to 200 Mm to connect opposite polarities at the edges of the active

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\textsuperscript{1} https://github.com/pencil-code/

\textsuperscript{2} Implemented in SolarSoft (http://www.lmsal.com/solarsoft/).
Fig. 2. Comparison of observed emission and emission synthesized from model. The left panel shows the emission of the AIA 171 Å channel of AR 12139 on 16th of August 2014 at 23-30-48 UT near disk center. The right panel shows the synthesized emission of the same channel from the simulation as viewed from the top of the computation box. For better visibility, we use a non-linear scaling of the images (power of 0.7 for observation, of 0.4 for synthesized emission). The color bars reflect this. The peak value of counts in the observations (corresponding to 1.00) is 3500 DN/pixel, while this is a factor of six less for the model. This difference corresponds to a factor of 2.5 in density (see Sect. 5). The inlay shows zoom-in of the region indicated by the white square showing a compact small loop. There the color scaling is linear. The observations and the model cover the same physical space on the Sun with a FOV of (515.9′)² corresponding to (374.4 Mm)². The numbers indicate features discussed in Sect. 3. The blue dashed rectangle indicates the zoom-in used in Fig. 3.

region in the northern (top) and the southern areas. These loops are associated with the large-scale potential-like magnetic field of the active region. The model loops look less helical than the observed ones, which probably is because of a lack of magnetic helicity in the observed magnetograms (see Sect. 5). Like in the observations, the model shows quite a few distinct long loops in the southern part, some being even at roughly the same location (1a). In the northern part, the observations show a more complex broad bundle of loops, where the model shows only a single long loop (1b). Still, the long model loop in the north shows a rather broad structure with a clear loop in the middle.

(2) Fan loops. In our model we find fan loops in particular on the western (right) side of the active region, at the same locations as very similar features are seen in the observations. A number of thinner structures quickly diverge forming a funnel-type structure in which the thinner strands are embedded (2a). Our model even reproduces a smaller feature of this type outside of the main part of the active region (2b) in an area of enhanced magnetic field (cf. Fig. 1). The fan loops in this setup appear also because of the horizontal periodic domain, see discussion about this in Sect. 5.

(3) Diffuse emission. Loops in the corona have a rather low contrast, often sticking out of a diffuse non-resolved background only by 10% to 30% (Del Zanna & Mason 2003; Peter et al. 2013). This is a general pattern we also see in our model. Most of the thin loops are embedded in much thicker structures of diffuse emission. In our model this is due to the high magnetic resistivity, but might well reflect the situation on the real Sun (for a discussion of the resistivity in the MHD models see Peter 2015).

(4) Compact loops. In the core of an active region, observations show an abundance of small transient features, maybe low-lying loops and related to small-scale magnetic patches in the photosphere (Peter et al. 2013). In the model we see only a few of these, probably because of the limited spatial resolution (see Sect. 5). The example shown in the inset of Fig. 2) exists for only less than 10 min in the simulation and is indeed a low-lying loop (cf. Sect. 4) rooted in two small opposite polarity patches that evolve quickly.

4. Energy deposition in the corona

The coronal structures that appear in the model do so because of energy deposition along field-lines that are driven at their footpoints by horizontal motions. Here, we briefly discuss the relation of the loops that appear to the energy input per particle. In Fig. 3 we display the distribution of the energy input at the same time as the snapshot of the emission shown in Fig. 2, but integrated in time for the 120 s leading up to that time. This accounts for the Alfvén transit time through the coronal structure so that disturbances of the magnetic field have time to spread.

Integrating the energy input per particle vertically shows loop-features not unlike those seen in emission (compare Fig. 3 to the emission in the blue dashed rectangle in Fig. 2). We see more spatial variation along the field-lines in the energy input than in coronal intensity. This is because of the efficient redistribution of energy through (Spitzer) heat conduction parallel to the magnetic field. Heat conduction quickly evens out temperature inhomogeneities leading to a comparably constant temper-
5. Limitations of the model

Despite the general success of this model in reproducing the observed corona of the active region there are several limitations that need to be kept in mind. Probably the main limitation is the moderate spatial resolution that does not allow to properly resolve the small-scale magnetic features on granular scales of 1000 km and less. Most of the shortcomings of our model might be traced to this limitation.

