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ENERGY CONVERSION IN THE CORONAL PLASMA

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INTRODUCTION

Solar and stellar X-ray emission is the observed waste product of the interplay between magnetic fields and the motion of stellar plasma.

The prevalent scenario these days is that stellar magnetic fields are generated and maintained by convective motions and differential rotation in the stellar interior (see Zeldovich **et al.**, 1983 for a review on dynamo theory). Any stellar magnetic field will tend to concentrate in flux tubes and break out to the stellar surface because of its buoyancy (see Parker, 1979), and thus a magnetic link is established between the stellar interior, photosphere, and the outer layers, the so called corona. While in the convection zone and photosphere the magnetic field only has a minor influence on the plasma motions and energy flow, it completely dominates the dynamics and the energetics of the stellar corona.

For example, Parker (these proceedings) emphasizes the enormous differences in temperature, emission measure, and density between solar coronal holes and active regions. The basic difference between them, causing these discrepancies, is that in the former the magnetic field lines are open and find their way into the interstellar space, while in the latter the field lines are closed, i.e. reentrant into the photosphere.

Clearly then, the radiation signatures from stellar coronae, and probably also from chromospheres, as well as the wealth of phenomena they represent, like steady X-ray emission from loops and X-ray bright points, flares and winds, must find their explanation in the growth, evolution, and final dissipation of coronal magnetic fields. In particular, the constant high temperature of stellar coronae, both in open and closed coronal regions for the solar case, requires continuous non-thermal heating, which is the result of the dissipation of free magnetic energy that enters the corona in the form of currents or MHD waves. Theoretical understanding of the process of coronal heating is of the utmost importance, since the high temperature is what defines the corona in the first place. Most of the research described in this chapter deals with aspects of the several rivalling theories for coronal heating. The rest of the papers deals with processes of energy conversion related to flares.

GENERATION AND TRANSPORT OF ENERGY INTO THE CORONA

Before describing and contrasting the presently prominent theories of coronal heating, I will go several steps back and outline a scenario for the generation and transport of the energy that eventually gets dissipated in stellar coronae. The theoretical description of the last part of this process, the conversion of energy in the corona, is the subject of the coronal heating theories.

As was mentioned above, magnetic fields are believed to be generated and maintained in the convection zone by the dynamo process. From the convection zone the field is buoyed upwards to form the photospheric and coronal field. The magnetic field that enters into the corona, is likely to carry currents from the onset, that can dissipate and contribute to the coronal heating. However, without much justification, these currents are generally ignored in coronal heating theories and it is assumed, often implicitly, that the field that enters the corona is potential (i.e. current free). It is then further surmised that part of the enormous amount of kinetic energy present in the plasma flows in the photosphere is converted into either MHD waves or field aligned currents by the interaction of these flows with the fields. This energy in the form of waves or currents propagates upwards along the field and enters the corona, where at least part of it is dissipated and results in coronal heating.

Both in the corona and the photosphere the time scale for the dissipation of magnetic fields is very long, so the field is essentially "frozen in", i.e. the plasma and the field move together. However, in the corona the magnetic forces completely dominate the thermal pressure gradient and therefore the coronal plasma has to follow the coronal field in its motion, while in the photosphere and below the situation is completely the opposite and the movement of the magnetic field lines is dominated by the plasma motions. Field aligned currents are then generated in the photosphere by **slow** motions of the footpoints of the coronal field lines, while the **faster** sloshing motions of the field lines generate the MHD waves that propagate upwards into the corona along the field lines. This leads to the generalized concept of the photospheric layers below the corona as the "driver" that generates the free energy that propagates into the corona (see Ionson, 1986, for a review). The "driver" represents the spectrum of photospheric motions over all timescales and all length scales. MHD waves and field aligned currents are simply the response of the coronal magnetic field to respectively the high-frequency and low-frequency part of the photospheric power spectrum.

A closed coronal structure, for example a loop, will evolve through a series of magnetostatic equilibria when its footpoints are moved on a timescale which is long compared to the time an Alfven wave needs to travel along the structure. When the footpoints move on a timescale shorter than the Alfven crossing time the field in the loop will not have the time to settle in a new equilibrium and the response will be a wave motion in the loop. Open coronal structures, such as coronal holes, always have a wave response to the photospheric driver, since their length, and hence their crossing time, is infinite.

