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Models for magnetic heating of the solar atmosphere

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Abstract. Sustaining the hot solar corona requires an energy flux of up to about 10^7erg cm^{-2}s^{-1} whose source must be the photospheric motions below. However, the precise way this energy is transferred and damped still remains an open question. Here a review of recent advances in theoretical models for coronal heating, in the light of the fundamental observational results of the last decade, will be presented.

1. Introduction

The longstanding coronal heating problem may be summarized as follows: why is the coronal plasma at temperatures which are hundreds of times higher than those in the photosphere below? Nowadays there is little doubt that the old picture of heating by shocked sound waves produced by turbulent convective motions below the photosphere may be good for the low chromosphere, but that the heating at larger distances of the low-β (i.e. magnetically dominated), almost collisionless coronal plasma must be of intrinsic magnetic nature. Well known reviews of the several proposed mechanisms are those of Narain & Ulmschneider (1990; 1996); see also Chiuderi (1997), Malara & Velli (2001), Del Zanna & Velli (2002).

A quantitative analysis of enery losses and requirements in the various layers of the solar atmosphere, and in different regions, was pursued for the first time by Withbroe & Noyes (1977) (see also Withbroe, 1988, and Parker, 1991). According to these authors, the energy losses in conduction and UV radiation in the chromosphere and in the transition region require an energy flux input of about $F \sim 5 \times 10^5$erg cm^{-2}s^{-1} for quiet regions and coronal holes (where extra mechanical losses to drive the solar wind must be taken into account), and $F \sim 2 \times 10^7$erg cm^{-2}s^{-1} for active regions, where energy losses are the highest, also at coronal levels. Since we know that the temperature profile is an increasing function of height, moving from the photosphere to the corona, reaching maxima of $T \sim 1 - 1.5 \times 10^6$K in quiet regions and coronal holes and of $T > 2 \times 10^6$K in active regions, the fundamental questions are how this energy is transported up in the corona (if it is not generated there directly) and how it can be damped there. Concerning this last point, since collisions are very rare in the coronal plasma due to the low density, the question could

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be translated in how small scales can be reached, in order for dissipation to be efficient.

Any model for (magnetic) heating of the solar corona should therefore be able to account for the three basic aspects: generation (where?, how much?), transport (how?), and dissipation (how?, how efficiently?). Once the fundamental role of magnetic fields is estabilished, the first aspect is usually explained by the shuffling of magnetic fieldlines due to granular and supergranular photospheric velocity fields. The generated energy flux is then given by the vertical component of the Poynting vector that, assuming flux-freezing in the photosphere, is

$$F \sim S_{\parallel} = \frac{c}{4\pi} E_{\perp} B_{\parallel} = \frac{1}{4\pi} B_{\parallel} B_{\perp} v_{\perp} \qquad (1)$$

that is about $10^7 \mathrm{erg\ cm^{-2} s^{-1}}$ for $B_{\parallel} \sim 100\,\mathrm{G}$, $B_{\perp} \sim 10\,\mathrm{G}$, and $v_{\perp} \sim 1\,\mathrm{km\ s^{-1}}$, (here the perpendicular components actually refer to root mean square values), so more than enough at least for quiet regions and coronal holes, to which this review is particularly devoted especially in its last part, where the connections to solar wind properties will be discussed.

To be able to disentangle ourselves in the *jungle* of different theories and physical mechanisms proposed for energy transport and damping in the corona, here the usual distinction between DC and AC mechanisms will be maintained. In active regions, where large magnetic loops are present, the Alfvénic time scale $\tau_A = L/v_A$ (L is the typical length scale) of response to footpoint motions is usually very short, leading to a quasi-static series of magnetic equilibria that dissipate energy through Ohmic diffusion in thin current-sheets (flare and nanoflare models). Coronal holes are instead characterized by open magnetic fieldlines, along which the solar wind is believed to escape, so that L is very large and footpoint perturbations must propagate upwards in the form of MHD waves (AC mechanisms).

