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Nonlinear Damping of Fast Waves and Plasma Heating in the Solar Corona

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Abstract. A nonlinear mechanism for the damping of fast magnetoacoustic wave in the solar corona is studied. It is shown that the nonlinear coupling of finite-amplitude fast waves to small-scale Alfvén waves can be much faster than damping mechanisms involving classic transport coefficients.

1. Introduction

Fast waves (FWs) and Alfvén waves (AWs) can be excited in the corona by perturbations of the magnetic field lines which are anchored into the dense convective zone and displaced by the plasma motions there (Tirry & Berghmans 1997; De Groof, Tirry, & Goossens 1998; De Groof & Goossens 2000). The consequent dissipation of these waves in resonant layers can contribute to coronal heating (De Groof & Goossens 2000, and references therein).

A difficulty of this dissipation mechanism is that the setup time of the linear resonance (the time required for the creation of sufficiently short length-scales) is long compared to the sub-minute variations in the coronal heating process, as seen by SOHO (Berger et al. 1999). To avoid this difficulty, anomalous transport coefficients (resistivity and viscosity) can be invoked. But current-driving and velocity shear-driving instabilities, that produce anomalous resistivity and viscosity, are weaker or absent at all at longer length-scales: they can be significant at length-scales not much different from the dissipative ones, based on the classic transport coefficients.

There are also another, observational constraints. Assume that the compressible (i.e. fast mode) perturbations are excited in the corona. Then, if these waves are responsible for the coronal heating, the amplitudes and scales of these waves should be sufficient to make the waves observable in the (quasi-) periodic modulations of coronal emission due to plasma compression in waves (about 5%). In fact, observations show little evidence for such amplitudes of fast waves, they rather suggest Alfvén or kink modes (Koutchmy, Zugzda, & Locans 1983; Doyle, Banerjee, & Perez 1998), even under the presence of a strong driver, e.g. flare (Nakariakov et al. 1999; Aschwanden et al. 1999).

Taking in hands the theoretical prediction that fast waves can be excited in corona by footpoint motions, and the observational evidence of very low amplitudes of fast waves in the corona, we come to conclusion that these waves should be dissipated strongly by a more efficient process.

Here we tackle the problem of a damping mechanism for FW that place the limit on FW amplitude from the nonlinear point of view. In the framework of two-fluid MHD we show that fast waves are nonlinearly coupled to the kinetic Alfvén waves - Alfvén waves (AWs) with short wavelengths across B_0, background magnetic field (large perpendicular wavenumbers $k_\perp$). Because of their ability to interact strongly with space plasmas, such short-scale AWs are now under intensive investigation (Hollweg 1999; Voitenko & Goossens 2000a, and references therein).

2. Nonlinear excitation of short-scale Alfvén waves by fast waves

The nonlinear eigenmode equation for short-scale Alfvén waves has been derived by Voitenko & Goossens (2000a). In the limit of high perpendicular wavenumbers, the equations for the short-scale Alfvén waves coupled to the large-scale compressional magnetic field ($B_{\mathrm{P}\|} \parallel B_0$) of the fast waves are:

$$\left[\frac{\partial}{\partial t} - \gamma_{L1}\right] \Phi_1 = i\frac{\omega_2}{k_{2\perp}^2}\frac{\rho_T^2 k_{1\perp}^2}{K_2^2}\left(\mathbf{k}_{1\perp}\cdot\mathbf{k}_{2\perp}\right) b_{\mathrm{P}\|}\Phi_2^*. \tag{1}$$

$$\left[\frac{\partial}{\partial t} - \gamma_{L2}\right] \Phi_2^* = -i\frac{\omega_1}{k_{1\perp}^2}\frac{\rho_T^2 k_{2\perp}^2}{K_1^2}\left(\mathbf{k}_{1\perp}\cdot\mathbf{k}_{2\perp}\right) b_{\mathrm{P}\|}^*\Phi_1. \tag{2}$$

