FLUCTUATIONS, DISSIPATION AND HEATING IN THE CORONA

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Abstract. Mechanisms for the deposition of heat in the lower coronal plasma are discussed, emphasizing recent attempts to reconcile the fluid and kinetic perspectives. Structures at the MHD scales are believed to act as reservoirs for fluctuation energy, which in turn drive a nonlinear cascade process. Kinetic processes act at smaller spatial scales and more rapid time scales. Cascade-driven processes are contrasted with direct cyclotron absorption, and this distinction is echoed in the contrast between frequency and wavenumber spectra of the fluctuations. Observational constraints are also discussed, along with estimates of the relative efficiency of cascade and cyclotron processes.

1. Introduction

A recurring theme in recent studies of the physics of the corona has been the issue of the mechanism by which heat is deposited within two or three solar radii of the photosphere (Holzer 1977; Habbal *et al.* 1995) in sufficient quantities to both accelerate the solar wind and to account for high temperatures inferred from recent SOHO observations. One of the models which has been proposed to explain these observational constraints (McKenzie *et al.* 1995; Axford and McKenzie 1997) relies upon the cyclotron absorption of relatively high frequency ($\sim$ kHz) waves propagating upward in the lower solar atmosphere. There is no observational evidence for waves of such high frequency. Here we will discuss several physical and observational issues of relevance to this model as well as alternatives that would involve MHD cascade as an essential feature. We will emphasize the possibility that magnetic fluctuations with high transverse wavenumber may be dynamically driven in a way that allows heating to occur without requiring a pre-existing reservoir of high frequency waves. The possible importance of Landau damping and cyclotron absorption of highly oblique structures will be discussed, especially in view of recent observational evidence from solar wind data. These discussions motivate the development of models based upon anisotropic, reduced MHD equations, in which quasi-two dimensional (2D) turbulence plays a central role in the dissipation of fluctuations and the subsequent heating of the corona.

2. Damping of High Frequency Alfvén Waves

The Axford-McKenzie model (McKenzie *et al.* 1995; Axford and McKenzie 1997) of coronal heating envisions generation of broadband waves due to disturbances in or near the chromospheric network. In this model the waves are launched upwards at the Alfvén speed (perhaps thousands of km/s) and within 1–2 solar radii the

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waves dissipate, heating the corona and imposing signatures of cyclotron damping in the form of a high perpendicular temperature ($T_\perp$) for protons and minor ions. The hot coronal plasma produces an outward flow at altitudes sufficiently low to satisfy constraints on radial acceleration of the solar wind inferred from remote sensing observations (Grall *et al.* 1996). Recently Tu and Marsch (1997) elaborated upon the cyclotron wave damping model, investigating the upward propagation, transport, and dissipation of a flux of Alfvén waves generated at the base of a model corona. Their study lends support to the direct cyclotron heating model, provided that sufficient wave power is supplied at high enough frequencies. This appears to require a spectrum no steeper than $1/f$ (C.-Y. Tu, private communication) extending out to kHz frequencies.

This coronal dissipation scenario descends conceptually from earlier work on collisionless damping of MHD waves (Barnes 1969), and even earlier work on thermal excitation of instabilities through cyclotron resonance (e.g., Rowlands *et al.* 1966; Kennel and Engelmann 1966). Based upon linear theory, one concludes typically that fast and slow mode waves are very heavily damped through kinetic processes. If one observes a broad persistent spectrum of MHD waves, as one does in the solar wind (Tu and Marsch 1995), there is an expectation that these fluctuations would be in the Alfvén mode. Direct observations frequently support this conclusion (Belcher and Davis 1971). The same predisposition exists in coronal physics, but is less well bolstered by observations than is the solar wind case. The perspective of Tu and Marsch (1995) is that coronal Alfvén waves propagate upwards until reaching an altitude at which the height-dependent cyclotron frequency is low enough to absorb them. This mechanism might be called "cyclotron resonance sweeping," or simply "cyclotron sweeping," given that the absorption sweeps towards lower frequency, progressively eating away the spectrum of fluctuations. This idea appeared earlier in several contexts, including solar wind particle anisotropies (Schwartz *et al.* 1981) and acceleration of He^{++} (Hollweg and Turner 1978).

