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# HEATING OF THE SOLAR CORONA

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**Abstract.** The mechanisms of transport and dissipation of energy in the corona are the subject of a long-lasting controversy in solar physics, with implications on Solar-Terrestrial physics. I review some classical models of wave or current dissipation, and I discuss the role of turbulence, how it can help providing the small scales at which dissipation is more efficient, what observational and computational difficulties arise, what is being done to overcome them, and what new challenges we meet.

## 1 Introduction

The presence of a faint halo around the Sun during eclipses is known since ancient times, but its origin remained unclear during thousands of years. Following the eclipse of 18 August 1868, Janssen provided evidence for the solar (as opposed to atmospheric or lunar) origin of the glow thanks to spectroscopy. But later, spectroscopy raised new interrogations. Indeed, spectral lines of a new chemical element, then called "coronium" had been discovered in spectra of the corona. However, around the beginning of the 1940s, these lines were actually identified to lines of already known elements, but at very high ionization states, like Iron XIII (Edlén 1943). This implied that the corona is hot enough to sustain such ionization states, i.e. that it should have temperatures of the order of a million of kelvins, much higher than what had been thought before.

A new problem appeared: if we consider that most of the energy of the corona comes from the Sun via the photosphere and not from outer space, how can the corona be sustained at much higher temperatures than the photosphere ($< 6000$ K)? This seems indeed to be in contradiction with the second law of thermodynamics — and to everyday experience — according which heat should flow from the hot region (the corona) to the cold region (the photosphere.) The solution to this paradox lies in the fact that energy can be transported to the corona in other forms than heat (including macroscopic kinetic energy, energetic particles, and above all magnetic energy), and then this energy can be dissipated and heat the coronal plasma. The question that remains is how exactly this happens and according to which physical mechanisms.

In particular, theories of coronal heating must provide evidence that the physical mechanisms involved do provide sufficient power to sustain coronal temperatures; this power has been shown to be $10^2$ to $10^4$ W/m$^2$ by Withbroe & Noyes (1977), depending on the region considered. Other interesting questions include the comparison between mechanisms at play in different regions of the corona or in different stars (with different activity and magnetization levels), and the coupling with heliospheric physics and Earth's magnetosphere. In addition to providing sufficient heating, the theories of coronal heating must also be compatible with — and perhaps even explain — the whole range of structures observed in the corona and its very dynamical nature, from the large active regions and large flares (as first observed by Carrington 1859) to the smallest bright points. They must also be of course compatible with all the plasma properties deduced from observations, in particular spectroscopic observations.

Sources for this paper include the review papers by Zirker (1993), Cargill (2004) and Klimchuk (2006).

## 2 Some physical mechanisms involved in coronal heating

**"AC" and "DC" mechanisms, and the involvement of turbulence.** Historically, physical mechanisms for the heating of the corona have been divided into "AC" (alternative current) and "DC" (direct current)

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mechanisms (see the review by Zirker 1993 for details). The main problem of mechanisms of both these classes is that their dissipation processes can be efficient only at small scales, much smaller than the smaller scales that we can observe with the current (and probably future) instruments. Such small scales can however be produced in the corona by the break-up of large-scale structures by turbulence, under the effect of the nonlinear terms of the magnetohydrodynamic (MHD) equations (Heyvaerts & Priest 1992; Gómez & Ferro Fontán 1992) or of equations of any similar physical framework. This is possible because the corona is indeed in a very turbulent state with Reynolds numbers up to $10^{14}$, corresponding to a huge range of scales with smaller scales being less than 1 km, where the dissipation mechanisms can be efficient. Therefore turbulence can help the other mechanisms to be efficient; this is widely recognized, but the detailed processes still need to be determined.