Any coronal heating theory must explain how the corona responds to the energy input by the driver, and in particular, how the free energy is eventually dissipated. The essential input parameter for such a theory is the form of the photospheric energy spectrum (both its frequency and wave vector dependence) and this has to be established through careful observations of the motions of the photospheric magnetic field. Such observations have been made from Spacelab 2 (July 1985) and even better quality observations are expected from the High Resolution Solar Observatory, the follow up of SOT. At this moment we do not know enough about this spectrum to rule out certain heating theories. However, it is reasonable to expect that most of the power will be within the 100-1000 seconds range. Within this range one finds the convective turn-over time, 800 seconds, the photospheric 5 minute oscillations and the chromospheric 3 minute oscillations. According to numerical estimates for length scales and Alfven speeds given in **Parker's** contribution to these proceedings, such a power spectrum will generate a wave-like response in large coronal structures and field aligned currents in small structures. For example, on one hand, large coronal loops have Alfven crossing times in excess of 200 seconds, while on the other hand X-ray bright points have a typical response time of 20 seconds. Therefore, a comprehensive theory of coronal heating should address the problem of the dissipation of both waves and currents.

THE BASIC PROBLEM OF CORONAL HEATING

So far I have discussed a scenario for the generation of free energy and the transport of it into the solar corona. Coronal heating theories take this process usually for granted, i.e. use it as an input parameter, and try to explain how and in what rate the energy that enters the corona is dissipated. This is by no means an easy task, and all theories for coronal heating run into the same basic problem in trying to explain the heating rates that are derived from observations of coronal X-ray emission. The problem is that given the classical coefficients for resistivity and viscosity (Spitzer, 1962), and reasonable estimates for current density and wave amplitude (see Parker's contribution to these proceedings for numerical values) the theoretical heating rates are orders of magnitude less than those required to balance the energy losses through conduction and coronal X-ray emission.

Any coronal heating theory has to explain how the dissipation is enhanced over the classical estimate, and different theories come up with different, often very ingenious and elegant ways of achieving this. The irreversible conversion of magnetic energy into thermal energy is found from the induction equation,

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) - \eta \vec{\nabla}^2 \vec{B} \qquad (1).$$

By taking the inner product of this expression with the magnetic field one finds the decay of magnetic energy into thermal energy from the last term. The second term describes the conversion between magnetic and flow kinetic energy and this process is reversible. In the derivation of Eq. (1) the spatial derivative of the resistive coefficient η has been neglected. It is clear that in order to enhance the resistive dissipation for a given magnitude of the field, either the coefficient of resitivity has to increase, or the spatial derivative of the field has to become large.

The irreversible conversion from flow kinetic energy into thermal energy is found in an analogous way from the Navier Stokes equation

$$\rho\frac{d\vec{v}}{dt} = -\vec{\nabla}p + \vec{j} \times \vec{B} + \rho\nu\{\vec{\nabla}^2\vec{v} + \frac{1}{3}\vec{\nabla}(\vec{\nabla}.\vec{v})\} \qquad (2).$$

Here ν is the kinematic viscosity coefficient (Spitzer, 1962). After taking the inner product with the velocity, the second term on the right hand side describes the work done against or by the Lorentz force, while the third term describes the irreversible decay of flow kinetic energy into thermal energy. This form of energy decay is relevant for the damping of MHD waves that consist of both particle motions and currents and thus are subject to both resistive and viscous damping. It is clear that in order to increase the viscous damping rate, either the coefficient of viscosity has to become much larger than its classical value, or the velocity amplitude of the MHD-waves has to be much larger than what the observations suggest, or the velocity shear has to become very large.

None of the theories described hereafter explores the possibility of an increase of many orders of magnitude of either viscosity or resistivity. The current heating theories of **Parker** (1979, 1986) and **Van Ballegooijen** (1986 and these proceedings) are based upon the development of very large field gradients, or equivalently, very large current densities. The resonance wave heating theory by **Ionson** (1982, 1985) relies on the development of large wave amplitudes in the resonant coronal loops. An extension and revision of this theory by **Davila** (these proceedings) is based on the development of large wave amplitudes in a very thin resonant layer. An alternative form of dissipation in resonantly heated coronal loops is investigated by **Heyvaerts and Priest** (1983). They describe the development of enormous velocity shears all over a loop due to a slow cross field variation of the Alfven speed. Finally **Hollweg** (1984, 1986) hypothesizes a cascade of wave energy from (resonant) long wavelengths to short wavelengths, which implies the build up of large velocity gradients.

