Electron trapping and acceleration by kinetic Alfven waves in solar flares

Artemyev A.[1,2], Zimovets I.[1,3], Rankin R.[4]

[1] IKI of RAS, Moscow, Russia
[2] UCLA, Los Angeles, USA
[3] NSSC of CAS + ISSI-BJ, Beijing, China
[4] University of Alberta, Edmonton, Canada

Introduction

- Flares are associated with magnetic reconnection in the corona
- Reconnection is related with plasma and magnetic field disturbances and hot plasma outflows
- These processes can lead to MHD waves and hot proton beams, which, in turn, can cause excitation of kinetic Alfven waves – KAWs (e.g., Hasegawa 1976; Voitenko 1998)
- Due to parallel electric field component KAWs can heat/accelerate electrons (e.g., Hasegawa & Chen 1974; Wu & Fang, 1999; Fletcher & Hudson 2008; Artemyev et al. 2015)
- The goal of the work is to show that warm/hot electrons trapped by KAWs can principally be accelerated up to ~10^2-10^3 keV in course of the transport to footpoints of flare flux tubes (loops)

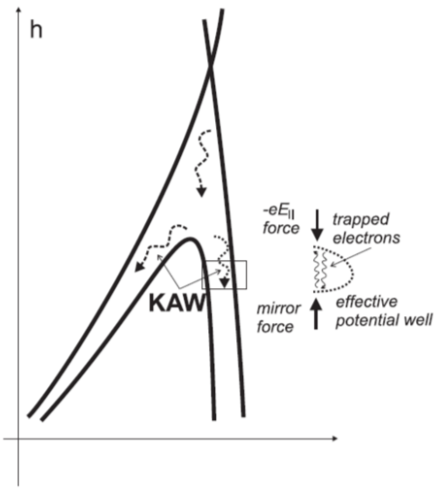


Fig. 1. Schematic view of electron acceleration scenario.

Some properties of KAWs

- $\omega < \omega_{ci}$ - ion-cyclotron frequency
- Perpendicular wavelength: $\lambda_\perp = \frac{2\pi}{k_\perp} > r_{ci} > T_i^{1/2} B^{-1} \sim 10-100$ cm
- KAWs are dispersive: $\omega = K v_A k_\parallel$, where $K = \sqrt{\frac{1+\rho_s^2 k_\perp^2}{1+\lambda_e^2 k_\perp^2}}$

$\rho_s = \sqrt{\frac{k_B(T_i + T_e)}{m_i}} \frac{1}{\omega_{ci}}$ - ion effective gyroradius, $\lambda_e = \frac{c}{\omega_{pe}}$ - electron inertial length (skin depth)

- In case of the kinetic plasma β , i.e. $Q = \frac{m_e}{m_i} << \beta << 1$, dispersion relation is reduced to $\omega = v_A k_\parallel \sqrt{1+\rho_s^2 k_\perp^2}$

Some properties of KAWs

- <u>Polarization of KAWs:</u>

(e.g., Stasiewicz et al. 2000)

$$\left|\frac{E_\parallel}{E_\perp}\right| = \frac{k_\parallel k_\perp \rho_s^2}{1+k_\perp^2 \rho_i^2} \sim \frac{k_\parallel}{k_\perp}$$

$$\left|\frac{E_\perp}{B_\perp}\right| = \frac{v_A}{c}\left(1+k_\perp^2\rho_i^2\right)\left[1+k_\perp^2\left(\rho_s^2+\rho_i^2\right)\right]^{-1/2} \sim \frac{v_A}{c}$$

$$B_\perp \sim E_\parallel \left(\frac{k_\perp}{k_\parallel}\frac{c}{v_A}\right)$$

(Zhao et al. 2013)

For $n \sim 10^9 cm^{-3}$, $T \sim 10^6 K$ we have $\frac{B_\perp}{B_0} \sim \left(\frac{k_\perp}{k_\parallel}\right)\left(\frac{E_\parallel}{E_D}\right)\left(\frac{10^{-2} G}{B_0}\right)^2$ and for $\left.\begin{array}{l}\frac{E_\parallel}{E_D} < 10^3 \\ \frac{k_\perp}{k_\parallel} \sim 10^1\end{array}\right\} \frac{B_\perp}{B_0} < 10^{-2}$