Here $\Phi_{1,2}$ are the slowly varying amplitudes of the coupled waves, γ_L is the rate of linear AW interaction (decrement or increment), $b_{\mathrm{P}\|} = B_{\mathrm{P}\|}/B_0$ is the parallel (compressional) component of the pump magnetic field, and

$$K^2 \approx \frac{1+\rho_T^2 k_\perp^2}{1+\delta_e^2 k_\perp^2} - \beta\frac{\left(\rho_T^2-\delta_e^2\right)k_\perp^2}{\left(1+\delta_e^2 k_\perp^2\right)\left(1+\rho_T^2 k_\perp^2\right)} \tag{3}$$

is the AW dispersion function (square of the phase velocity divided by Alfvén velocity). $\rho_T^2 = \sqrt{\left(T_e+T_i\right)/m_i}/\Omega_i$ is the effective gyroradius, and δ_e is the electron skin length. The wave field is presented in the form of fast oscillating waves with slowly varying amplitudes, $\phi_{1,2} = \Phi_{1,2}(t)\exp\left(-i\omega_{1,2}t + i\mathbf{k}_{1,2}\cdot\mathbf{r}\right)$.

When we put $k_{1\perp}^2 \approx k_{2\perp}^2 \equiv k_\perp^2$, and look for exponential solutions, $\Phi_{1,2} \sim \exp(\delta t)$, we find the total growth (of damping) rate $\delta = \gamma_{NL} + \gamma_L$, where the rate of nonlinear pumping of FW energy into daughter AWs is

$$\gamma_{NL} = \frac{1}{2\sqrt{\beta}}\omega_{\mathrm{P}}\frac{\rho_T^2 k_\perp^2}{K^2} b_{\mathrm{P}\|}. \tag{4}$$

In the low-frequency range, the collisional damping of AW dominates $\gamma_L = \gamma_c \approx -0.5\beta^{-1}\left(m_e/m_i\right)\nu\left(\rho_T^2 k_\perp^2\right)$,where ν is the electron collisional frequency ($\nu = 1 - 100\ s^{-1}$ and $\beta \sim 0.1$ in the corona).

The threshold of the instability in the collisional regime is found from the marginal condition $\gamma_{NL} + \gamma_c = 0$:

$$\left(b_{\mathrm{P}\|}\right)_{thr} \approx \frac{m_e}{m_i}\frac{1}{\sqrt{\beta}}\frac{\nu}{\omega_{\mathrm{P}}}\left(1 + \frac{k_{\mathrm{P}\perp}^2}{k_{\mathrm{P}\|}^2}\right). \tag{5}$$

We take into account that the resonant conditions determine the perpendicular wavenumbers of excited AWs: $\rho_T k_\perp \approx k_{\mathrm{P}\perp}/k_{\mathrm{P}||}$. Then for the FW with $b_{\mathrm{P}||} = 10^{-2}$, $\omega_{\mathrm{P}}/\nu = 10^{-1}$, and $k_{\mathrm{P}\perp}/k_{\mathrm{P}||} \sim 1$, we can estimate the typical time of the instability to develop and the plasma to heat:

$$\tau_\delta \sim \tau_{NL} \sim \tau_c \sim 10 - 100 \text{ s}.$$

With the same parameters, the threshold amplitude is $\left(b_{\mathrm{P}||}\right)_{thr} \approx 3 \times 10^{-3}$.

3. Summary and Discussion

We found a new channel for the dissipation of fast waves in the solar corona: fast waves nonlinearly couple their energy to Alfvén waves with short wavelengths across $\mathbf{B}_0$. In the framework of two-fluid MHD we investigated a resonance decay of the pump FW into two short-scale AWs: FW→AW+AW. The nonlinear coupling is strong for fast waves launched with amplitudes of the order of 0.01 for B/B_0. The nonlinear damping of such waves is much stronger than linear damping based on classical transport coefficients.

An important feature of this process is that the excited AWs have very short wavelengths in the plane perpendicular to B_0, and thus are damped almost immediately by the linear kinetic or collisional dissipation (Voitenko & Goossens 2000b). As a consequence, the overall timescale of the heating process is determined mainly by the characteristic time of the nonlinear mode conversion. Our estimations shown that the overall time scale of the heating can easily be in the (sub-)minute range, as observed by SOHO (Berger et al. 1999).

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