The question explored in those theories is then: what physical mechanism causes the build-up of strong gradients in the magnetic field or velocity field, or what causes the large wave amplitudes? The different theories give different answers and I will contrast those answers in the following. This comparison will at the same time serve as an introduction to the majority of the papers in this chapter.

THEORIES OF CORONAL HEATING

The most radical solution to the problem is given by **Parker** (1972, 1979, 1983, 1986, and these proceedings). Parker argues that a static coronal magnetic field that is smooth and force free everywhere, and satisfies the boundary conditions at the photosphere, simply cannot exist. The governing equations overdetermine the problem and therefore some sort of symmetry has to exist in force free fields. This symmetry is in general incompatible with arbitrary boundary conditions and the "frozen in" condition of the magnetic field and hence no regular and smooth solutions exist. Parker points out that instead the mathematical solutions to the problem will exhibit discontinuities, where the field gradients are infinitely large. In physical reality this means that current sheets will develop, where enough dissipation may take place to heat the corona. Hence the development of large field gradients is an **intrinsic** property of coronal magnetic fields, and there is no need to force the origin of current sheets by discontinuous motions of field lines in the photosphere. Specifically it is Parker's assertion that **continuous** footpoint motions of an originally **continuous** force free coronal field will create

discontinuities in the coronal magnetic field. This stands in contrast with the solutions for force free coronal fields with continuous boundary conditions: there is no doubt that these solutions will be continuous. The difference between the two situations is that in the former the history of the footpoint motions is an essential part of the problem. Knowledge of the photospheric power spectrum is still necessary to determine the amount of energy that is transported into the corona, but once the energy is there it will surely be dissipated. This process is called **topological heating.**

Three papers in this chapter deal with the problem of the existence of smooth force free fields in the solar corona. **Antiochos** presents evidence that in general force free coronal magnetic fields are **not** overdetermined by the constraints that the boundary conditions impose, and therefore that the formation of current sheets is not an intrinsic property of the coronal magnetic field (see also Antiochos, 1986). He finds that all the information of the wrapping of coronal field lines is contained in the boundary conditions to the field and hence there is no additional constraint on the field by the history of the footpoint motions. The problem then reduces to one that is very similar to a Dirichlet problem and the Dirichlet problem is known to have regular smooth solutions. Zweibel (1987) has recently derived similar results.

Berger in his contribution reaches exactly the opposite conclusion: he finds that thin current layers separating flux tubes will form in general. His argument is based on the nature of the magnetic field at the photospheric boundary. It is well known that in the photosphere the magnetic field is concentrated in flux tubes, with very little intertube flux. Arbitrary motions of these flux tubes in the photosphere necessarily create current sheets in the corona. Antiochos and Berger seem to agree that the photospheric footpoint motions in Berger's examples are discontinuous, and the formation of a current sheet is known to be trivial in that case. The real problem is to explain the formation of coronal current sheets by a continuous photospheric velocity field. However, this does not invalidate Berger's results: he shows quite convincingly that even a simple braiding pattern of three flux tubes is inconsistent with a smooth force free coronal field.

The last paper on the coronal magnetic field is by **Martens.** His basic approach is to try to determine the restrictions that the equations for force free fields impose on the geometry of these fields. For that purpose he derives the magnetohydrostatic equations in general non-orthogonal coordinate systems. The idea is then to find out what conditions the MHS equations impose on the metric tensor. This work is in a rather preliminary stage, but the first results do not seem to indicate the necessity of some sort of symmetry in force free fields, contrary to Parker's result (1986).