**Cross-scale physics.** Because of turbulence, the evolution of the system becomes intrinsically very difficult to study, even in the framework of relatively simple MHD equations, as it is chaotic and has a complex dynamics involving many modes, over a very wide range of scales. This becomes an even bigger challenge when considering that at the small scales produced in the corona by MHD turbulence, MHD is likely not to be entirely valid anymore. First, additional effects like the Hall term of Hall-MHD are not negligible anymore at scales smaller than the ion inertial length. Furthermore, kinetic effects begin to become important when the small-scale electric fields exceed the Dreicer field and accelerate particles such that their distribution is not Maxwellian anymore; these accelerated particles can also transport energy to far regions.

## 3 Simulations of MHD turbulence in a coronal loop

I will focus here on MHD simulations because MHD is the most widely used framework to study turbulence in the solar corona, but one must not forget the importance of the other effects mentioned in the previous paragraph, especially at the smaller scales near the dissipative range of turbulent spectra.

### *3.1 Direct numerical simulations (DNS)*

Many DNS of MHD turbulence have been performed; in the framework of heating of the solar corona, one possibility is to model a magnetic loop in the corona, or a part of a loop. The turbulent energy release in a 2D reduced-MHD (Strauss 1976) cross-section of a loop yields events whose statistics are power-laws consistent with observations (Dmitruk et al. 1998; Einaudi & Velli 1999). With a 3D model of reduced MHD submitted to boundary conditions corresponding to photospheric motions, Dmitruk et al. (2003) have studied further the turbulent spectra in a loop and the formation of small-scale current sheets. Another possibility is to model a larger region of the corona, without assuming the existence of loops; this has for example been done by Gudiksen & Nordlund (2005), who have shown that MHD in a region bounded by a photosphere is sufficient to get the right order of magnitude for the power of energy dissipation, and to obtain the formation of loops like those observed by TRACE.

### *3.2 Other approaches to MHD turbulence*

Although being promising, all these DNS are limited to low resolutions, and thus there is a huge discrepancy between modelled and coronal Reynolds numbers. Even though Galsgaard & Nordlund (1996) argue that it is not a problem when looking for the average heating rate (as the energy flux in the dissipation range is not determined by the dissipation scale, and all this energy flux is ultimately dissipated), it is a problem if one wants to study the dynamical nature of the corona and the specific physics of large-Reynolds turbulence, such as intermittency. Furthermore, even these quite low-resolution DNS are computationally intensive, which makes them unsuitable to perform statistics on long time series or on a large number of runs. There is therefore a need for other approaches to MHD turbulence, complementary to DNS, that would allow to perform such statistics for MHD turbulence at higher Reynolds numbers.

**Cellular automata (CA).** CA are lattice models with local interactions between cells of the lattice, according to some given rules; they often exhibit a behavior of Self-Organized Criticality (SOC: Bak et al. 1988), in which the energy loading makes the system evolve slowly to a critical (metastable) state, which can then suddenly relax and release energy (similarly to avalanches in sand piles). CA models allow to study the emergence of a global behavior of a system, given the properties of its basic components; they have a broad range of applications from the statistics of earthquakes (Carlson & Langer 1989) to substorms in the magnetotail (Takalo et al. 1999) and star formation in spiral galaxies (Lejeune & Perdang 1996). They have first been applied to the heating of the solar corona by Lu & Hamilton (1991): the nonlinear terms of MHD are modelled (albeit in a manner inconsistent with MHD in this early model) by a threshold condition for avalanches to occur. This modelling of the nonlinear terms is what allows the CA models to be faster than DNS. They have then been improved to be consistent with MHD in a 3D region of the corona (Vlahos et al. 1995), to model a coronal loop by one of its cross-sections (Einaudi & Velli 1999; Krasnoselskikh et al. 2002), or a full 3D loop including the propagation of Alfvén waves from the photospheric boundaries (Buchlin et al. 2003).

