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# ALFVEN WAVES IN SPACE PLASMAS: DISPERSIVE AND KINETIC EFFECTS

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New linear and nonlinear properties of Alfven waves induced by finite-ion-Larmor radius effects in space plasmas are discussed.

## 1. INTRODUCTION

An Alfven wave with a large transversal wave-vector component, $k_x \gg k_z$ ($k_\perp \perp B_0$, $B_0$ is the ambient magnetic field), when the perpendicular wavelength become comparable to the ion gyroradius ($\rho_i = V_{Ti}/\Omega_i$), is known as a kinetic Alfven wave (KAW) [10]. The linear dispersion relation for KAWs may be written as

$$\omega_k = |k_z| V_A K_k .$$

The dispersion function $K_k = K_k(\mu)$ has the following asymptotics:

$$K_k \approx 1 + \frac{1}{2}\left(\frac{3}{4} + \frac{T_e}{T_i}\right)\mu^2 \quad \text{for}\, \mu^2 \ll 1,$$

$$K \approx \left(1 + \frac{T_e}{T_i}\right)^{1/2} \mu \quad \text{for}\, \mu^2 \gg 1,$$

where $\mu = k_\perp \rho_i$.

KAWs have become known mainly because of the extensive investigations for their kinetic properties, which are important for processes of plasma heating and particles acceleration (see e.g. Hasegawa 1993 and references therein). It has been shown explicitly that finite-ion-gyroradius and electron-inertia effects produce $E_z$ in Alfven waves, which brings about collisionless wave-particle resonant interaction, resulting in enhanced plasma heating and anomalous transport in the presence of kinetic Alfven waves.

Linear and nonlinear properties of KAWs play an important role in the dynamics of space plasmas. Examples are plasma heating [3, 30] and current drive [5] in the coronal loops of the solar atmosphere, instability of the interstellar plasma [25], particles acceleration in the galactic radio jets [2], impulsive plasma energization in solar flares [28, 29], plasma instability and wave turbulence in the Earth magnetosphere [35, 11], anomalous magnetic diffusion in coronal current layers [27], and many others. In fusion devices, the efficiency of the energy exchange between waves and plasma particles caused by kinetic properties of KAWs has been proved recently both by the theory and by experiment (see e.g. [15] and references therein).

In the present paper we concentrate on the new aspects of wave dynamics in space plasmas that are possible due to ion gyroradius effects in KAWs.

## 2. NONLINEAR INTERACTION AMONG KAWS

A dynamic equation governing the weak interaction between KAWs in a low (plasma has been derived using a plasma kinetic model [31, 32]). This allowed us to keep kinetic and dispersive finite ion Larmor radius corrections in the nonlinear dispersion relation for KAWs. The general expression for the coupling coefficient of the three-wave resonant interaction among KAWs with arbitrary values of the kinetic variable $\mu$, has been calculated, and the growth rate and threshold amplitude of the KAW decay instability in a Maxwellian plasma have been obtained. In the limit $k_\perp \rho_i \ll 1$ we found the growth rate scaling prop prop $k_\perp^2$, more favourable for three-wave resonant decay than the scaling previously elaborated, $\propto k_\perp^3$. Note that only parallel propagation of interacting KAWs has been implicitly implied previously [6, 36, 39]. The first study of parametric KAW instability in the domain $k_\perp > \rho_i^{-1}$ is presented, where the same growth rate behaviour, $\propto k_\perp^2$ is found. These results show a growing efficiency of the three-wave interaction among Alfven waves with growing $k_\perp$.

