KINETIC ALFVÉN TURBULENCE AND NON–THERMAL BROADENING IN SOLAR FLARES

Yu. Voitenko[1,2] and M. Goossens[2]

[1] *Main Astronomical Observatory, NAS of Ukraine*
27 Zabolotnoho St., 03680 Kyiv, Ukraine
e-mail: voitenko@mao.kiev.ua

[2] *Centre for Plasma Astrophysics, K. U. Leuven*
Celestijnenlaan 200B, 3001 Heverlee, Belgium

Recent observations of soft X-ray nonthermal line broadening and hard X-ray emission in solar flares suggest that the nonthermal broadening is due to plasma turbulence created in the energy release [1]. We develop a model of the impulsive excitation of Alfvén wave turbulence and propose the mechanism for the interruption of spectral energy fluxes in flaring loops. This interruption determines the nonthermal broadening in flares and is important for the selective heating of plasma species and for the acceleration of particles to high energies.

INTRODUCTION

Observations suggest that the bulk flare energy is carried by the ≥ 0.1 MeV proton beams at the onset of solar flares ([4], and references therein). Yohkoh observations provide an additional support for the hypothesis of magnetic reconnection operating in different kinds of solar flares [5]. Fast magnetic reconnection converts the energy of the inflowing magnetic field into the bulk kinetic energy of outflowing plasma, moving with a typical velocity equal to the Alfvén speed based on the inflow condition, $V_{(\mathrm{out})} \approx V_{A(\mathrm{in})}$. For typical coronal conditions, these outflows provide the kinetic energy flux $(0.1 - 10) \times 10^{11}$ erg cm^{-2} s^{-1}, carried mainly by outflowing ≥ 0.1 MeV protons. A principal question that needs to be answered is the following: how the kinetic energy that is carried by the ≥ 0.1 MeV proton beams is transformed in the corona?

A viable mechanism for the conversion of the proton-beam energy, which accounts for a strong interaction of kinetic Alfvén waves (KAWs) with a plasma, has been proposed ([6], and references therein). The theory was applied to both impulsive compact-loop flares and long-duration events. It was shown that the beam-driven instability of KAWs provides an effective mechanism for the conversion of beam kinetic energy into the energy of waves in the coronal part of just-reconnected flaring loops. Using the theory developed in [7]–[10], we discuss here the properties of the spectral fluxes of energy in the KAW turbulence.

EXCITATION OF ALFVÉN WAVE TURBULENCE IN FLARING LOOPS

In a Maxwellian background plasma, the increment of the KAW instability, driven by the V_z-shifted Maxwellian proton beam with bulk velocity V_{b0}, is [6]:

$$\gamma_k = \sqrt{\frac{\pi}{8}}\omega_k \frac{\mu^2}{K^2}\frac{T_e}{T_i}\left(g_b\frac{n_b}{n_0} + g_i - \frac{V_k}{V_{Te}} + \frac{E_0}{E_{Dr}} + \frac{E_0}{E_{ke}}\right), \tag{1}$$

where $V_k = \omega_k/k_z = V_A K$ is the wave phase velocity along $\mathbf{z} \parallel \mathbf{B}_0$, ω_k and $\mathbf{k}$ are frequency and wave vector of the excited waves, $g_\alpha = \Lambda_{0\alpha}(T_e/T_\alpha)[(V_{\alpha 0} - V_k)/V_{T\alpha}]\exp[-0.5(V_{\alpha 0} - V_k)^2/V_{T\alpha}^2]$ with $\alpha = b$ or i, $E_{ke} = k_z T_e/e$.

In addition, to Cherenkov wave-particle interaction, the effects of the beam-induced electric field E_0 are taken into account in (1). For a super-Alfvén proton beam ($V_{b0} > V_A$), the destabilization in (1) comes from beam–induced inverse Landau damping ($\sim n_b/n_0$), and beam-induced electric field E_0 ($\sim E_0/E_{Dr}$ and $\sim E_0/E_{ke}$) terms. Stabilizing effects are due to the electron Landau damping (term $\sim -V_k/V_{Te}$), and the ion Landau damping (term $\sim g_i$, $g_i < 0$).