2. DC flaring activity, the Parker scenario and MHD turbulence

In the photosphere magnetic flux is continuously replaced by the emerging, fragmenting and cancelling of ephemeral regions bipoles, which usually are born at supergranule cell centers and then migrate to the cell boundaries, where cancellation with neighbouring fields occur. The SoHO/MDI instrument have recently shown that this process (*magnetic carpet*, Schrijver et al. 1998) is much more rapid and frequent than previously believed, so that 90% of the total quiet Sun magnetic flux is replaced in approximately one day! It is clear that in this way miriads of reconnection events could occur in the overlying corona (see the *tectonics* model by Priest et al., 2002), providing a continuous release of energy in the corona.

Similar models were previously applied to explain X-ray bright points (Priest et al. 1994), where a 2-D force-free field evolves quasi-statically due to the converging motions of magnetic fragments of opposite polarity: during the interaction phase, reconnection occurs at the null point, the plasma is heated (giving rise to the observed X-ray emission), and later the fragments annihilate and the flux is cancelled. Going in 3-D, a wild variety of different geometries suitable for quasi-static reconnection of force-free fields naturally arise (Priest & Schrijver 1999). Related problems are those of the energy release by large flares (Priest & Forbes, 2002, for a review) and also the heating and temperature profiles along coronal loops (see Reale's contribution in these proceedings). DC dissipation in current sheets formed due to the motion of magnetic structures is certainly a viable method for energy release in corona. However, due to the huge value of magnetic Reynolds numbers there ($\sim 10^{12}$) extremely small scales must form in the process, unless the dissipation is not Ohmic but rather of some non collisional type.

Another basic aspect to consider is the frequency of the flaring events as a function of the energy released. Parker (1988) was the first to suggest that the corona might be heated through a moltitude of small flaring events, rather than thanks to rare large flares of the kind described in the previous section. Let us consider the distribution of energy release events $f(E) \propto E^{\alpha}$, supposed to be a power law, integrated between $E_{\rm min} = 10^{24}$ erg, corresponding to the lowest energy events that can be measured in EUV (nanoflares), and $E_{\rm max} = 10^{32}$ erg, corresponding to a large flare:

$$E_{\rm tot} = \int_{E_{\rm min}}^{E_{\rm max}} E f(E) {\rm d}E. \quad (2)$$

Two possible situations may arise: when $\alpha + 2 > 0$ we have $E_{\rm tot} \propto E_{\rm max}^{\alpha+2}$, so rare but large events dominate, whereas when $\alpha + 2 < 0$ we have $E_{\rm tot} \propto E_{\rm min}^{\alpha+2}$, so it is actually the moltitude of small events that gives the bulk of the released energy. Observations during the last decade have tried to measure a definitive value for the power law index α: while statistics of flares and microflares in X-rays seem to give $\alpha \sim -1.5$, promising measures from EUV data by both SoHO/EIT and TRACE, in the most interesting low-energy range, appear to yield $\alpha \sim -2.5$, thus supporting the Parker scenario. A compilation of these observations can be found in the review by Aschwanden (2001).

From a theoretical point of view, usually the spectrum of events is simulated by inducing an MHD turbulent cascade in a numerical box where some random time-dependent forcing is applied at the boundaries. The typical situation is that of a 2-D periodic plane of low aspect ratio ($l_\perp/L \ll 1$, where $l_\perp$ is the dynamical scale lenght) normal to a dominant constant field B_0 (the cross section of a magnetic loop, representative of a coronal small region). In this case the so-called reduced MHD incompressible equations apply and we find the scalings

$$\tau_\parallel = \sqrt{\rho_0}\frac{L}{B_0} < \tau_\perp = \sqrt{\rho_0}\frac{l_\perp}{b_\perp} \ll \tau_{\rm phot}, \quad (3)$$

so that we are well in the DC regime (typical dynamical time scales are about $\tau_\perp \sim 100$ s). The application of a stochastic boundary driver along the loop simply translates into a forcing term in the reduced MHD equations, which drives a nonlinear turbulent cascade to small scales, while on the largest scale the system tends to rearrange itself in a way to be insensitive to the external forcing. Dissipation occurs where thin current sheets form during the dynamical process: long term time histories of the spatially averaged resistive terms clearly shows the highly intermittent nature of the process, while a Fourier analysis yields the required power laws. However, probably due to the approximations made (2-D, reduced MHD) and to the limited spatial dynamical range, the values of α are well above the -2 critical value (see Velli, 1996, and Einaudi & Velli, 1999, for discussions and references on MHD simulations of the Parker scenario; see also Carbone's contribution in these proceedings for a broader discussion on turbulence and intermittency in plasma modeling).