Inverse and direct energy cascades, and Kolmogorov type spectra $W_k \propto k_z^{-1/2}\ k_\perp^{-4}$ and $W_k \propto k_z^{-1/2} k_\perp^{-3.5}$, may be formed in the $k_\perp < \rho_i^{-1}$ and $k_\perp > \rho_i^{-1}$ domains respectively by the interaction including parallel-propagating KAWs. The remarkable property of this interaction is spectral energy escaping out from the region $k_\perp \propto \rho_i^{-1}$. If the interaction including counter-streaming KAWs dominates, the turbulent energy always cascades into lower wavenumbers, forming $W_k \propto k_z^{-1/2} k_\perp^{-3.5}$ and $W_k \propto k_z^{-1/2} k_\perp^{-2}$ spectra in the limits $k_\perp > \rho_i^{-1}$ and $k_\perp < \rho_i^{-1}$. In contrast, entropy tends to concentrate at wavenumbers $k_\perp \propto \rho_i^{-1}$, resulting in $W_k \propto k_z^{-1/2} k_\perp^{-5}$ and $W_k \propto k_z^{-1/2} k_\perp^{-3}$ spectra.

Of critical significance for the energy and entrophy cascades and the resulting turbulent spectra is the type of three-wave interaction, as well as position of the source in $k$-space with respect to $k_\perp = \rho_i^{-1}$.

## 3. QUASISTEADY HEATING OF THE SOLAR CORONA: FLR EFFECTS IN ALFVEN WAVES

The physical mechanisms responsible for the heating of the solar corona still *lack* unambiguous identification. Resonant absorption and phase mixing (see [7] and references therein) are two popular theories of Alfven wave heating which involve spectral energy transfer towards small length-scales in the plane $\perp$ $\mathbf{B}_0$. Both are due to the transversal plasma inhomogeneity, typical for the corona. The phase mixing of Alfven wave which leads to enhanced wave dissipation and consequent plasma heating, has been first proposed as a coronal heating mechanism by [12]. Since then, phase mixing has been studied in linear approximation both for closed and open magnetic configurations (see for recent papers [13] and [22]). There are also a few papers which concentrate on nonlinear effects in phase mixing [12], and resonant absorption [21]. But all these investigations have been carried out in the one-fluid MHD approximation, missing important properties of Alfven waves induced by FLR effects.

A significant input of energy into a plasma, as observed in the solar corona, can only be achieved if the launched waves have sufficiently large amplitudes. E. g., AWs can balance the energy loss from the loop structures of active regions and from coronal holes, if the wave magnetic field amounts to 1—5 % of background magnetic field $B_0$. The energy flux $F \sim 10^8$ erg cm$^{-2}$s$^{-1}$ is required to heat active region coronal loops of $L \sim 5 \cdot 10^9$ cm length, where $T_e \approx T_i \approx 5 \cdot 10^6$ K [16]. Supposing that this energy flux is supplied by Alfven waves, and taking typical for coronal loops $B_0$ = 100 G and $V_A = 10^8$ cm/s, we get the wave amplitude $B_k/B_0 = 3.5 \cdot 10^{-2}$ and corresponding (non-thermal) plasma velocity $V_{pl} = 35 \cdot 10^5$ cm/s due to motion of plasma in the waves. It is interesting to note that the observed non-thermal broadening of spectral lines yields the same rms velocities [23]

$$V_{pl} = (25...45) \cdot 10^5 \text{ cm/s}.$$

The nonlinear effects become important for the waves of such amplitudes, and the ability of the waves to participate in the different kinds of nonlinear interaction have to be thoroughly examined.

In the coronal plasma with transversal ($\perp \mathbf{B}_0$) inhomogeneity of Alfven speed (scale $L_A \sim 10^6$ cm, see. [38]), the growth of transversal wavenumber $k_\perp \propto (\omega_k/L_A)t$ brings about a kinetic effect of Landau damping for $\omega_k \geq 1\ \text{s}^{-1}$, or enhanced collisional dissipation for $\omega_k < 1\ \text{s}^{-1}$ [30]. Then the condition of effective wave dissipation over loop length $L$ ($\geq 10^9$ cm), $\gamma_k^L \geq V_A/L$, is $\mu^2\omega_k \geq V_{Te}/L$. Such a waves becomes also nonlinearly unstable if $\gamma_k^{NL} \geq V_A/L$. We found that the condition for decay instability of KAWs, heating coronal loops, is satisfied in a wide frequency range $\omega_k < \omega_{cr}$, where

$$\omega_{cr} = 0.3(V_{Te}/\rho_i)(B_k/B_0).$$

Under typical coronal conditions $\omega_{cr} \approx 0.5\cdot 10^6\ \text{s}^{-1}$, and condition $\omega_k < \omega_{cr}$ covers the whole MHD spectrum. Therefore, the nonlinear spreading and turbulent character of Alfven wave spectra should be taken into account investigating plasma heating and current drive in coronal loops.