They allow to explore a wide range of parameters, and one of their main achievements is to reproduce power-law distributions of the energies dissipation events with slopes $\alpha$ close to the observed ones. These slopes have been thought to be particularly important since Hudson (1991) had pointed out that if event energies are distributed as a power-law of index $\alpha$ and if $\alpha < -2$, the smallest unobservable events such as the nanoflares predicted by Parker's (1988) model of magnetic field braiding and reconnection account for most of the energy dissipation in the corona. However the values of $\alpha$ obtained from most observations and models are slightly above $-2$, indicating that smaller events are not dominant. On the other hand, as in reality and in continuous models (as opposed to discrete models like CA) an event is not well defined unless using an arbitrary definition (Buchlin et al. 2005), the fact that $\alpha$ is above or below the critical value of $-2$ should be taken with care.

**Shell-models.** In MHD shell-models (e.g. Gloaguen et al. 1985; Giuliani & Carbone 1998) the nonlinear terms of MHD are simplified by assuming local triad interaction between modes which are scalar values of velocity and magnetic field in concentric shells in Fourier space. They allow to simulate MHD at high Reynolds numbers ($> 10^6$) while retaining the full evolution of the turbulent spectra. The coefficients of their nonlinear terms are entirely determined by the conservation of the MHD invariants. Their behavior reproduces naturally most of what is expected from MHD turbulence, like a dynamo effect, turbulent power-law spectra in the inertial range (with the associated nonlinear transfer of energy between scales), and intermittency.

Shell-models have been extended to model a coronal loop: thousands of shell-models of 2D MHD are piled up along the axial magnetic field, Alfvén waves travel in the loop between the shell-models, and the boundary conditions mimic the photospheric motions and allow the injection of energy in the loop (Nigro et al. 2004; Buchlin & Velli 2006). This model provides the turbulent spectra and the heating function (power of dissipation per unit volume as a function of time and position along the loop); for a model loop, the heating is sufficient to sustain the coronal temperatures. It also allows to study statistics of long time series of energy dissipation in a loop, the evolution of turbulent spectra before and after heating events, the anisotropy of spectra in directions perpendicular and parallel to the loop due to the anisotropic nonlinear transfer, and the lifetimes of oscillations accompanying dissipation events. In addition, it produces power-law distributions for events energies, durations, and (unlike most CA models) for the waiting times between events, showing that the dissipation events are a non-Poissonian process.

## 4 Towards a better comparison between models and observations

Some statistics from the turbulence produced by these models, like coronal velocities in some regions, can be compared directly to observations (e.g. Buchlin et al. 2006), but as this is often not the case inversions are usually performed so as to get physical quantities from observations. However, this is often a hazardous method, and there a need to forward-model observable variables that would be compared directly to observations; this is for example done by Gudiksen & Nordlund (2005); Reale et al. (2005); Patsourakos & Klimchuk (2006); Parenti et al. (2006). These last two papers in particular show that observations of lines emitted at very high temperatures (five to several tens of millions degrees) are needed to observe the heating phase of nanoflares (as opposed to their cooling phase, when the signatures of the heating processes have already been smoothed out by the thermalization). Such observations will become more widely available with Hinode (ex-Solar B, launched in September 2006) and SDO (2008).

However the coupling of heating and radiative emission that all these models compute (via the cooling mechanisms of the coronal plasma) is incomplete, as they do not take into account the feedback of the cooling mechanisms on the heating mechanisms, via changes in temperature and density. A complete model of coronal heating should be an integrated model taking into account simultaneously turbulent heating, cooling by conduction and radiation, and atomic physics for emission of radiation. Alternatively, it should at least be a chain of models for these three processes, with bidirectional couplings between elements of this chain. Work is currently being done towards this direction.

## 5 Conclusion

Many progresses have been made towards the resolution of the long-standing problems raised by the sustainment of high temperatures in the corona, but there is still a lot of work to be done. It is indeed a very complex problem, involving a huge range of scales, nonlinear cross-scale couplings by turbulence, many different but interconnected physical processes (some of them becoming active only at small, unobservable scales). New results can be expected in the near future from both the progresses in modelling (including more physical processes and their interactions) and the observations with the new solar observatories.

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