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Heating the solar corona

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Abstract. The heating mechanism at work in the solar corona has been unknown since the temperature of the corona was discovered in the late nineteen thirties. Here I will present results from a model which we believe is the first model which allows forward modeling of observational signatures, and can fit several observational features of the solar corona. If this model proves to be a correct representation of the solar corona, the question of the coronal heating mechanism will finally be solved.

Key words. Magnetic Fields - Sun: corona - Sun: magnetic fields

1. Introduction

The corona of our Sun is extremely hot compared to its surface. The temperature rises from roughly 5500 K in the solar photosphere to an average temperature of one million K in the corona. The temperature increase happens over a distance of a few thousand kilometers which is roughly 0.01 % of the solar radius. Observing the layers between the solar surface and the lower corona, makes it clear that the magnetic field plays an ever increasing role with increasing height. The reason being that the pressure scale height of the gas is much smaller than the distance over which the magnetic field strength decreases. This leads to a rapid change of the dominant force in the solar atmosphere. In the photosphere the plasma motions are much stronger than the magnetic field, except for extreme locations such as sun spots, while in the corona the magnetic forces are much stronger than the gas forces. It has been known for some time that the heating of the solar corona has to be connected with the magnetic field. Consequently a number of theories that utilize the magnetic field as a main component have been developed to explain the heating of the solar corona. All rely on the fact that the kinetic energy available in the solar photosphere is much larger than the energy needed to heat the solar corona. The heating theories are split into two main categories depending on the frequency of disturbances the magnetic field is subjected to. Alternating Current (AC) heating theories rely on the photosphere to excite disturbances in the magnetic field faster than the magnetic field can relax to an equilibrium. The waves excited in the magnetic field then have to dissipated in the corona which is not easy, but several suggestions to how this major hurdle can be overcome have been made, among them mode conversion, resonant absorption (Ionson 1978; Davila 1987) and phase mixing (Heyvaerts & Priest 1983). Direct Current (DC) heating mechanisms rely on slow movements in the photosphere to tangle the magnetic field until the build up of stress reaches a level where the magnetic field configuration becomes unstable and magnetic energy will have to be dissipated, converting magnetic energy into heat.

Observational evidence in favor of one or the other is hard to come by. The reconnection events produced by DC heating have been observed, but it is unclear if the observed events provide enough energy. Alfvén waves are extremely hard to observe in the solar corona, because the only observable signature they produce is a time varying Doppler shift. Observing Doppler shifts of emission lines in the solar corona cannot be done with high enough cadence to find clear signatures of Alfvén waves with present instruments.

Modeling efforts have not been able to solve this problem, mainly because of the many complications involved in modeling the solar corona. Consequently most models have only been able to argue that a theory is plausible but not been able to reduce the number of free parameters enough, nor been able to forward model observational signatures of a specific theory. That has left the coronal heating problem unsolved since the temperature of the corona was discovered in the late nineteen thirties.

2. Modeling requirements

It has become increasingly clear that a new generation of models of the solar corona is required to at least include the following points. New models should include the whole solar atmosphere from the driving surface in the photosphere to the corona as was pointed out by Aschwanden (2001). Kuperus et al. (1981) pointed out that models need to be time dependent, they should contain the correct driving, and finally such models should be non specific in the sense that they should be representative for most of the active regions on the sun. On top of these requirements it would be advantageous to keep the number of free parameters at an absolute minimum in order to minimize the available parameter space.

Those requirements have been very difficult to satisfy until recently. The complications are mainly the large range of length scales and time scales needed to be included. The length scales range from the dissipation length scale of a few meters to the scale of solar active regions of typically tens of megameters. The time scales range from the short time scale connected with thermal conduction to the lifetime of active regions.