## 4. IMPULSIVE PLASMA HEATING IN SOLAR FLARES

One of the most intriguing discoveries of Yohkoh mission is impulsive heating of collisionless coronal plasma in solar flares. The heating mechanism incorporating intermediate turbulence of KAWs has been proposed by [28, 29]. The kinetic theory of the excitation of kinetic Alfven waves (KAWs) in the just-reconnected magnetic flux tubes above soft X-ray loops is further developed in the papers [33, 34]. Using linear and quasilinear theory, it is shown that the proton-beam-driven instability of KAWs provides an effective mechanism for the PB-kinetic energy conversion into the energy of wave turbulence in the coronal part of just-reconnected flaring loops. In the wide range of PB parameters, the distance of quasilinear relaxation ( $\sim 10^6$ cm) is by several orders less than the typical length of a flaring loop ($10^9$—$10^{10}$ cm), and KAW/beam energy flux partition $\sim 1$ after relaxation. The fast plasma heating by these KAWs provides the temperature and flux of escaping electrons enough to produce observed microwave emission from the loop leg and hard X-ray bremsstrahlung from the footpoints and loop top.

Let us estimate the saturation level of the KAW turbulence excited by proton beams in flaring loops [31]. Taking typical value for (linear) instability growth rate $\gamma_k^L/\omega_i = 500$ in flaring loop with magnetic field $B_0 = 100$ G, Alfven velocity $V_A = 10^8$ cm/s, and ion temperature $T_i = 5\cdot 10^6$ K, we get the saturation level of wave amplitude in the source ($k_\perp\rho_i \leq 1$) region: $B_k^{(s)}/B_0 = 500$. The calculated from saturation level (non-thermal) velocity of wave motions, $V_{pl} = 50\cdot 10^5$ cm/s, is 3 times smaller than $V_{pl} = 150$ km/s, observed at flare onset [1]. This discrepancy between the calculated and observed nonthermal velocity we consider as a significant indication that the turbulent cascade and concentration of KAW energy at lower wavenumbers occur in flaring loops. With spectrum $\propto (k_\perp)^{-2}$ we calculate the lower boundary of the inertial range, $k_{\perp\min} = k_{s\perp}/3 \leq 0.7\cdot 10^{-2}\ \text{cm}^{-1}$, where the energy of KAW turbulence is concentrated.

## 5. SPECTRAL DYNAMICS AND TURBULENCE OF KAWS IN THE AURORAL MAGNETOSPHERE

Kinetic Alfven waves of a large amplitude $B_k/B_0 = 0.01...0.001$, propagating along the geomagnetic field lines in the auroral zones of the Earth's magnetosphere, have been observed by satellites at altitudes $h = (0.1...2)\cdot 10^4$ km on a background of large-scale field-aligned currents [9, 4]. Current-driven instability of KAWs can develop at altitudes $h = (2...4)\cdot 10^4$ km and excite the observed wave flux [35]. For the magnetospheric conditions at $h = 4\cdot 10^9$ cm, where $\Omega_i \sim 10\ \text{s}^{-1}$, $V_A \sim 10^8$ cm/s, $\rho_i \sim 2\cdot 10^6$ cm, and $T_i = T_e$, the exciting waves have wavenumbers $k_\perp\rho_i \approx 0.5$, $k_\parallel\rho_i \approx 0.05$, and amplitudes $B_k/B_0 \approx 2.5\cdot 10^{-3}$.