An alternative theory of coronal heating by **Van Ballegooijen** is the subject of the next paper (see also Van Ballegooijen, 1986). Van Ballegooijen (1985) recently pointed out an error in a proof of Parker (1972) of the necessity of an ignorable coordinate magnetohydrostatic (MHS) fields and further presented an algorithm for actually calculating fully three dimensional MHS fields subject to arbitrary boundary conditions. Consequently Van Ballegooijen takes the point of view that the formation of current sheets is not an intrinsic property of the coronal magnetic field, but that instead the field evolves through series of smooth equilibria in response to footpoint motions. In his contribution to this chapter Van Ballegooijen assumes that the photospheric footpoint motions are random in nature and that as a result of this the separation between any two neighbouring fluid particles increases exponentially with time and consequently steeper and steeper gradients will develop in the magnetic field. As the field gradients grow larger, finally dissipation will grow to a large enough rate to balance energy input and a stationary state will develop. An interesting result of this analysis is that the timescale for establishing the stationary state is remarkebly short, of the order of the "braiding time".

The heating rate predicted by the theory of Van Ballegooijen is a factor 40 short of the required heating rate for the solar corona and this result is mainly based on the observed value of the effective diffusion constant for photospheric motions. However, there may be small scale photospheric motions that so far have escaped detection and these could result in a much larger value for the effective diffusion constant and alleviate the discrepancy between theory and observations. Clearly then, high resolution observations are needed to determine the photospheric power spectrum.

It has been pointed out above that if most of the power in the photospheric spectrum is concentrated in motions with periods between 100 and 1000 seconds, large coronal magnetic structures are probably heated by the dissipation of MHD waves, while the small scale structures are heated by field aligned currents. Wave heating therefore must play a role in the solar corona, and, since most of the coronal X-ray emission comes from large loops, it may well be the dominant source of coronal heating.

Davila in his contribution calculates the heating rate that results from the mechanism of resonance absorption of Alfven waves, that was proposed by Ionson (1978, 1982) as the heating mechanism for coronal loops. The physical basis of this mechanism is that Alfven- or fast MHD waves get trapped in a coronal loop after entering it from the photosphere. Once in the corona, they keep on reflecting back and forth between the two footpoints of the loop, where there is a very sudden density increase by two orders of magnitude. Those waves that have a period equal to the Alfven crossing time of the loop (or an integer fraction of it) are in phase with the incoming waves of the same period as they bounce of the loop footpoints and therefore they become reinforced. Thus the amplitude of the resonant waves in these loops builds up until dissipation limits further growth. In this situation the dissipation of energy equals the energy input at the footpoints and consequently the heating rate is independent of the damping coefficients. What doés depend on these coefficients is the amplitude that the resonant waves attain in the stationary situation: the lower the damping rate, the higher the stationary amplitude. Observations of non-thermal line broadening in UV restrict this amplitude to 10-20 km/sec, but other observations in X-ray lines (Acton **et al.**, 1981) indicate amplitudes around 100 km/sec.

Davila assumes in his paper that a coronal loop is excited by an Alfven wave with a given frequency. The Alfven speed varies slowly over the loop and in a narrow layer the frequency of the incoming wave exactly matches the local resonance frequency. The incoming waves over the whole loop are resonantly absorbed in this layer and dissipate there. Essential in this process is the coupling between waves on neighbouring field lines because of the compressibility of the plasma. Davila calculates that the wave amplitude needed to supply the required coronal heating is 2-6 km/sec, well below the limit set by the observations.

This wave heating theory is in many ways an attractive alternative to the current heating theories discussed above. It explains why a coronal loop, once it is formed, is preferentially heated. The increased density in the loop, compared to the surrounding corona, makes the Alfven velocity in it smaller than that of the surrounding corona, and therefore its Alfven crossing time larger. This means that the loop responds to a different part of the photospheric power spectrum than its surroundings and that part of the spectrum may contain more power. The theory, being concerned with the stationary heating of loops, does not explain why a loop should form. However, the current heating theories explain neither the formation nor the persistence of coronal structures at all, so in this aspect the wave heating theory is ahead. Clearly, any future comprehensive coronal heating theory should not only reproduce the required heating rate, but also its spatial distribution in loops, X-ray bright points, etc.