3. A DC Heating Model

We developed a model of an active region that could satisfy these requirements. It is based on a three dimensional magnetohydrodynamics simulation of a solar active region. The reason such a simulation can satisfy the length scale requirement is due to experiments performed by Galsgaard & Nordlund (1996) and Hendrix et al. (1996). These groups performed a number of simulations of a simplified DC heating setup that were identical except for the numerical resolution. In such numerical models, a localized shock resistivity means that increasing the resolution is equivalent to lowering the magnetic resistivity. In these experiments neither reached the very low resistivity of the solar corona, but over the range they investigated, they saw no change in the dissipated energy when keeping the magnetic field driving identical. From an energetic view point this makes sense, because the stressing of the magnetic field loads the magnetic field with energy, which at some point reach a point where the twist and tangling of the field are so high that some instability makes the field reconnect and thereby dissipate some of the stored energy. This process must take place, since the magnetic field otherwise would act as an energy sink, and when the magnetic field reaches some maximum stable stress state, it has to dissipate energy at the same rate as it is pumped in and that cannot depend on the resistivity. The change in resolution showed that for low resolution the dissipation was localized in a few large regions, while for higher resolution, these broke apart into numerous smaller regions, the total dissipated energy remained the same. This supports the idea of nano flares as the energy dissipated by the smallest events given by the maximum stress level of the field at the smallest scale set by the coronal resistivity.

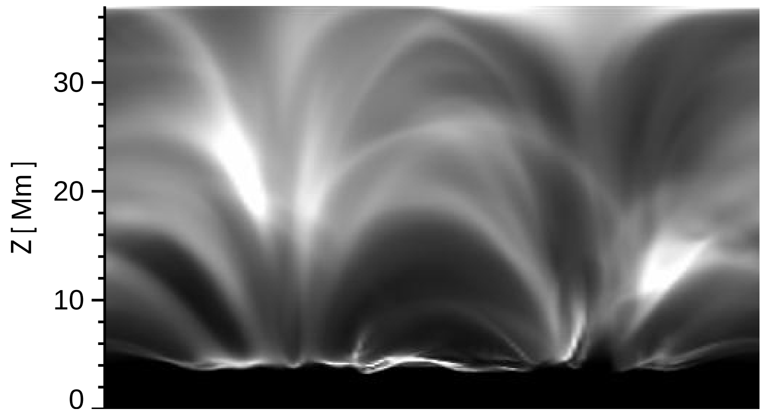

Fig. 1. The simulated box seen from the side, in a forward modeled TRACE 171 Åpass band, showing thin plasma loops with a temperature of roughly one million K.

3.1. Implemented Physics and Initial Conditions

The simulation (Gudiksen & Nordlund 2005b,a; Peter et al. 2004) contains a small solar active region with a box size of $60\times60\text{Mm}^2$ horizontally, reaching from the photosphere and 37 Mm into the corona. The volume is resolved by a 150^3 gridpoint cube, providing a horizontal resolution of 0.4 Mm and a vertical resolution varying from 0.15 Mm in the chromosphere and transition region, to 0.25 Mm in the corona. This resolution is not quite adequate to resolve the large jump in temperature over the transition region, but is not too far from it, because this simulation does not solve for temperature, but for internal energy which makes the scale height in the transition region somewhat larger than for temperature.

The initial atmosphere is a VAL-C (Vernazza et al. 1976) atmosphere with a one million K hydrostatic corona above the transition zone included in the VAL-C atmosphere. The initial magnetic field is a potential extrapolation of an MDI observation of AR 9114, scaled down to fit inside the box. This seems reasonable since the magnetic field in active regions are close to self-similar over a large range in length scales. AR 9114 was at the time of the observation a typical active region, with a large sun spot containing most of the flux of the leading polarity, and a secondary polarity which is more spread out.

Cooling of the atmosphere is provided by a cooling function in the optically thin part of the atmosphere while the region where cooling is provided by optically thick lines or continuum, a Newtonian cooling method, that cools the atmosphere towards the VAL-C temperature structure on a timescale of a few seconds, is used. The model also includes thermal conduction in the form of the classical Spitzer conductivity along the magnetic field.

We constructed a method of creating a time evolving photospheric velocity field that follows the geometrical nature of the granulation field in the photosphere while maintaining the powerspectrum of velocity amplitude and vorticity amplitude of the solar photospheric velocity field, leaving no free parameters for the driving.

