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Small scale Alfven waves and isotropization of energetic protons

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Abstract. The problem of isotropization of energetic protons in the H_α emitting region during flare energy release is considered. It has been shown that absence of the linear polarization of H_α emission in some events can be caused by excitation of small scale Alfven waves by anisotropic protons. Consequences of the proposed model are discussed.

Keywords. Sun: flares, chromosphere, transition region, turbulence, polarization

1. Introduction

There are many indications that the observed linear polarization of the H_α emission in solar flares (1–5%) caused by the beam of the low energy protons ($E < 200 - 400\,\mathrm{keV}$) propagated in the upper chromosphere (e.g. Bianda *et al.* 2005). In contrast to electrons they are not scattered by thermal particles and the beam of protons becomes more collimated due to collisions (Hénoux *et al.* 1990). Therefore, if the acceleration of the low energy protons in corona is the typical phenomena of solar flares, we can expect that the impact polarization of the H_α emission must be observed in most quite powerful events (H_α knots). However, this is not the case (Babin & Koval 1983; Bianda *et al.* 2005) and the following question arises: can we explain this phenomenon within the framework of the standard solar flare model?

Bianda *et al.* (2005) proposed that the absence of linear polarization in many events is connected with the process of isotropization of energetic protons in the H_α emitting region. First of all, it can be caused by increase of pith–angles of protons due to the magnetic field convergence. Secondly, anisotropic protons can excite small scale Alfven waves, which effectively scatter energetic particles.

The aim of this work is to verify the possible mechanisms of isotropization of protons in the H_α emitting region.

2. Isotropization and conservation of the magnetic moment

Miller & Ramaty (1989) have shown that the magnetic moment of accelerated protons η due to negligible scattering on atoms and charge particles of target is conserved. Therefore pitch–angles of protons α must be increased as a result of the magnetic field convergence. It suggests that collimation of the beam due to collisions becomes impossible when diamagnetic force $F_d = \eta dB/ds$, were s is the depth of penetration of protons, exceeds the friction $F_f = Mv/\tau$, where M and v are the mass and velocity of a proton,

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respectively, τ is the characteristic time of deceleration, i.e.

$$\eta \frac{dB}{ds} > \frac{Mv}{\tau}.$$

Since the magnetic moment $\eta = Mv_{\perp}^2/2B$ and the mean free path $l_f = v\tau$, the last inequality takes the form

$$H < \frac{l_f \sin^2 \alpha}{2}, \tag{1}$$

where $H = Bds/dB$ is the characteristic scale length. The mean free path for protons with $E = 10 - 100$ keV is (Orrall & Zirker 1976)

$$l_f \approx 4.18 \times 10^{15} \frac{E^2}{n_e \ln \Lambda + n_a \ln \Omega} \ \ [\mathrm{cm}]. \tag{2}$$

Here n_e and n_a is the number density of electrons and atoms in cm^{-3}, $\ln \Lambda = \ln[5.2 \times 10^7 (T/n_e)^{1/2} E]$ and $\ln \Omega = \ln(0.145)$ are the Coulomb logarithms, the energy E and the temperature T are in keV and K, respectively. For example, taking in equation (2) $E = 50$ keV (most optimum energy for polarization), $n_e = 10^{11} - 10^{12}$ cm^{-3}, $n_e/n_a \approx 1$ (Machado *et al.* 1980; Qu & Xu 2002), we obtain $l_f = 10^6 - 10^7$ cm. At $\alpha = \pi/6$ inequality (1) gives $H < 1 - 10$ km, which seems unlikely under chromospheric conditions.

3. Alfven wave turbulence

Hua *et al.* (1989) claimed that Alfven waves can not be excited by energetic protons in the chromosphere due to strong damping of waves in the dense partially ionized plasma. Let's consider this problem in more details.

The damping rate of Alfven waves Γ_d with $\omega \gg 1/\tau$ propagated along the magnetic field is (Ginzburg & Rukhadze 1975)

$$\Gamma_d = \frac{1}{2} \left[\frac{m}{M} (2\nu_{ei} + \nu_{ea}) + \nu_{ia} \right], \tag{3}$$

where m is the mass of electrons, ν_{ei}, ν_{ea}, ν_{ia} are the appropriate frequencies of electron-ion, electron-atom, and ion-atom collisions. It easy to show that collisions between ions and atoms play a crucial role in the H_α emitting region, because $m/M \ll 1$ and $n_e, n_i \sim n_a$. Taking into account that (Leake *et al.* 2005)

$$\nu_{ia} \approx 10^{-10} n_a \sqrt{T} \ [c^{-1}], \tag{4}$$

and adopting $T = 10^4$ K, $n_a = 10^{11} - 10^{12}$ cm^{-3}, equations (3)–(4) yield $\Gamma_d \approx 5 \times (10^2 - 10^3)$ s^{-1}.

The growth rate of Alfven waves propagated along the magnetic field is

$$\Gamma_A = \frac{\pi^2}{2n} \frac{\Omega_i^2}{\omega} \int_{-1}^{1} \int_{v}^{\infty} \left\{ \left(k - \frac{\omega \mu}{v} \right) \frac{\partial f}{\partial \mu} + \omega \frac{\partial f}{\partial v} \right\} \delta(\omega + \Omega_i - kv\mu) v^3 (1 - \mu^2) \, d\mu dv, \tag{5}$$

where Ω_i is the cyclotron frequency of ions, k is the wave number, n is the number density of ions or electrons ($n = n_i = n_e$), $\mu = \cos \alpha$. Note that the resonance condition $\omega + \Omega_i - kv\mu = 0$, as well as the dispersion relation for Alfven waves, $\omega = kv_A$, suggest that at $v = 3 \times 10^8$ cm/s ($E = 50$ keV) and $\Omega_i = 9.6 \times 10^3 B_{Gauss} = 5 \times 10^6$ s^{-1}. Hence the wave length is $\lambda \approx 2\pi v/\Omega_i \approx 4$ m, so we have small scale waves.

