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An Ab Initio Approach to the Solar Coronal Heating Problem

B.V. Gudiksen

Inst. for Solar Physics, Albanova University Center, Stockholm Observatory, 10691 Stockholm, Sweden

Å. Nordlund

Astronomical Observatory, NBIfAFG, Copenhagen University, Øster Voldgade 3, 1350 Copenhagen K, Denmark

Abstract. We approach the solar coronal heating problem *ab initio*. Starting from a potential extrapolation of a SOHO/MDI magnetogram, a FAL–C atmospheric stratification, and a realistic photospheric velocity field, Spitzer conductivity and magnetic dissipation creates a corona where more than $2\,10^6 \mathrm{ergs\,s^{-1}\,cm^{-2}}$ is dissipated. The winding of the magnetic field by the horizontal velocities in the solar photosphere is sufficient to provide a major part of the heating in the solar corona. The heating is intermittent on the smallest scale, but on average follows the magnetic field strength squared, as is expected from a force free magnetic field configuration. The intermittent heating creates large temperature and density fluctuations in the corona. The total dissipated energy in the corona is at least constant if not increasing with magnetic Reynolds number, making this heating process unavoidable as a major contributor to the heating of the solar corona.

1. Introduction

The heating of the solar corona has been largely unexplained for several decades. The consensus is that the heating is produced by dissipating magnetic energy, which has been supplied by the convective motions in the solar photosphere. The exact mechanism responsible for the conversion from magnetic energy to internal heat of the gas is still debated. The two main theories of the heating are often referred to as AC (alternating current) heating and DC (direct current) heating. In the AC scheme, the field is the conduit for magnetic waves that are then dissipated in the corona, while the DC scheme uses the fact that the magnetic field builds up energy when the magnetic foot points are shuffled around in the photosphere, until at some level the energy has to be dissipated. The work of Galsgaard & Nordlund (1996) showed that this level corresponds to average angles at the boundaries produced by twisting the magnetic field about once from end to end.

Through the last few years a lot of work has gone into producing semi-empirical models and into empirically deducing where the heat is deposited in the corona, using observed loop properties and scaling laws. Both of these approaches have a number of free parameters which are poorly known. This creates an inherent uncertainty when trying to compare models with observations.

We chose to approach the problem from another angle, by direct numerical modeling of a small region of the solar corona, including all the physics we know to be important, and including properties of the solar photosphere as a lower boundary condition. As a consequence there are essentially no free parameters. One of the important parameters that is often of concern when dealing with plasma physics is the electrical resistivity. In the solar corona it is so low that it would be impossible with today's computer power to handle it directly, since the resistive scale would be so small that the numerical resolution would have to be of the order meters. It is impossible to include even the smallest resolved scales of today's telescopes; roughly 90 km (Scharmer et al. 2002). However, the theoretical arguments of Parker (1979) and the numerical work of Hendrix et al. (1996) and Galsgaard & Nordlund (1996) makes this point unimportant since these works show that the energy supplied to the magnetic field from the boundaries will have to be balanced by the dissipation of magnetic energy, whatever the resistivity is. Therefore the resistivity only decides at which typical scales the energy is dissipated, but not the total amount.

1.1. The Physics and the Implementation

We use a staggered mesh MHD code with 6'th order accurate derivative operators and 5'th order accurate interpolation operators which is well tested (see for instance Nordlund, Stein & Galsgaard 1994; Dorch & Nordlund, 1998). We incorporate the Spitzer thermal conductivity (Spitzer 1956) along the magnetic field and a radiative cooling function which handles radiative losses from transitions in H, He, C, O, Ne and Fe in the optically thin corona. In the optically thick regime this function is quenched, while a Newtonian cooling towards the initial chromospheric temperature takes over with a cooling time of 0.1 s.

We also incorporate a method for generating a photospheric velocity field similar to the one observed on the Sun. The velocity field in the solar photosphere is characterized by having an average amplitude that is approximately inversely proportional to the scale over which one is looking, all the way from super–granules to granules, where the distribution breaks. This statistical fingerprint of the velocity field is important to reproduce. Another important feature of the velocity field is the geometrical shape of granules, which was not included in the initial work (Gudiksen & Nordlund 2001). Granules may be well approximated by multiplicative weighted Voronoi tessellations (Schrijver, Hagenaar & Title 1997). We constructed a procedure that produces a time dependent velocity field, with granules that appear and disappear, having life times and other properties that match the solar photospheric velocity field over a range of scales, from just larger than granules to supergranules. The velocity and vorticity power spectra of the velocity field were normalized to solar values, deduced from the simulations of Stein and Nordlund (1998). It is important to notice that there are no active regions specific flows, such as rotating sunspots or the like, making this a *minimal assumption* in the sense that it produces only a generic solar photosphere velocity field. Additional, active region specific

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motions may be expected to inject more Poynting flux into the corona, creating more heating.

1.2. The initial conditions

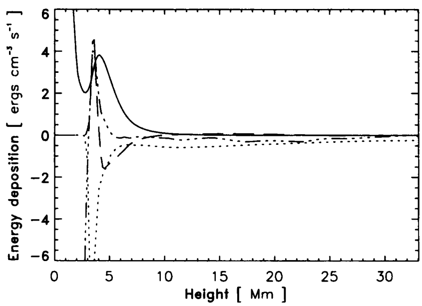
The simulation runs on a grid of 150^3 cells (with shorter runs at $250^2 \times 150$), spanning $60 \times 60 \times 37$ Mm^3, with the z-direction vertical starting in the photosphere. The z-axis has a resolution varying from 0.15 Mm in the chromosphere to 0.25 Mm in the corona, in order to resolve the steep density drop through the photosphere and chromosphere. The initial condition for the magnetic field was constructed by performing a potential extrapolation from a high resolution MDI-magnetogram of AR 9110, scaled down to fit inside the computational box. A potential field was used because this is again a *minimal assumption*, since any other magnetic field configuration would induce currents from the start in the corona, creating more heat. For the initial stratification of the photosphere and chromosphere we used the FAL–C model atmosphere (Fontenla, Avrett & Loeser 1993).