Two alternative forms of resonance wave heating of the stellar corona, with regard to the detailed dissipation process, have been proposed by Heyvaerts and Priest (1983) and by Hollweg (1984, 1986). There are no papers in these proceedings dealing with those theories, but I will discuss them briefly here for comparison. Heyvaerts and Priest consider a coronal loop with a slowly varying Alfven velocity across it and assume the plasma is incompressible. The coronal waves that build up in it consequently have slightly different frequencies and will gradually grow out of phase across the the field lines. Thus an increasingly large velocity shear develops in the loop until at a certain point dissipation limits further growth. This model has the advantage that the wave amplitude required to achieve the necessary coronal heating are not as large as that in Ionson's (1982) original work. Indeed they can remain within the constraints imposed by the observations. However, the time it takes to set up a stationary state in this model is very long compared with the lifetime of individual coronal structures.

A similar theory has been developed by Hollweg (1984, 1986). He describes a cascade of wave energy to smaller and smaller wavelengths until dissipation taps the wave energy at the smallest wavelength. The cascade is driven by the discontinuities in the wave velocities that are present along the boundary layers of the parts of the coronal field that are attached to different photospheric fibrils. Again the necessary heating is obtained by the development of strong shears in the velocity field.

The last contribution to this chapter on the subject of steady coronal heating is by **Choudhuri**. His basic result is that no net magnetic helicity is transferred into the corona by completely random footpoint motions, since these are as likely to introduce positive as negative helicity on a small scale. This result is relevant with regard to recent work of Heyvaerts and Priest (1984), in which it was pointed out that on a short time scale only as much energy can be dissipated in the corona as is consistent with helicity conservation. According to the paper by Choudhuri then, the conservation of magnetic helicity introduces no effective constraint on energy dissipation.

NON STATIONARY RELEASE OF MAGNETIC ENERGY

The emphasis of this introduction so far has been on the steady conversion of magnetic energy into thermal energy, that is responsible for the continuous X-ray emission from stellar coronae. This is justified because this process is responsible for the mere existence of stellar coronae and at the same time only poorly understood. Apart from this phenomenon, however, stellar coronae exhibit the splendid spectacle of stellar flares, a very sudden conversion of an enormous amount of energy (up to 10^{33} erg for solar flares) into radiation and mass ejections. It is generally assumed that the flare energy is built up and stored in the corona prior to the eruption, but the process is only partially understood.

The last five papers in this chapter are all related to the storage and sudden release of coronal magnetic energy. They form by no means a complete review of solar flare theory, as the papers on steady coronal heating do, and in this introduction I will neither make an attempt to review flare theory.

Hood and Velli, in their back to back contributions, investigate the stability of magnetic arcades in the corona to respectively ideal and resistive instabilities. Cylindrically symmetrical arcades of loops are widely used as a description of the field of a coronal filament prior to its eruption. The eruption of a filament is the origin of a two ribbon flare. A viable scenario for the physical cause of the filament eruption is that a threshold for the onset of an MHD instability is surpassed at the onset of the eruption. Checking the stability of coronal magnetic structures is a complicated procedure that involves the solution of series of ordinary differential equations, or the solution of partial differential equations, and generally it can only be done numerically. In his contribution Hood finds an approximate analytical criterion that is sufficient for the origin of localised instabilities. Nonlinear coupling of the unstable modes can lead to an explosive instability as those in filament eruptions. Hoods criterium is very convenient for a quick check of models for the magnetic field.

Velli in his paper includes the effect of resistivity in the same problem and finds that in some regions where the ideal MHD approximation predicts stability, slowly growing resistive instabilities may be present, which lead to energy release in 10 to 100 Alfven crossing times. This result may be relevant with regard to preflare heating. One could imagine that that as a coronal arcade evolves, it first becomes resistively unstable, and only later on surpasses the threshold for ideal instability. Consequently energy will be released in modest amounts before the whole structure erupts, just as is observed in two-ribbon flares.

Finally, it has been noted by Hood and Velli that the instabilities they describe automatically generate the sort of length scales needed for a steady heating mechanism. Indeed, as soon as the magnetic field departs from potential, resistive ballooning modes are exited and the saturation of these modes should lead to enhanced transport properties. The consequences for coronal heating have yet to be worked out.

In the contribution of **Einaudi** a similar problem regarding the stability of of a model coronal field structure is addressed. He considers the influence a flow and viscosity have on the stability of a given magnetic field configuration. It turns out that viscosity is in general more important than resistivity for the dissipation of energy, and since flows are regularly observed in the corona, especially in relation with filaments and promimences, this should be taken into account in any model for energy conversion.