The distribution function of energetic protons can be represented as

$$f(v,\mu) = Dv^{-\beta}\begin{cases} \mu, & \mu \geqslant 0; \\ 0, & \mu < 0; \end{cases} \tag{6}$$

where D and $\beta > 3$ are constants. Then, substituting (6) into (5), we obtain

$$\Gamma_A = \frac{\pi^2}{2n}\frac{\Omega_i^2}{\omega}Dv^{-\beta+3}\left\{\left(\frac{1}{\beta-3} - \frac{\mu^2}{\beta-1}\right)\right.$$
$$\left.+\frac{\omega}{kv}\left(\frac{\mu^2}{\beta+1} - \frac{1}{\beta-1}\right)(1+\beta\mu)\right\}\Bigg|_{\mu = \dfrac{\omega+\Omega_i}{kv}}, \tag{7}$$

It follows from equation (7) that the self–absorbtion of Alfven waves will be negligible at $v > \beta\mu v_A$. In this case assuming $\omega \ll \Omega_i$ and taking into account that

$$\int\limits_0^1\int\limits_v^\infty f v^2\, d\mu dv = n',$$

where n' is the number density of energetic protons, equation (7) is reduced to the formula (see also Kennel & Petchek 1966)

$$\Gamma_A \approx \Omega_i \frac{\Omega_i}{\omega}\frac{n'}{n}. \tag{8}$$

According to (3), (4), and (8) the condition for excitation of Alfven waves by protons in the upper chromosphere takes a form

$$\frac{n'}{n} > 0.5\frac{\omega}{\Omega_i B}. \tag{9}$$

For $B = 500 - 1000$ G and $\omega/\Omega_i = 0.1$ inequality (9) gives $n'/n > 5\times10^{-6} - 10^{-4}$.

The condition for the efficient generation of waves over characteristic distance l can be written as

$$2\Gamma_A l \gg v_g,$$

where v_g is the group velocity of waves. Assuming $l = l_f = 10^6 - 10^7$ cm, $\Gamma_A = 10^3\ s^{-1}$, we obtain $2\Gamma_A l = 2\times(10^9 - 10^{10})$ cm/s. Since the typical group speed of waves in the upper chromosphere $v_g = v_A = 10^7 - 10^8$ cm/s, the last inequality is well fulfilled.

It should be note that protons can excite Alfven waves, if their velocity $v = 4.36\times 10^7\sqrt{E}_{\rm keV}$ [cm/s] exceeds the Alfven one $v_A = 2.18\times10^{11}B_{Gauss}/\sqrt{n}_{cm^{-3}}$ [cm/s], i.e.

$$E > 2.5\cdot10^7\frac{B^2}{n}\ \ [keV].$$

For example, at $n = 10^{12}$ cm^{-3}, $B = 500 - 1000$ G, the energy of protons $E > 6.25 - 25$ keV.

Thus, for reasons given above we may conclude that small scale Alfven waves can be effectively excited by low energy protons in the H_α emitted region.

Alfven wave turbulence will play a dominant role, when the characteristic time of particle diffusion on waves is (Kennel & Petchek 1966)

$$\tau_d \approx \frac{1}{\Omega_i}\left(\frac{B}{\delta B}\right)^2,$$

where δB is the characteristic amplitude of Alfven waves, is less than τ. In accordance

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to (2) this condition suggests the following inequality

$$\left(\frac{\delta B}{B}\right)^2 > \frac{1}{\Omega_i \tau_c} = \frac{l_f}{v\Omega_i}. \tag{10}$$

Supposing $v = 3 \times 10^8$ cm/s, $l_f = 10^6 - 10^7$ cm, and $B = 500$ G, we obtain $(\delta B/B)^2 > 6 \times (10^{-5} - 10^{-6})$. Hence, the density of wave energy $W = \delta B^2/8\pi = 6 \times (10^{-1} - 10^{-2})$ erg cm^{-3}. On the other hand for the average energy of energetic protons $\bar{E} = 100$ keV and the number density $n' = 10^7 - 10^8$ cm^{-3} the total energy of protons is $E_\Sigma \approx n'\bar{E} = 2 \times (1 - 10)$ erg cm^{-3}. Since $W \ll E_\Sigma$ the necessary level of Alfven turbulence can be easy achieved in the upper chromosphere.

4. Discussion and conclusion

We have shown that during the flare energy release the low energy protons can be efficiently scattered by the small scale Alfven waves in the H_α emitting region. As a result, the impact polarization of H_α emission becomes impossible. Therefore the absence of the linear polarization in the chromospheric lines does not mean that acceleration of the low energy protons is a quite rare phenomenon, because the process of isotropization of protons in the upper chromosphere depends strongly on their spectral index β as well as the level of the Alfven wave turbulence.

According to our results the influence of magnetic field convergence on the distribution function of energetic protons is negligible in the H_α emitting region. Alfven wave turbulence is the most probable reason of the proton isotropization. However, we can't exclude the possibility of proton acceleration in the upper chromosphere. In this case the distribution of protons depends on the mechanism of particle acceleration.

In conclusion it should be emphasized that three regimes of the pitch–angle diffusion of energetic particles in solar loops (magnetic traps) are possible: weak, moderate, and strong (see e.g. Stepanov & Tsap 2002). The similar approach can be used in the case under consideration too, if we adopt the characteristic length of the trap $L = l_f$. Thus, our main result is reduced to the statement that moderate and strong diffusion regimes of energetic protons on Alfven waves can be realized in the H_α emitting region.

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