We estimate the growth rate of the KAW instability, excited in a flaring loop by a proton beam (typical velocity $V_{b0} \leq 2V_A$, and $n_b/n_0 = 0.2$) as $\gamma_k^L/\Omega_i = 5 \times 10^{-2}$. As it has been shown in the framework of quasilinear theory, the beam-driven instability of KAWs can be saturated by the velocity-space diffusion of the beam protons [6]. Here we take into account the stronger nonlinear saturation mechanism [7], giving a saturation level of the wave amplitude in the source ($k_\perp \rho_i \leq 1$) region: $B_s/B_0 = 5 \times 10^{-2}$. The nonthermal plasma velocity due to waves may be calculated from the amplitude of wave magnetic field B: $V_{pl} = V_A \left(B/B_0\right)$. With the above values this gives a nonthermal plasma velocity $V_{pl} = 50$ km s^{-1} induced by the waves initially excited by beam.

THE MECHANISM OF THE SATURATION OF SPECTRAL FLUX AND NONTHERMAL BROADENING IN FLARES

The nonthermal velocities, observed as the excess line width of the soft X-ray line emission, are very high at a flare onset, $V_{nt} = 200 - 400$ km s^{-1}, and suggest that the nonthermal broadening is due to plasma turbulence created in the energy release [1]. The direction of energy cascade in the KAW turbulence is towards small k, forming a so-called inverse cascade and the inertial-range spectrum, $\sim k_z^{-1/2} k_\perp^{-2}$ [8], suggesting that the enhanced wave amplitudes in the small-$k_\perp$ domain can explain the nonthermal velocities observed in flares.

The turbulent cascade can be stopped at small $k_\perp$ by the KAW phase mixing [9], and by ion Compton scattering [10]. Here we support the idea that the spectral flux can be eventually stopped by the ion Landau damping [9], even if plasma $\beta_i \left(= V_{Ti}^2/V_A^2\right)$ is initially low, $\beta_i < 0.1$. Indeed, if initially the wave spectrum falls in the domain of strong electron Landau damping, the resulting electron heating will rise β_i to 0.2 via $e - i$ collisions at time scale $\sim 10^{-2}$ s. Then ion Landau damping come into play, and the resulting quasi-stationary dynamic equilibrium comprises: 1) the linear wave excitation at a wavenumber k_s, 2) the nonlinear saturation of the instability at a level B_s/B_0, 3) the inverse turbulent cascade induced by the three-wave resonant interaction, 4) the cascade interruption at a wavenumber $k_{\min} \left(= k_{d\perp}\right)$ by the ion Landau damping. The conditions of the equilibrium, $\gamma_k \left(k_{s\perp}\right) = \gamma_k \left(k_{d\perp}\right)$, $\gamma_k \left(k_{s\perp}\right) = \gamma_{NL} \left(k_{s\perp}\right)$, and $\gamma_{NL} \left(k_{d\perp}\right) = \gamma_k \left(k_{d\perp}\right)$, allow us to determine the energy-containing wavenumber as $k_{\perp\min} \sim 0.3 k_{s\perp}$, and the amplitude of magnetic fluctuations as $B \simeq k_{s\perp}^2 k_{\perp\min}^{-2} B_s = 0.2 B_0$. This estimation gives the non-thermal velocity of $V_{nt} = 200$ km s^{-1}.

SUMMARY

We investigated the mechanism of the saturation of the spectral flux in the KAW turbulence in flaring loops. This phenomenon determines the nonthermal broadening in flares and selective heating of electrons and ions. The nonlinear saturation level of the wave amplitude in the energy-containing region, $B \sim 0.2 B_0$ gives the non-thermal velocity of $V_{nt} = 200$ km s^{-1}, which is typical at flare onset. The heating process undergo a transition from the preferable electron heating at the initial stage of turbulence to the ion heating at the developed stage.

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