Electron trapping by KAWs in converging magnetic field

- Landau resonance condition for trapping of e- by a wave: $v_{e\parallel} \approx \omega/k_{\parallel} \sim v_A$
- If $B_0(h) = const \rightarrow \langle v_e \rangle = const$
- If $\nabla_{\parallel} B_0(h) \neq 0 \rightarrow \langle v_e \rangle \neq const$
- Energization is due to joint action of KAWs electric field force and magnetic mirror force
- Parallel kinetic energy is converted to perpendicular energy

System of dimensionless equations of e- motion

$$\begin{cases} \dot{s} = p/\gamma \\ \dot{p} = -r_0 b'(s)/\gamma - \varepsilon K(s) F'(\phi) - f_n \nu p/\gamma \\ \dot{\phi} = \chi[aK(s)\dot{s} - 1] \\ \gamma = \sqrt{1 + p^2 + 2r_0 b(s)} \end{cases}$$

$$E = E_{\parallel} F(\phi)$$

$$\phi = \int^{h} k_{\parallel}(h) dh - \omega t$$

$$\omega = k_{\parallel} v_A \sqrt{1 + (k_{\perp}\rho_s)^2}$$

$$F(\phi) = \cos(\phi)\exp(-\phi^2/100)$$

$$\mu = (mc^2/B_0)\sin^2(\alpha_0)[\gamma_0^2 - 1] = (mc^2/B_0)$$

$$b = B/B_0$$

$$b' = db/dh$$

$$F' = dF/d\phi$$

$$s = h/R_s$$

$$p \rightarrow p/mc$$

$$t \rightarrow tc/R_s$$

$$k_{\parallel} R_s = \frac{R_s \omega}{v_A \sqrt{1 + (k_{\perp}\rho_s)^2}} = K(s) \frac{\chi(c/v_{A0})}{\sqrt{1 + (k_{\perp}\rho_s)^2}}$$

$$\varepsilon = eE_{\parallel} R_s / mc^2$$

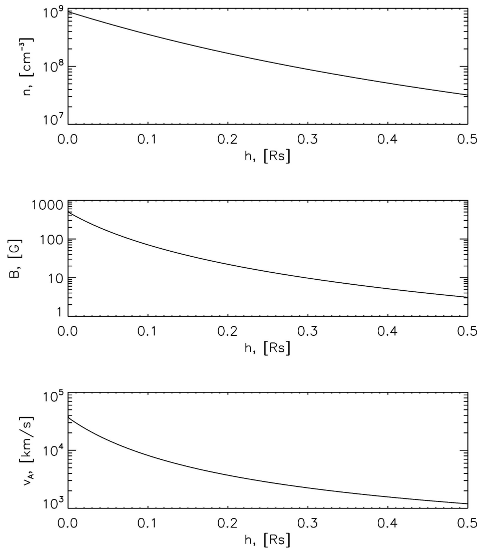
Magnetic field and plasma concentration profiles

$$n(h) = 4.2\times10^4 \times 10^{\frac{4.32R_s}{h}}\ cm^{-3}$$ (Newkirk, 1961)

$$B(h) = B_s\times\left(1+\frac{H}{H_s}\right)^{-3} + B_f\times\left(1+\frac{H}{H_f}\right)^{-3} + B_w\times\left(1+\frac{H}{H_w}\right)^{-3} G$$

$H_s = 0.5Mm, H_f = 75Mm, H_w = 696Mm$ (Gary 2001)