A higher spatial resolution would reveal smaller features of the photospheric magnetic field driving the model. These small magnetic patches would give rise to an enhanced (transient) energy input that would lead to more small-scale hot structures at low heights appearing as compact transient loops. Observationally, there are clear hints to such small-scale opposite polarities leading to heating of coronal structures (Chitta et al. 2017, 2019). With the current setup, we need observations of the photospheric magnetic field of the whole active region, and such data are available only at moderate spatial resolution of about 1″, as provided by HMI that we use here. High-resolution observations would provide only an insufficient field-of-view not covering the whole active region.

Also, our model does not produce regions at high temperature of 5 MK or above at sufficiently high density to give rise to X-ray loops in the core of the active region. Again, this could be due to the lack of resolution preventing opposite polarities to cancel and providing high energy fluxes into the corona (cf. observations by Chitta et al. 2018). In a model with a smaller computational domain, Archontis & Hansteen (2014) indeed see plasma heated to flare-like temperatures in compact (few Mm) structures. So, in general we would expect a higher energy input into the upper atmosphere if we would be able to feed the model with magnetic field data at significantly higher spatial resolution.

A corollary of the energy flux being too low in the model is that the model density might be too low, too. According to the scaling laws of Rosner et al. (1978) the coronal density scales roughly with the heat input to the power of 4/7. Thus the densities in our model, and hence the count rates, might be lower than in the observed active region. The count rates in the model are too low by about a factor of six corresponding to the density being too low by about a factor of 2.5. This probably also affects the distribution of the densities along the loop, which is why we scaled our model emission non-linearly with a power of 0.4 in Fig. 2 (while the observations are scaled closer to linear with a power of 0.7).

The loops in our model corona look more potential-field-like than the loops in the observations. In our model we prescribe the vertical component of the magnetic field only, but not the horizontal component (that is not available at 45 s cadence and this large field of view with HMI). Thus, we would miss any helical component of the magnetic field which would lead to a more twisted appearance of the magnetic field. Also, this would increase the energy input into the system and thus help alleviate the problem mentioned above, at least to some extent.

Finally, in our model we assume periodic boundary conditions (as most other 3D MHD models of the solar atmosphere do). This implies that the field-lines of the fan loops on the western (right) side of the active region leave the box on that side and enter the box again on the other. So in the model the fan loops connect to an (other) active region. On the real Sun such a connected active region would be far away, much further than the size of an active region. In the model we tried to account for this by having the active region surrounded by enough quiet Sun, so that hopefully the appearance of the fan loops is realistic.
We think that none of the above limitations would alter the main conclusion of our study, namely that our data-driven model can account for the structures seen on the real Sun. Still, future models will have to address these issues step by step.

6. Conclusions

In our study we show that we can reproduce many aspects of the corona above an active region using a data-driven 3D MHD model. The emission we synthesize from the model reproduces qualitatively the observed coronal features of this active region: long loops, fan like loops, small transient loops in the active region core. Also, we see these model features embedded in a diffuse background of coronal emission as it is the case on the real Sun, where a typical loop has a small contrast of only 10% to 30% to the background.

Our data-driven model shows that the structure of the observed photospheric magnetic field and its temporal evolution fully governs the appearance of the corona in an active region. Driving the magnetic field at the surface induces currents in the corona just at the right places: here the plasma is heated and forms extreme UV loops in the model just where they also appear in the real observations. The energy input in our model is solely based on the driving of the magnetic field and is thus very similar to the scenarios of field-line braiding (Parker 1988) and fluxtube tectonics scenarios (Priest et al. 2002). Consequently the success of our model supports these heating scenarios.

The major shortcoming of our work is the lack of spatial resolution of the photospheric field: to cover a full active region, observational data are available only at moderate resolution of around 1″. However, we can expect smaller magnetic patches to play a significant role in energizing the corona. This could lead to a higher energy input and, in particular, also to a higher structuring of the corona in the core of the active region. Likewise, including the horizontal component of the magnetic field would increase the energy input and, in particular, lead to a more twisted appearance of the coronal loops in the model, bringing them closer to the actual observations.

Despite the limitations outlined in Sect. 5, our data-driven 3D MHD model does reproduce the overall appearance of the corona in an active region. This first look at the results shows that the driving of the corona by the observed magnetic field at the surface level indeed gives rise to coronal structures that appear in the model at (roughly) the same time and location as in the observations of the real Sun.

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