3. Frequency vs. Wavenumber: Transfer in k-space

If one focuses upon the dynamics of parallel propagating MHD Alfvén waves, it is tempting to assume tacitly that frequency ω and wavenumber k are in a one-to-one correspondence. For the slab model with wave vector $\mathbf{k}$ parallel to the large scale mean magnetic field $\mathbf{B}_0$, and for Alfvén waves having $\omega \sim \mathbf{k} \cdot \mathbf{B}_0 \equiv k_\parallel B_0$, the correspondence is accurate. However, the perpendicular component of wavenumber $k_\perp$ is unaccounted for in this assumption. If one talks about a "cascade in frequency," there is an assumption that nonlinear transfer is to higher $k_\parallel$ with no implied transfer in $k_\perp$. Conversely, a cascade in wavenumber may imply various possibilities in the frequency domain.

This distinction seems not have been fully appreciated in the past. For example, the assumption of a steady spectral distribution in parallel wavenumber is indeed useful in estimating cyclotron effects on minor ions (Isenberg and Hollweg 1983)

or other test particles in which only small fractions of the total fluctuation energy may be involved. It is quite a different story to assume that the rate of replenishment of fluctuation energy by cascade to higher parallel wavenumber is sufficient to heat the thermal plasma. However, this assumption is implicit in the solar wind theory of Tu (1988) in which cyclotron sweep was neglected in favor of a large cascade rate computed in terms of an *isotropic* Kolmogoroff-like inertial range phenomenology. This theory assumes a strong cascade, but one equally strong in all directions. At this point one must ask what simulations and MHD theory have to say about transfer of energy in wavenumber space.

Numerical simulations show that a strong, large-scale magnetic field $\mathbf{B}_0$ produces relatively enhanced spectral transfer in the directions transverse to $\mathbf{B}_0$. This is a consequence of the suppression of spectral transfer in the parallel direction because of Alfvénic propagation effects. This phenomenon has been seen in two-dimensional, three-dimensional, incompressible and compressible MHD (Shebalin *et al.* 1983; Oughton *et al.* 1994; Matthaeus *et al.* 1996). The expectation that nonlinear activity preferentially involves high transverse wavenumber is also implicit in the structure of "reduced MHD" (Strauss 1976; Montgomery 1982), which is widely believed to be a leading order low frequency dynamical description of laboratory plasmas at low plasma beta. There are also a variety of indications that the spectrum of observed solar wind turbulence is highly anisotropic, containing what appears to be a rather large admixture of high $k_\perp$ fluctuations (e.g., Matthaeus *et al.* 1995). This anisotropy has sometimes been idealized as a two component mixture (Matthaeus *et al.* 1990) of so-called 2D fluctuations (varying $k_\perp$ with $k_\parallel = 0$) and slab fluctuations (varying $k_\parallel$ with $k_\perp = 0$). When parameterized in this way, fits to Helios data (Bieber *et al.* 1996) suggest that 80% of the energy is in 2D modes, and the remaining 20% in slab modes.

Such evidence represents a strong break with the more traditional view that solar wind fluctuations are pure slab (or, isotropic), and a corollary is that the simple correspondence of frequency and wavenumber discussed above may be strongly violated. 2D turbulence may emerge from a variety of causes, including the anisotropic spectral transfer alluded to above. Several studies (Kinney and McWilliams 1998; Matthaeus *et al.* 1998) support the view that spectral transfer purely transverse to the mean field, i.e., purely in the $k_\perp$ direction, is a reasonable first approximation. In this case spectral transfer of Alfvén modes may occur at *constant* frequency, while something resembling a Kolmogoroff-type nonlinear cascade occurs in $k_\perp$.