$B_s = 50G, B_f = 500G, B_w = 1G$



Some examples of e- acceleration profiles: dependence on $E_{\|}, \alpha_0$

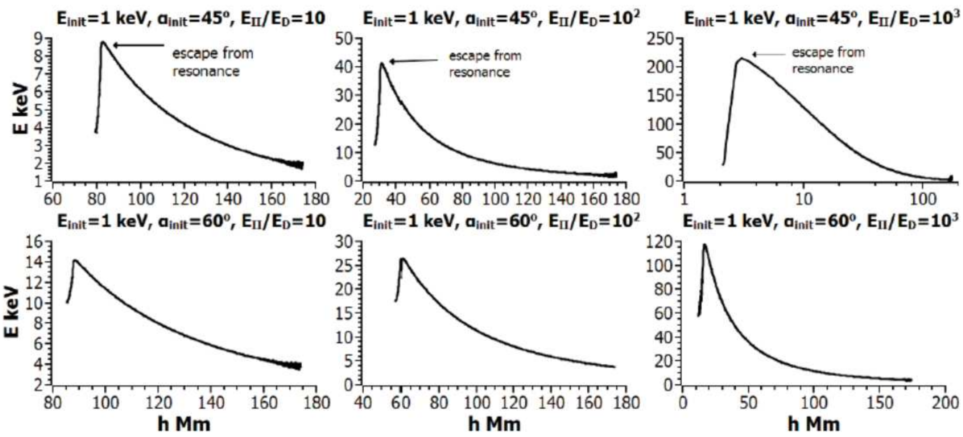


Fig. 2. Six trajectories of electrons accelerated by KAW: three values of wave amplitude and two values of the electron initial pitch angle are considered.

Dependence on friction term

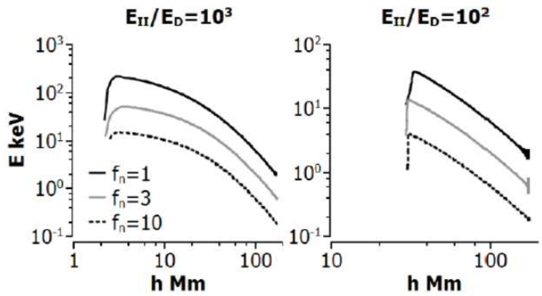


Fig. 3. Three profiles of the energy of trapped electrons for three values of f_n factor.

Transformation of energy distributions

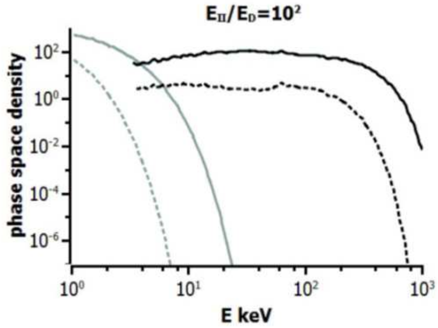


Fig. 4. Two examples of evolution of electron spectra owing to electron acceleration by KAWs (the solid curve corresponds to the initial temperature, which is equal to 1 keV, and dashed curve is for 300 eV). Grey colour shows the initial spectra.

Maximal and average energy gained by e-

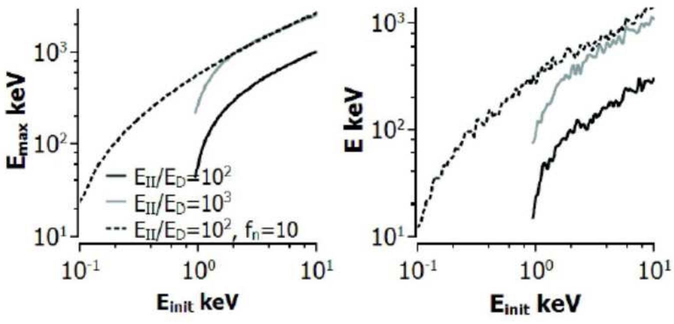


Fig. 6. *Left panel*: maximum energy gained by the majority of trapped particles is shown as a function of the initial energy. *Right panel*: average energy gained by the majority of trapped particles is shown as a function of the initial energy. Data are shown for two wave amplitudes.

Conclusions

- KAWs of reasonable amplitudes can trap and accelerate e- to ~10^2-10^3 keV in converging flare flux tubes
- Acceleration is coupled with e- transport
- Acceleration is quite slow (t~1-10 s)
- It is expected that accelerated e- are distributed mainly perpendicular to magnetic field
- More detailed modeling (taking into account more realistic n(h) and B(h), pitch angle scattering of e-, and wave transport effects) is necessary