With these initial conditions and the included physics, we have a setup with only well known physics, and with conditions that do not promote any additional heating, other than what we know has to happen in a general solar active region.

2. Results

The simulation is allowed a 5 min. startup period, where the potential field is wound up by the photospheric velocity field. In this period no conductivity or radiative cooling are included because the magnetic field is unable to do any heating when it is close to a potential state. When this period is over the thermal conductivity and the radiative cooling are enabled, leading to a few minutes where the gas is reorganized in order to balance the new conditions. After these initial phases the atmosphere goes into a statistical equilibrium, where over all the total energy flux divergence is zero. Since the thermal conduction time scale and the radiative cooling time scale are very short, the atmosphere reaches a statistical equilibrium on a time scale significantly shorter than the total simulated time of ~40 min. This also ensures that the initial stratification is quickly forgotten.

The statistical equilibrium is quantified by Fig. 1 (left), where the average horizontal energy deposition is plotted as a function of height for four different terms: conductive flux divergence, convective flux divergence, radiative cooling and heating. Even though a horizontal average generally is not a good measure, the contributions are very close to canceling. The heating and cooling are very intermittent at every height. The heating has values that are generally 100 times larger and 1000 times smaller than the horizontal average at any given horizontal slice, making the heating attain values over five orders of magnitude at every height. The heating is in general proportional to the magnetic field strength squared, even though there are large deviations. Fig. 1 (right) shows the heating (proportional to the current squared) as a function of height, in a 2-D histogram, with the colors proportional to the PDF. One sees that at every height there is a large range of values for the heating, but that overall



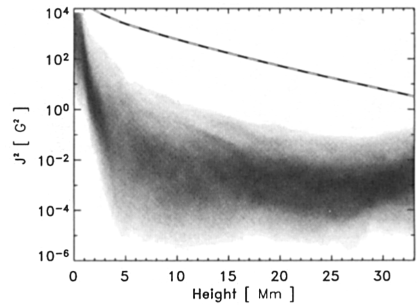


Figure 1. Horizontally averaged deposited energy (left) from resistive dissipation (full), Spitzer conductivity (long dash), convective flux (dash-dotted) and radiative cooling (dotted). Current squared PDF as function of height, with darker colors meaning higher values of the PDF. Over plotted is the horizontally averaged magnetic field strength squared (dashed line)

the heating roughly follows the horizontally averaged magnetic field strength squared as would be expected for a magnetic field in a force free configuration. A heating distribution like this was proposed by Schrijver et al.(1999), and later found from observations (Mandrini, Demoulin & Klimchuck 2000; Aschwanden, Schrijver & Alexander 2001; Foley et al. 2001; Schrijver & Aschwanden 2002; Demoulin et al. 2003). It is furthermore included in the models that agree with new observations from the Flare Genesis Experiment (Schmieder et al. 2004). The total heating in the simulated active region is at any point in time roughly $2 - 4 \cdot 10^6 \mathrm{ergs\,cm^{-2}\,s^{-1}}$ which is within the normally stated limits of $10^6 - 10^7 \mathrm{ergs\,cm^{-2}\,s^{-1}}$ based on X–ray and EUV flux from the corona.

In spite of the decreasing spread in magnetic field strength with height, the gas density and temperature show very large fluctuations. On what corresponds to the size of a TRACE pixel the temperature can change by 0.7 MK, and densities vary by as much as four orders of magnitude at a specific height. These combinations give changes in the DN in the TRACE filters of eight orders of magnitudes. Emulated TRACE images in 171 and 195 Å filters (see Fig.2) agree qualitatively with observations. Quantitative comparisons are complicated by considerable uncertainties in the TRACE response functions, and because the temperature profile of the upper chromosphere has a large influence on the average density in the corona.

3. Conclusion

The *ab initio* approach has shown that with boundary conditions based on well established properties of the photospheric velocity field, an active region magnetic field can dissipate enough energy to keep the coronal temperature at of the order of a million Kelvin. The heating is variable and intermittent on even the smallest scale. The heating profile roughly follows the magnetic field strength squared in the corona, even though there are large deviations. Below the transi-

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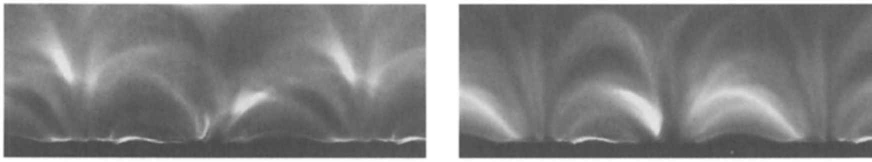

Figure 2. Emulated TRACE 171 (left) and 195 (right) images

tion region the dissipated energy is even larger (cf. Fig. 1b), because of the low β environment, which keeps the magnetic field in a non-equilibrium state. The intermittent heating creates intermittency in the thermodynamic variables. The temperature and density changes on the smallest scales by large factors, creating changes in the simulated TRACE filters of up to eight orders of magnitude on a scale of 350 km, equivalent to a TRACE pixel. The heating produced under the minimum assumptions adopted here indicates that DC heating produced by the relatively slow photospheric motions is at least a major contributor to the total heating in the corona.

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