4. Cyclotron Absorption vs. Cascade

In evaluating the possible roles of the cyclotron sweep mechanism and the anisotropic nonlinear cascade mechanism in coronal heating, it is useful to estimate directly their respective heating rates. Let us denote the cascade heating rate as $\epsilon_\perp$ and the cyclotron sweep heating rate as ϵ_c. The cascade heating rate is estimated in the standard way (Zank *et al.* 1996) as $\epsilon_\perp = \delta u^3/\lambda_\perp$ where δu is the rms turbulent

velocity and $\lambda_\perp$ is the similarity scale, or energy containing scale of the quasi-2D fluctuations, often taken to be the perpendicular correlation length. Note that this is a *perpendicular* heating rate and that the concomitant transfer rate into high parallel wavenumbers is much smaller.

The cyclotron sweep damping rate (Tu and Marsch 1997; Schwartz *et al.* 1981) may be estimated as $\epsilon_c \sim (U + V_A)\, P(f_c)\; df_c/dr$ where U is the flow speed, V_A the Alfvén speed, $P(f)$ the frequency dependent power spectrum of the fluctuations, and f_c is the local proton gyrofrequency, varying with radius r. Defining λ_h as the scale height for gyrofrequency variation, and δu^2_{diss} to be the energy in dissipation range fluctuations (Leamon *et al.* 1998a, b), we find that $\epsilon_c \sim (U + V_A)\delta u^2_{\text{diss}}/\lambda_h$. Regrouping terms, we estimate that the ratio of cascade heating rate to gyrofrequency sweep heating rate is

$$\frac{\epsilon_\perp}{\epsilon_c} = \quad \frac{\delta u^2}{\delta u^2_{\text{diss}}}\Bigg)\left(\frac{\delta u}{V_A}\right)\left(\frac{\lambda_h}{\lambda_\perp}\right). \tag{1}$$

The first of these factors expresses essentially the ratio of fluctuation energy at the correlation length scale to that at the cyclotron dissipation scale. Thus, it is large for a broadband inertial range, perhaps $\sim 10^3$ unless the spectrum is very flat, say $1/f$ as assumed by Tu and Marsch (1997). In the latter case this factor is ≈ 1. The second factor is unknown for the corona, but (simply guessing) it may be "small," say 10^{-2}, or up to a "saturated" value, ≈ 1. The final factor is also hard to estimate, since the transverse correlation scale of coronal fluctuations is unknown. However, based upon remote sensing of anisotropic density fluctuations (Grall *et al.* 1997), and our knowledge of solar wind anisotropies, we might expect that $\lambda_\perp \ll 1R_\odot$. The scale height for gyrofrequency variation (see Tu and Marsch 1997) is typically assumed to be a few tenths of a solar radius or more. Thus the third factor may be, say, 10^2 or perhaps much larger. On balance one concludes that the cascade mechanism may be dominant, and almost certainly cannot be neglected.

Tu and Marsch (1997) reached the opposite conclusion, examining only the cyclotron sweep mechanism for coronal parameters, while discarding the direct cascade. However, the cascade model they employed was one in which the total energy transfer rate is inversely proportional to V_A. This type of model (see, e.g., Galtier *et al.* 1997) is based upon the isotropic inertial range theory of Kraichnan (1965) and does not take strong anisotropy into account. In addition a decay rate $\propto V_A^{-1}$ is apparently inconsistent with MHD simulations at moderate Reynolds number (Hossain *et al.* 1995). Tu and Marsch present no quantitative support for their approximation and, on the basis of the estimates above, we can see no reason why the perpendicular cascade should be neglected for coronal parameters.

5. Dissipation Mechanisms

In either the cascade model or the cyclotron sweep model, the net dissipation rate

of energy depends crucially on the full three dimensional energy spectrum $E(\mathbf{k})$ (energy here refers to flow kinetic energy plus magnetic energy). For example, if the dissipation function is of the form $(dE(\mathbf{k})/dt)_{\text{diss}} = -\gamma(\mathbf{k})E(\mathbf{k})$, then the dissipation rate for the total energy E is

$$\frac{dE}{dt} = -\int d^3k\, \gamma(\mathbf{k})E(\mathbf{k}) \tag{2}$$

where the integral extends over all wave vectors. Clearly, $\gamma(\mathbf{k})$ alone does not determine the dissipation rate, as the integral also involves the distribution of energy. Thus, in the cyclotron sweep picture one must specify a spectrum of noninteracting waves that is supplied to the corona. The nature of the spectrum is then deferred to a discussion about wave generation at the base of the corona. The cascade picture might also retain some sensitivity to the boundary or input spectrum, but the spectrum sufficiently far from the boundary may be almost fully determined by local nonlinear interactions, i.e., by spectral transfer.