3. AC mechanisms, MHD modes and Alfvén waves

Let us move now to regions in the Sun where the heating is most probably due to AC-type mechanisms, because of the presence of open magnetic structures and thus to long characteristic time scales of response to photospheric perturbations, namely coronal holes. These regions are colder than the quiet Sun and active regions ($T \sim 1 \times 10^6$ K), but additional work must go in the acceleration of the (fast) solar wind, which is known to escape from the open fieldlines of coronal holes.

The idea that Alfvén waves might be responsible for the heating of coronal holes and for the acceleration of the solar wind comes from both observations, thanks to *in situ* measurements, and theoretical speculations.

The celebrated paper by Belcher & Davis (1971) was the first to show that the low frequency part of the spectrum (say between 10^{-4} and 10^{-2} Hz) of fluctuations in fast streams (fast wind produced in coronal holes sweeping the ecliptic plane) is dominated by Alfvénic modes propagating outwards from the Sun. This was demonstrated by showing that magnetic and velocity fluctuations are highly correlated (the sign depends on the background average magnetic field), and that normalized density, pressure and total magnetic field fluctuations are small. Later it was shown (Grappin et al. 1990; see also Goldstein et al., 1995, for a review) that the turbulence spectrum in fast streams is different from that of slow streams, which shows the properties of a well developed Kolmogorov-type turbulence. In fast streams the evolution is slower and the spectral index is between $-5/3$ and -1. These results were confirmed for the polar wind too by the Ulysses mission, which has measured plasma parameters at high heliospheric latitudes for the first time.

Thus, the fast solar wind shows the presence of a whole spectrum of Alfvén waves. Are these waves produced inside coronal holes? Are they able to account for the heating and the acceleration of the coronal hole – fast wind system? Unfortunately, MHD waves are very difficult to measure at coronal levels, so the field is open for theoretical speculations. The solar atmosphere is characterized by very strong density vertical gradients, due both to gravity and to the sudden increment of the temperature at the transition region. Just to give some numbers, consider the simplest possible 1-D atmosphere as made up of two isothermal layers separated by a discontinuity, so that the density decreases as $\rho \sim \mathrm{e}^{-z/H}$ in both regions, where $H = 2kT/m_p g$ is the local scale-height, and abruptly of two orders of magnitude at the transition region at $z \simeq 2000$ km. The sound and Alfvén speeds both increase with height, since $c_s = \sqrt{\gamma p/\rho} \sim T^{1/2}$ and $v_A = B_0/\sqrt{4\pi\rho} \sim \rho^{-1/2}$. In the chromosphere we can take $T = 10^4$ K, $H = 500$ km, $c_s = 15$ km s^{-1} and $v_A = 100$ km s^{-1}, whereas at the coronal base $T = 10^6$ K, $H = 50,000$ km, $c_s = 150$ km s^{-1} and $v_A = 1000$ km s^{-1}.

Consider now the propagation in such atmosphere of the various MHD normal modes (see also Roberts, 2000, for a review on MHD waves in the solar corona and for references). Slow waves, which are essentially acoustic waves in parallel propagation when $\beta \ll 1$, suffer fast nonlinear steepening and shock dissipation on very short heights. The characteristic length of steepening to shocks is approximately given by the time needed for a wave peek, moving at a speed $c_s + \delta v$, to reach the next wave valley, moving at a speed $c_s - \delta v$, multiplied by the sound speed, so that

$$L_s \sim \frac{\lambda/2}{2\delta v} c_s = \frac{\tau c_s^2}{4\delta v}, \qquad (4)$$

where τ is the sound wave period. By using reasonable values, we find that L_s is about the chromospheric scale height, so that it turns out that slow modes can contribute only to chromospheric heating (Ulmschneider 1991). This estimate is actually valid only for a uniform medium; if stratification is taken into account we have that for short enough wavelengths (WKB) energy flux conservation takes on the simple expression $\rho(\delta v)^2 c_s \sim \text{const} \Rightarrow \delta v \sim \rho^{-1/2}$, thus due to this wave amplification the length L_s decreases even more.

