ALFVEN WAVE GROWTH DRIVEN BY STREAMING PROTONS IN CORONAL LOOPS

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EXTENDED ABSTRACT. In the process of resonant scattering, an initially anisotropic distribution of charged particles drives the growth of plasma waves which then tend to reduce the anisotropy. We address the stability of an anisotropic, streaming, power-law distribution of super-Alfvénic ($v \geq v_A$) protons in a coronal loop by considering the conditions for the effective growth of Alfvén waves. Protons of these velocities, which fall in the energy range of 10 to 1000 keV, are the subject of increasing interest and speculation in the flare physics community (see, *e.g.*, Simnett, 1986; Simnett and Benz, 1986; Tamres *et al.*, 1986; Canfield and Chang, 1985; Hudson, 1985), hence it is timely to consider the constraints which streaming instabilities impose on their distributions.

The absorption coefficient $\gamma^\sigma(\mathbf{k})$ specifies the rate of absorption ($\gamma^\sigma>0$) or growth ($\gamma^\sigma<0$) of plasma waves, where σ denotes the wave mode and $\mathbf{k}$ the wavevector. In quasi-linear theory (Melrose, 1980) it is given by

$$\gamma^\sigma(\mathbf{k}) = -\sum_{s=-\infty}^{\infty} \int d^3p\; w^\sigma(s,\mathbf{p},\mathbf{k})\, \hbar \left[\frac{s\Omega_c}{v_\perp}\frac{\partial}{\partial p_\perp} + k_\parallel \frac{\partial}{\partial p_\parallel}\right] f(\mathbf{p}) \tag{1}$$

where $f(\mathbf{p})$ is the particle distribution function in momentum space, Ω_c is the particle gyrofrequency, $\hbar$ is the Planck constant divided by 2π, and the subscripts $\parallel$ and $\perp$ specify the components of vector quantities parallel and perpendicular, respectively, to the ambient magnetic field. The factor $w^\sigma(s,\mathbf{p},\mathbf{k})$ is the probability per unit time and per unit elemental range in k space that a spiralling particle of momentum $\mathbf{p}$ emits a wave of wavevector $\mathbf{k}$ and simultaneously suffers a decrease of $s\hbar\Omega_c/v_\perp$ in $p_\perp$ and $\hbar k_\parallel$ in $p_\parallel$. Evaluation of $w^\sigma(s,\mathbf{p},\mathbf{k})$ requires the dispersion relation for the waves; for Alfvén waves in a cold, magnetized, charge-neutral hydrogen plasma, this is (Stix, 1962)

$$n^2 = \frac{c^2}{2v_A^2(1-\chi^2)}\left[1 + \sec^2\theta + (\tan^4\theta + 4\chi^2\sec^2\theta)^{1/2}\right] \tag{2}$$

where n is the index of refraction ($n^2 = c^2k^2/\omega^2$), χ is ω/Ω_c, θ is the waveangle (= $\arccos(k_\parallel/k)$), v_A is the Alfvén speed (= $B/(4\pi\rho)^{1/2}$), and c is the speed of light in vacuum.

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For the purposes of our study, the streaming protons are assumed to have a distribution given by $f(p) \sim (p/p_o)^{-2\delta}(1 - \varepsilon\cos\alpha)^{-n}$ for $p > p_o = m_p v_A$, where α (= $\arccos(p_\parallel/p)$) is the pitch angle. This distribution features a power law in energy with spectral index δ and a directional asymmetry described by the anisotropy parameter ε; it is isotropic for ε=0 and becomes increasingly biased in the direction of the magnetic field as ε approaches unity. We restrict our quantitative analysis to the parameter ranges $3 \leq \delta \leq 5$, $0.1 \leq \varepsilon \leq 0.9$, and $2 \leq n \leq 4$. Furthermore, we limit our investigation to the regime in which the dominant contributions to $\gamma^\sigma(\mathbf{k})$ in equation (1) come from the ($s = \pm$ 1) terms. Wave growth is found to occur principally through the anomalous Doppler effect ($s = -$ 1).

The criterion for stability of the proton beam, namely that the time scale for wave growth be larger than the time for protons to stream from the apex to the chromospheric footpoint of a loop, sets an upper limit on the density of energetic protons relative to the background. A threshold parallel velocity $v_\parallel^* = [(2\delta)/(n\varepsilon)]v_A$ is associated with the above distribution: we find that the proton beam is stable provided that

$$\frac{n(v_\parallel > v_\parallel^*)}{n_o} < 6\times10^{-7} L_9^{-1} n_{10}^{-1/2} \qquad (3)$$

where L_9 is the loop semi-length in units of 10^9 cm, n_o is the background proton density, and $n_{10} = n_o/10^{10}\text{cm}^{-3}$. Studies of the proton/wave system evolution at density ratios exceeding this upper limit need to consider the nonlinear effects through which wave growth is saturated.

In terms of temperature and chemical composition, the flare atmosphere represents a departure from the idealized cold hydrogen plasma. We find that thermal corrections imply wave damping in the frequency range $\Omega_c(1 - \Delta\chi) < \omega < \Omega_c$, where $\Delta\chi \approx (V_i/v_A)^{2/3}$ and V_i is the thermal proton speed. Cyclotron resonances associated with heavy ions are quenched at solar abundances, with a possible exception in the case of ^{4}He; an unquenched resonance may give rise to significant wave damping in the vicinity of the ^{4}He cyclotron frequency, leading to systematically larger values of $v_\parallel^*$.

A more detailed account of our study is given by Tamres *et al.* (1987).

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