Using the above parameters, we found a growth rate of the parametric decay instability of these KAWs, propagating towards the Earth, $\gamma_k^{NL} \approx 0.025$ s$^{-1}$ [31]. Since the decay growth time, $\tau_{NL} \approx 1/\gamma_k^{NL} \approx$ $\approx 40$ s, is much less than Alfven wave propagation time, $\tau_A = \Delta h/V_A = 50...100$ s, we conclude that KAWs excited at the distant magnetosphere undergo parametric decay instability, and observed wave spectra should be modified by three-wave couplings among KAWs. The lowest frequency (of the anti-parallel-propagating KAW) is well above the decay growth rate, $\omega_2 \approx 0.5\mu^2\omega \approx 0.5$ s $\gg \gamma_k^{NL} \approx 0.025$ s$^{-1}$, and hence the weak-interaction approach is justified.

Let us consider spectral energy distributions in KAW turbulence [32]. Let some source in a distant magnetosphere pumps the energy into modes $k_\perp \propto k_{s\perp}$; this may be current-driven KAW instability, excited at altitudes $h = (2...4)\cdot 10^4$ km [35]. The turbulent KAW spectrum formed by three-wave $s_1 =$ $= -s_2 = 1$ interaction in the domain $k_{s\perp} < \rho_i^{-1}$ varies as $\propto (k_\perp)^{-2}$ in the vicinity of the source; the spectrum $\propto (k_\perp)^{-4}$, formed by $s_1 = s_2 = 1$ interaction, can appear at smaller wavenumbers, where $s_1 = -s_2 = 1$ interaction may be forbidden by finite correlation length of waves [32]. Then the tendency for turbulent KAW spectra is to become steeper, up to $\propto (k_\perp)^{-4}$, as a result of dominant role of $s_1 = s_2 = 1$ interaction at low wavenumbers. Also, since the growth rate of nonlinear interaction attains its maximum at $k_{2\perp} =$ $= 0.776k_{s\perp}$, the energy transfer is most efficient into modes concentrated around $(k_\perp)^{(1)} \propto 0.776k_{s\perp}$, $(k_\perp)^{(2)} \propto 0.776(k_\perp)^{(1)}$, and so on. As a result, the humps on the above-mentioned spectra appear at $k_\perp$ $\propto (0.776)^n k_{s\perp}$, where $n = 1, 2, 3...$ is the decay (step) number.

All of these features of turbulent KAW spectra, following from our theoretical consideration, have been revealed by spacecraft observations [9, 4].

The general tendency for the KAW turbulence is energy concentration in the spectrum $\propto (k_\perp)^{-4}$ at low wavenumbers. Spectra $\propto (k_\perp)^{-4}$ have been often observed in the space plasmas with intense field-aligned currents [9, 18]. These observations supply strong evidence for the nonlinear spreading of spectra generated by the current-driven KAW instability at $k_{s\perp} \leq \rho_i^{-1}$ [35].

## 6. GENERATION OF KINETIC ALFVEN WAVES BY UPPER-HYBRID PUMP WAVES

It has been shown [19], that lower-hybrid waves can be generated as a result of UHW decay. Three-wave interaction including UHW has been considered in [17], [40], where pump wave was an ordinary electromagnetic wave. Parametric excitation of MHD (non-dispersive) Alfven (and /or magnetosonic) and electron-cyclotron waves has been considered in [26].

Taking into account perpendicular dispersion of KAW, caused by effects of finite ion Larmor radius and electron inertia, we examined a new channel for UHW decay, in which a pump UHW decays into another UHW and an ultra low-frequency wave, KAW: UHW → KAW + UHW [41].