Fast magnetoacoustic waves suffer much slower steepening, partly due to their greater phase velocity and partly due to slower amplification: in a low-β plasma fast waves are essentially compressible Alfvén waves and now it is $\rho(\delta v)^2 v_A$ to be constant, leading to $\delta v \sim \rho^{-1/4}$, since $v_A \sim \rho^{-1/2}$ for a uniform background magnetic field. The problem with fast waves is that they cannot propagate at any direction because of refraction in a stratified medium with increasing $v_A(z)$. Suppose that ω and $k_\perp$ are given constants, then

$$\omega^2 = [k_\parallel^2 + k_\perp^2] v_A^2 \Rightarrow k_\parallel^2 = \omega^2/v_A^2 - k_\perp^2, \qquad (5)$$

and this will be a negative quantity for z great enough. If slow modes dissipate low down in the chromosphere and fast modes survive only in quasi-parallel propagation, we are left with Alfvén waves alone. To lowest order they do not suffer either steepening nor refraction. In the WKB limit their amplitude increases with height according to

$$v_\perp \sim B_\parallel^{-1/2}\rho^{-1/4}, \quad B_\perp \sim B_\parallel^{-1/2}\rho^{1/4}, \quad (6)$$

($\rho v_\perp^2 \sim B_\perp^2$), whereas for wavelengths larger than or of the order of the typical scale of variation in v_A, $|(1/v_A)\mathrm{d}v_A/\mathrm{d}z|^{-1}$, the above relations are no longer valid and Alfvén waves can suffer significant reflection leading to a lower transmission of energy (Velli 1993; Orlando et al. 1996). Suppose then that a certain flux of Alfvén waves is able to reach the corona. The next problem to solve is how to dissipate it. Incompressible Alfvén waves are notoriously difficult to damp, since they are shear waves and the collisional shear viscosity is very small in the corona. The situation improves if large transverse gradients are at disposal, like for loops in active regions. In this case Alfvén waves can be efficiently damped through resonant absorption or analoug processes (e.g. Davila 1991; Malara et al. 1996; Einaudi et al. 1996; Califano & Chiuderi 1999). For coronal holes, where less structuring is present but still the Alfvén speed could in principle be different along neighbour vertical fieldlines, Heyvaerts & Priest (1983) proposed phase mixing as a possible damping mechanism: waves initially in phase at the coronal base become progressively more and more out of phase by moving upwards, while transverse gradients can develop. Under certain approximations the wave amplitude suffers a damping of the form $\exp[-(z/\Lambda)^3]$, where

$$\Lambda/\lambda \sim \left[\frac{\omega}{\eta}\left(\frac{k'}{k}\right)^{-2}\right]^{1/3}. \quad (7)$$

Unfortunately, for realistic values of the resistivity η and of the wave pulsation ω and wavelength λ, heating at reasonable coronal heights can be achieved only if the length scale of variation of the Alfvénic speed, $l = k/k'$, is of the order of a few kilometers. The situation can drastically improve in 3-D chaotic coronal magnetic fields, where initially neighbouring fieldlines may exponentially diverge and thus improve dissipation (see Malara's contribution in these proceedings and references therein).

How then can Alfvén waves possibly dissipate, by propagating upwards along vertical fieldlines in a coronal hole that is rather uniform in the transverse direction? How can small scales be reached? Let us see what happens to nonlinear Alfvén waves in a purely incompressible medium. By using the Elsässer variables $\mathbf{z}^\pm = \mathbf{v} \mp \mathbf{b}$, $\mathbf{b} = \mathbf{B}/\sqrt{4\pi\rho}$, the MHD equations may be rewritten in the form

$$\frac{\partial \mathbf{z}^\pm}{\partial t} + \mathbf{z}^\mp \cdot \nabla \mathbf{z}^\pm = -\nabla p^* + \eta \nabla^2 \mathbf{z}^\pm, \quad (8)$$

where $p^* = p/\rho + b^2/2$ and we have assumed for simplicity $\nu = \eta$. It is apparent that if upward propagating Alfvén waves $\mathbf{z}^+$ alone are initially present ($\mathbf{z}^- = 0$), the nonlinear term vanishes and cascade towards small scales will never be achieved. Two are the possible solutions: either partial reflection due to density stratification creates the necessary $\mathbf{z}^-$ to start the cascade (Velli et al. 1989; Mattheus et al. 1999), but the wavelengths must be long enough, or compressible effects must be taken into account.