4. Results

After the photospheric velocity field has twisted the magnetic field for roughly 10 m, the magnetic field starts to dissipate enough energy to keep the temperature of the corona at one million K. The heat produced by the dissipating magnetic field is on average between $10^6 - 10^7$ $\text{ergs}\,\text{s}^{-1}\,\text{cm}^{-2}$ exactly what is esti-

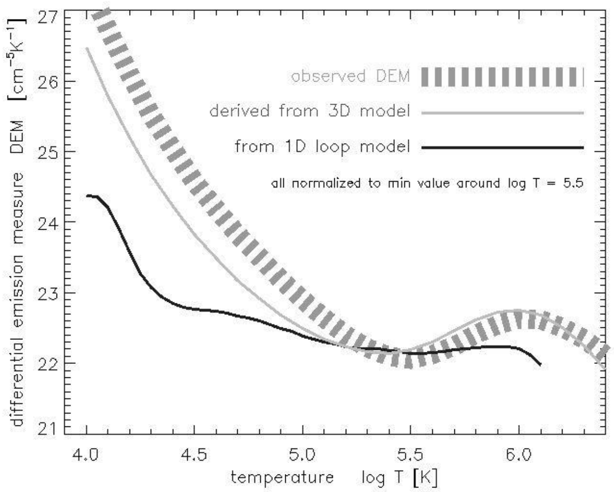

Fig. 2. A typical DEM curve measured by SUMER (thick dotted line) as well as forward modeled points from the simulation and a second degree polynomial fit to these points (solid grey line).

mated to be the energy input needed to heat the corona above active regions. As well as keeping the corona at the required one million K, the simulation also reproduces the Data Number count observed by the TRACE satellite in the 171 Åfilter meaning that not only is the temperature correct, but the amount of mass at roughly one million K is also correct. As shown in fig. 1, a simulated image of the TRACE 171 Åpass band shows thin loops as observed by TRACE. Further forward modeling of a number of spectral lines showed a very nice fit to the Differential Emission Measure (DEM) curve observed by the SUMER spectrograph on board SOHO (see fig. 2). It is the first time that a model has been able to fit this curve, and it is evidence for the simulation produces a solar atmosphere containing the correct mass at different temperatures from 50000 K to 1.2 million K.

The heating source is the magnetic dissipation, which would most likely occur in nano flare like events. The simulation is limited by its spatial resolution/numerical dissipation, and consequently cannot produce the shortest events, but rather produces longer lived current dissipation instead. An energy analysis shows that roughly 8 % of the Poynting flux flowing into the magnetic field is dissipated in the volume above the chromosphere. The rest is dissipated in the photosphere and chromosphere, but would hardly be noticed because of the large input and output of radiative energy in these layers. The important factor here is the height where the forces connected with magnetic field is as strong as the hydrodynamic forces. This height above which the magnetic field will become force free, and averaged over time and space, the amount of dissipated energy will be a constant times the magnetic energy with a scale height decided by the magnetic field scale height. If this surface is located high above the driving surface, the amount of magnetic flux will be small, and less heating will occur. That height is decided by the difference between the pressure scale height and the scale height of the magnetic field. For active regions on the Sun, the magnetic scale height is much larger than the pressure scale height, so the height of equal forces occurs in the transition zone.

It seems that this model is reproducing a number of key features of the solar corona, based only on a DC heating mechanism without the need for an artificial heating term, perhaps finally providing an answer to the question of what heats the solar coronal.

5. DC Heating in other Settings

The lessons learned from this model are by no means specific to the Sun. Similar processes should occur in a number of other astrophysical settings. The only requirement is that the system contains a driver located in a region where the driving forces are larger than the magnetic forces, and that the magnetic field is connected with a region in which the magnetic forces are stronger then the plasma forces. This requirement does not guarantee that the heating will be important, as this depends on a number of other factors and competing heating and cooling mechanisms.

The most obvious setting this could occur is the coronae of other stars that are similar to the Sun in certain respects. For this heating mechanism to work, such stars need a photospheric driving mechanism in the form of a convection layer. The size of granules, the velocity amplitudes in the convection zone, the magnetic field strength and topology control how much Poynting flux is generated and pumped into the magnetic field. As the magnetic field, as a first approximation, has a scale height which is comparable to the average distance between magnetic polarities, this distance compared with the distance from the surface to the height where the forces connected with the magnetic field becomes comparable with the hydrodynamic forces decides how much energy will be dissipated in the stellar corona. We are at the moment working on a number of models of stellar coronae similar to the one we have created for the solar corona.

The coronae above accretion discs are another example, even though the efficiency in this setting is more questionable. The main unknowns are the magnetic field strength and topology in the turbulent accretion disc. If the distance between magnetic polarities is too small, the corona above the disc will be almost field free, and will not contain much magnetic energy to dissipate. A number of other heating mechanisms are available to accretion disc coronae which are not available to solar-like stellar coronae. Radiative heating might be a possible candidate as the inner parts of accretion discs usually radiate strongly in X-rays.

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