We applied the results of our calculations to investigate a new way of KAW generation in the magnetosphere, where UHW is the most stable wave mode in the high-frequency region $\omega \gg \omega_{Be}$ ($\omega_{Be}$ — is an electron-cyclotron frequency): a high level of UHWs is continuously observed at the heights over 1000 km at all latitudes from the equator to the auroral zone [20]. Numerical calculations give sufficiently short times of the instability development:

$$\tau \cong \gamma_{NL}^{-1} \cong (0.1 \div 1) \text{ s}.$$

Taking into account that near the equator UHW emission enhancement is induced by the non-equilibrium electron velocity distribution in the transverse direction, KAW turbulence with $k_\perp\lambda_{De} \leq$ $\leq 0.35$ will be generated as a result of the UHW decay. In the auroral regions where UHW generation is caused by field-aligned electron beams [37], parametric decay instability of such UHWs generates turbulence of KAW with $k_{\perp}\lambda_{\mathrm{De}} \leq 0.1$. That is why in the satellite system of co-ordinates, the typical frequencies of KAW turbulence near geomagnetic equator and in the auroral regions can be different. Kinetic Alfven waves generated by parametric instability will be dissipated by electron Landau resonance with consequent heating of the electron component, and, owing to electron-ion collisions, with heating of the ion component as well.

## 7. PARAMETRIC EXCITATION OF ELECTROMAGNETIC WAVES IN THE MAGNETISED PLASMA

The detection of the electromagnetic waves (EMWs) with a frequency slightly higher than the local electron Langmuir frequency in the Earth's magnetosphere has been reported by Gurnett and Shaw (1973). The satellite measurements [20] show that upper-hybrid waves (UHWs) are the most widespread electrostatic waves in the magnetosphere.

We considered the possible mechanism of the excitation of radio emission by UHWs via parametric decay UHW = EMW + KAW, where EMW can be ordinary (O-mode) or extra-ordinary (X-mode) electromagnetic wave [42]. First we estimate the instability growth rate and characteristic time for the case of UH pump wave decay into the ordinary electromagnetic wave and KAW. The instability growth rate attains its maximum value $\gamma_1 \approx 0.3\ \mathrm{s}^{-1}$ at $k\perp/k_{0\perp} \approx -10$, where $k_{0\perp}$ is the perpendicular wave number of the pump wave. The minus sign here indicates that the exciting KAW propagate in the direction opposite to that of the pump wave. The characteristic time of instability development is $\tau_1 \approx 3$ s. The generation of KAWs and X-mode radiation in the perpendicular direction has been considered by [24], and the increment was found to be $\propto \Omega_e$. Since with the perpendicular O-mode the increment $\propto \omega_{pe}$, generation of the perpendicular O-mode is $\omega_{pe}/\Omega_e$ times more efficient than perpendicular X-mode. The threshold of decay instability is $E_{cr} \propto 1$ mV/m.

The characteristic time of the instability development in the case of UH pump wave decay into the left-hand polarised electromagnetic wave and KAW is $\tau_2 \sim 0.3$ s. Thus, the decay including left-hand polarised electromagnetic wave is much faster than the decay including ordinary and X-mode electromagnetic waves.

This mechanism of electromagnetic emission can also work in the solar corona during radio bursts. Type III radio bursts are most interesting from the theoretical point of view. They are observed in the wide frequency range varying from tenth of kHz (satellite observations) up to hundreds of MHz while an emission source moves from the Sun to the Earth. Excited by high-energy particle beams, UHW can generate KAWs and electromagnetic emission with frequencies close to the UH frequency.

## 8. CONCLUSIONS

The results discussed in the present paper show that due to the FLR effects, Alfven waves can interact with proton beams, among themselves, and with other wave modes more effectively than it have been known previously.

The main new findings are:

1. The strongest nonlinear coupling among Alfven waves includes counter-propagating waves. It results in the spectral energy transfer into lower wavenumber domain in flares. The turbulent state should develop before KAWs flux is dissipated in the solar corona.
2. Kinetic Alfven turbulence, excited by the reconnection outflow, can result in the impulsive plasma energization in flaring loops.
3. Parametric decay of UHWs, induced by their coupling with KAWs, introduces spectral redistribution of the wave energy, and can excite EMWs in the vicinity of upper-hybrid frequency.

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