In fact, although Alfvén waves are incompressible normal modes to first order, linear (or torsional) Alfvén waves are able to drive compressible modes to second order, due to the ponderomotive force caused by the variation of the total magnetic pressure. As an example, consider the simple case of a linear Alfvén wave propagating along a mean vertical B_0 in cartesian geometry, $B_\perp = b\sin[k(z - v_A t)]$. The equation for the density fluctuations is then

$$\left(\frac{\partial^2}{\partial t^2} - c_s^2\frac{\partial^2}{\partial z^2}\right)\delta\rho = \frac{\partial^2}{\partial z^2}\frac{B_\perp^2}{8\pi} \quad (9)$$

and its solution is

$$\delta\rho = \rho_0 \frac{\eta^2}{4(\beta - 1)} \cos[2k(z - v_A t)], \qquad (10)$$

where $\eta = b/B_0$ is the normalized wave amplitude and $\beta = c_s^2/v_A^2$. The solution has clearly the form of a forced oscillation, with same wave velocity as the Alfvénic pump but double frequency, with amplitude quadratic in η and with a resonance when the pump speed matches the normal mode speed c_s ($\beta = 1$). Thus, Alfvén waves of sufficient amplitude may drive compressible motions. This mechanisms has been applied, for example, to the problem of spicule formation (Hollweg et al., 1982; Kudoh & Shibata, 1999), although it cannot account for the overall coronal heating problem because amplitudes are generally small. Similar problems occur for compressible wave-wave interactions such as parametric decay, which however is more appropriate for solar wind conditions (see my other contribution in these proceedings).

Concluding this section, we may say that the Alfvén waves seen in the solar wind are most probably generated in coronal holes (other MHD modes are damped at lower heights), where Ohmic heating might be provided by some sort of enhanced phase mixing mechanism, while possibly this will be more efficient in active regions where more complex magnetic topologies are at disposal. In any case, Alfvén waves are a very good way of transporting momentum and heat in the solar wind at larger distances. Many MHD models where the wind is driven by Alfvén waves through the ponderomotive force have been proposed (starting from Alazraki & Couturier 1971) but the acceleration only occurs at large heliocentric distances. Even a subsequent turbulent cascade does not help much. In order to account for fast wind final velocities ($v \approx 750$ km/s) and especially for the rapid wind accelaration near the Sun (Grall et al. 1995; Fisher & Guhathakurta 1995), these kind of models would require extra heating close to the coronal base (Esser et al. 1997; McKenzie et al. 1997), usually taken in the form of a parametrized heating function in the equation for the *perpendicular ion temperature*. The physical reasons for such a choice will be explained in the next section.

4. Kinetic ion-cyclotron damping

From the early 80s it is known that ions in the solar wind are preferentially heated in the direction perpendicular to the magnetic field. Moreover, minor ions (especially He^{++}) flow faster than protons (the difference is the local Alfvén speed), and between two species i and j the relation $T_i/T_j > m_i/m_j > 1$ holds (reviews by Marsch 1991, 1999). These properties are clear signatures of resonant damping of ion-cyclotron waves, which is a well known wave-particle kinetic process at work in magnetized plasmas. The so-called *sweeping* models for the acceleration of the solar wind were proposed (McKenzie et al. 1979; Isenberg & Hollweg 1982) and this mechanism was also suggested to operate in coronal holes too. It was only almost 20 years later that these models were finally accepted as a viable mechanism to explain coronal heating, thanks to the revolutionary discoveries of the SoHO/UVCS spectrometer. Protons and minor ions (especially O^{5+}) were found to produce line broadenings compatible to extremely high perpendicular temperatures (up to $T_\perp \sim 2 \times 10^8$!), even hundreds of times larger than parallel temperatures (Kohl et al. 1998), while electrons are below the threshold of 10^6 K. Moreover, thanks to the *Doppler dimming* technique developed by G. Noci, UVCS was also able to infer oxygen flow velocities larger than hydrogen velocities by as much as a factor of 2 (e.g. Cranmer et al. 1999), in the range $1.5 - 4$ solar radii. All these observations confirm the importance of kinetic processes in the heating of coronal holes and in the related fast wind acceleration problem. How does resonant ion-cyclotron damping work? For a review on this subject the reader is referred to Hollweg's presentation at the *Solar Wind 10* conference, held in Pisa in June 2002. Ion-cyclotron waves are the high frequency kinetic extension of MHD Alfvén waves, with the following dispersion relation