In this perspective, we need to simultaneously confront the issues of MHD spectral transfer, governed by large scale dynamics, and kinetic dissipation mechanisms, controlled by microphysics. MHD spectral transfer, which we suspect to be highly anisotropic in coronal conditions, most likely sends energy vigorously to high transverse wave numbers. The net dissipative effect will be determined by whatever absorption rate $\gamma(\mathbf{k})$ is afforded by available kinetic processes. Several issues, some raised by recent solar wind work, warrant mention:

1. On the basis of linear theory, a very large $|\gamma|$ is expected for fluctuations with polarizations corresponding to the fast or slow mode (Barnes 1969). However, little seems to be known at present regarding how rapidly a strong nonlinear cascade of Alfvén modes supplies energy to the magnetosonic polarizations. If such rates are large, this would have important consequences for the existence of an inertial range, and might affect the dissipation range.
2. Recent investigation of $\gamma(\mathbf{k})$ associated with the Alfvén mode (Leamon *et al.* 1999) in the solar wind reveals that there is angular dependence of damping rates computed from linear Vlasov theory. Comparison with inferred spectral anisotropy (at 1 AU) leads to the conclusion that most of the energy damps at oblique angles.
3. Analysis of dissipation range magnetic helicity (Leamon *et al.* 1998b) suggests that both cyclotron resonant and non-cyclotron resonant processes (e.g., Landau damping) operate in the solar wind dissipation range.
4. For dissipation at highly oblique angles, where $k_\perp$ is important, the relevant length scale is likely to be the ion inertial scale ρ_i rather than the gyroradius λ_{ci} which enters more naturally into cyclotron absorption of high $k_\parallel$ structures. In the low-β corona, this distinction is significant.
5. Nonlinear kinetic mechanisms need to be considered as well as linear Vlasov results. Various possibilities exist for nonlinear effects which might contribute significantly to damping at oblique wave vectors, e.g., driving of magnetosonic

modes (mode conversion), dissipation at reconnection sites, and secondary instabilities associated with parallel electron beams.

6. Possibility of a Reduced MHD Model

Based in part on the considerations above, we recently proposed a model to examine the implications of a highly anisotropic nonlinear cascade in the corona (Matthaeus *et al.* 1999). In its simplest form the model consists of propagating Alfvén waves and quasi-2D MHD turbulence. The waves drive the turbulence and the latter dissipates the energy at small perpendicular scales. Specifically, we assume that the continual energy supply for the turbulent heating arises from (approximately) Alfvénic fluctuations generated in the chromosphere. These propagate into the corona where some fraction experience non-WKB reflection off the large-scale density and field gradients (Hollweg 1996; Velli 1993). When sufficient fluctuation energy resides in low frequency quasi-2D MHD modes, whose wavevectors are almost perpendicular to the (average) coronal magnetic field $\mathbf{B}_0$, then the waves can drive the turbulence (Shebalin *et al.* 1983; Matthaeus *et al.* 1996; Matthaeus *et al.* 1998). At large Reynolds numbers, the quasi-2D fluctuations engage in a transverse cascade involving successive reconnection of poloidal flux structures, thereby transferring energy to small (perpendicular) scales where it is dissipated.

Two preliminary implementations of this model have been examined. In the first, the turbulence is modeled by a simple one point phenomenology (e.g., Zank *et al.* 1996) and the reflections are modeled by reflection coefficients. In the second implementation, the turbulence is modeled as reduced MHD. In each case the results show that a significant fraction of the input energy in the form of propagating waves is converted to heat by dissipation of the 2D turbulence. The process is efficient ($\sim$ 50%) and the initial seed 2D turbulence is robustly regenerated. So far only scalar dissipation coefficients, incompressible MHD, and modeled reflection coefficients have been employed. However, the results are encouraging with regard to further exploration along these lines.

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