The generation of an electric field during the decay phase of a two-ribbon flare is the subject of the paper by **Kopp and Poletto.** The electric field is generated along an X-type neutral line. A scenario for the eruption of filaments and the evolution of two-ribbon flares, including the generation of an electric field, is presented by Kuin and Martens elsewhere in these proceedings. Kopp and Poletto concentrate on the derivation of the electric field strength from the observed ribbon velocity during the flare and the observed normal component of the magnetic field. The electric field they find is strong enough to accelerate electrons to the very high energies that are needed to explain the hard X-ray emission of flares. From their model and that of Kuin and Martens it appears that the current sheet set up at the X-type neutral line is the dominant location for the flare energy release.

Finally **Steinolfson** describes a numerical experiment that has relevance for the problem of compact flares and that I further expect to be related with the formation of filaments. The experiment consists of a time dependent two dimensional MHD simulation of the response of a cylindrically symmetric flux tube to rotational motions of its photospheric footpoints. Thermal pressure gradients are neglected and the plasma is assumed to be incompressible. The dynamics then uncouple from the energetics and the problem becomes tractable.

Steinolfson finds that the loop initially evolves through a series of force free equilibria, as one would intuitively expect. However, when the field in an appreciable portion of the loop has undergone óne rotation, a dynamical evolution sets in and the Lorentz force is now balanced by the flow dynamics. A rapid change in the field configuration then occurs, at the end of which some field lines make several rotations around the axis of the cylinder. Steinolfson notes that during the build-up stage enough energy is stored in the loop to account for the energy released in a compact flare. I further note that the rapid transition of the field in the loop from a situation with óne rotation of the field around the axis to one with several rotations is a good model for the origin of filaments and prominences. In this case the field in and around the filament is the first approximation modelled by this cylindrically symmetric loop, with the axis of the loop identical to that of the filament.

CONCLUSIONS

A comprehensive quantitative theory of stellar coronal heating cannot be expected before we are able to fully understand solar coronal X-ray emission. The two major elements of the latter will be a theory of solar flares and one of steady coronal heating. There is a considerable number of theoretical possibilities for steady coronal heating, and most of them are outlined in this chapter. The main task for the near future is to tighten the observational constraints on coronal heating theories, so that at least a number of possibilities can be ruled out. The observations of Spacelab 2 and HRSO (the successor of SOT) can be used to get a better hold on the temporal and spatial dependence of the photospheric power spectrum, while high sensitivity coronal instruments, like POF, may determine the magnitude of coronal wave motions.

On the theoretical side the problem of the spatial distribution of the heating in the solar corona - the preferential heating of loop structures and X-ray bright points - needs to be adressed. No coronal heating theory can claim any generality without solving this problem. Further the problem of the mere existence of force free coronal magnetic fields needs deeper analysis. Heating by topological dissipation of magnetic fields is difficult to rule out on observational grounds, even after a detailed photospheric power spectrum has become available, but then also, this theory can only be confirmed by ruling out all others.

Theoretical analysis, however, should be able to establish unambiguously the conditions for the existence of smooth force free magnetic fields, and hence the validity of the topological heating theory. Furthermore, the question regarding the conditions for topological dissipation transcends the problem of coronal heating. It is also of eminent importance for laboratory plasmas, especially in Tokamaks, and for many astrophysical magnetic fields, like the earth's magnetotail and galactic magnetic fields. Finally, in the view of the author, the problem has a great esthetical appeal: here we have a clear and well formulated theoretical question, and yet the final solution has eluded the astrophysical community for over 20 years.

Flare theory, the other building block for a theory of stellar X-ray emission, is even further from completion. A fairly general scenario for filament eruptions, leading to two ribbon flares (e.g. Kuin and Martens, these proceedings) has now become commonplace in the solar physics community, but we are far removed from **predicting** X-ray emission in flares from preflare observations of magnetic fields and velocity fields in the photosphere. The same spacecraft (HRSO and POF) that will determine photospheric and coronal motions in more detail for steady heating theory, as well as other satellites like MAX'91, will yield valuable information with regard to flare theory.

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