$$\omega = k_\parallel v_A \sqrt{1 - \omega/\Omega_p}, \tag{11}$$

where $\Omega_p = eB_\parallel/cm_p \approx 10^4$ Hz is the cyclotron frequency for protons. The resonance condition for the transfer of energy between the wave and the ion (with cyclotron frequency Ω_i and parallel velocity $v_\parallel$) is

$$\omega - k_\parallel v_\parallel = \Omega_i. \tag{12}$$

When this condition is satisfied the wave electric field is able to accelerate secularly the ions in the perpendicular direction, thus providing perpendicular heating, and, because of the particle drift in velocity space at constant $(v_\parallel - \omega/k_\parallel)^2 + v_\perp^2$, also acceleration in the parallel direction. Finally, ions are favoured over protons for three reasons: the resonance interval is larger, the resonance ω is smaller and so the phase velocity and the parallel acceleration are larger, perpendicular (squared) velocities are larger, so the temperature ratio is larger than the mass ratio.

The discoveries of SoHO/UVCS thus have given strong evidence in favour of ion-cyclotron damping in coronal holes, but obviously this does not mean that the problem of coronal heating is solved. The nature of the damping is probably kinetic, but the question is always how such small kinetic scales can be reached: is it the result of a turbulent cascade, since the peak of Alfvén waves energy should be at low frequencies, or ion-cyclotron waves are directly generated in corona in the kHz range, like in the *furnace* model (e.g. Axford 1999), due to small scale reconnection events? These questions are still open for future debate.

5. Kinetic models based on suprathermal particles

Before concluding, I would like to mention yet another class of models for coronal heating and solar wind acceleration, namely kinetic models based on suprathermal velocity distribution functions. In the solar corona the mean free path for a thermal particle (electrons or protons) is only $10^{-4} - 10^{-2}$ times smaller than the macroscopic density scale-heigth, that is the plasma is weakly collisional. This means that non-Maxwellian velocity distribution functions with supra-thermal tails (possibly produced by some Fermi acceleration process in the chromosphere) might be able to carry enough energy to higher altitudes, through a process known as *velocity filtration*, and thus to explain the high coronal temperatures (Scudder 1992). This completely collisionless effect has been later applied to solar wind acceleration models (Maksimovic et al. 1997), yielding realistic outflow speeds at 1 AU without the need of *ad hoc* energy or momentum deposition near the Sun, contrary to most fluid models. However, no observational support is available for the required (κ-*function*) distributions in corona, while electronic suprathermal tails are certainly observed in solar wind data. The kinetic filtration effect has been recently tested numerically by including collisions in the transition region (Landi & Pantellini 2001), demonstrating that only very strong suprathermal tails in initial electronic distribution functions are able to survive in the corona and to transport enough energy there, because the system collisionality is still too strong and thermalization actually takes over on relatively short distances.

6. Conclusions

In this review I have tried to summarize the basic aspects of coronal heating, in the light of the recent experimental evidencies. Depending on the region in the Sun, different mechanisms might be at work, due to the different dynamical time scales involved. The new observations by SoHO have provided evidence that the input of magnetic energy from below is more than enough, and that most probably the dissipation must be of kinetic nature, especially in coronal holes where Alfvén waves and the solar wind are supposed to be generated. The longstanding question on the nature of coronal heating, namely the AC/DC controversy, is however still unanswered. In any case, the two mechanisms are certainly connected together and the most important question to be addressed is how the extremely small scales needed for dissipation (either Ohmic or most probably kinetic) can be reached.

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