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Stability of the strahl electron distribution function and its dynamics

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Abstract. It is shown that core-strahl electron system in the solar wind plasma is unstable with respect to excitation of the lower hybrid waves at anomalous Doppler resonance due to anisotropy of the strahl electron velocity distribution. Dynamics of the strahl electron distribution due to interaction with excited waves is studied.

1 Introduction

Observations have revealed that the solar wind electron distribution can be considered to consist of a dense core component and more tenuous suprathermal population. The thermal core ($T \sim 10\,\mathrm{eV}$) contains $\sim 95\%$ of the total electron density while the supra-thermal population contains $\sim 5\%$ of the electron density. The suprathermal population consists of two energetic components: (i) a halo that can be approximated by Maxwellian distribution with hotter temperature in comparison with a core distribution and (ii) an anisotropic component, so called strahl – anti-sunward moving electrons with narrow pitch angle distribution (Rosenbauer et al., 1977; Feldman et al., 1978; Lin et al., 1981; Pillip et al., 1987; Ogilvie et al., 2000; Gosling et al., 2001, 2003, 2004a, b; Steinberg et al., 2005; Pagel et al., 2005, 2007). It was revealed that the relative number of halo electrons is increasing while the relative number of strahl electrons is decreasing with distance from the sun thus providing evidence that the heliospheric electron halo population consist partly of electrons that have been scattered out of the strahl (Maksimovich et al., 2005; Stverak et al., 2009).

The physical mechanisms of the strahl origin were investigated in theoretical studies of the evolution of the electron velocity distribution function in high speed solar wind streams from the collision-dominated corona and into the collisionless interplanetary space. It was shown that the strahl component can develop in the high corona as a result of two possible mechanisms. The first one is so called velocity filtration, due to the energy dependence of the coulomb cross section when only electrons with large energy can escape to interplanetary space (Scudder and Olbert, 1979; Scudder, 1992, 1994). In second mechanism the electron distribution function is mainly determined by the electric ambipolar field and the expanding geometry and consists of a population with almost isotropic core which is bound in the electrostatic potential and a high-energy tail of the electron distribution that can stream freely outward in the corona (Lie-Svendsen et al., 1997).

Numerous observations have found that the strahl pitch angle widths are larger than the one that can be found by considering the focusing effect due to conservation of the first adiabatic invariant in the divergent solar wind. In the absence of Coulomb collisions (Ogilvie et al., 2000), that could be explained only by invoking wave-particle interaction processes, specifically, cyclotron resonant interaction. The main question that remained was what type of waves is responsible for pitch angle scattering of the strahl electrons and what are the sources of these waves.

Studies, that were recently performed by using quasi-linear approach (Vocks and Mann, 2003; Vocks et al., 2005) and by particle-in-cell numerical simulations (Saito and Gary, 2007a, b), assumed that a likely scattering process for suprathermal electrons is their resonant interaction with right-hand polarized whistlers on normal Doppler resonance

$$k_{||} v_{||} = \omega_k - \omega_{\mathrm{ce}}, \quad \omega_{\mathrm{ce}} = \frac{|e| B_0}{m_{\mathrm{e}} c} \tag{1}$$

where $k_{||}$ and $v_{||}$ are the wave vector and electron velocity components parallel to the magnetic field, ω_k and ω_{ce} are the wave frequency and electron cyclotron frequency.

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It was assumed these whistlers are provided by the interplanetary turbulence. A study of additional potential sources of enhanced whistler populations (Saito and Gary, 2007a, b) found that whistlers can be generated through electromagnetic instabilities like the whistler cyclotron instability driven by the electron core anisotropy $T_\perp > T_{||}$ (Sagdeev and Shafranov, 1961), or whistler heat flux instability (Gary et al., 1975). However, it was shown that these electromagnetic instabilities, do not strongly scatter suprathermal electrons at relatively high energies (Scime et al., 2001; Saito and Gary, 2007a, b).

The purpose of this paper is to analyze another physical mechanism of pitch-angle diffusion of the strahl electrons that appears due to anisotropy of their distribution function. We will answer the questions: What is the role of the anisotropy of the strahl electron distribution function? Is this non-equilibrium distribution unstable and, if yes, what electron pitch angle scattering will be developed by excited waves?

2 The "fan" instability of the strahl distribution

As was discussed in the introduction, a tail of suprathermal electrons – a strahl is formed on the electron distribution function in collision-dominated corona and streams outward. We will study a new effective mechanism of the pitch angle scattering of the strahl electrons due to their resonant interaction with lower hybrid (LH) waves at anomalous Doppler resonance. This mechanism emerges as a result of so-called "fan" instability (Kadomtsev and Pogutse, 1968; Shapiro and Shevchenko, 1968) – cyclotron instability in the case when there is anisotropy in the particle velocity distribution with free energy in the direction parallel to the magnetic field. It can be understood by considering the quantum treatment of the wave emission by a charged particle. The charged particle is an oscillator with energy levels $n\hbar\omega_\mathrm{c}(n = 0, \pm 1, \pm 2, \ldots)$ moving along the magnetic field. Both the energy of longitudinal motion and the oscillator energy may change upon emission of a wave quantum. The resonance condition

$$\omega_k = k_{||} v_{||} + n\omega_\mathrm{c} \tag{2}$$

follows from conservation of energy and momentum in the process of the wave quantum emission

$$\Delta\varepsilon = \hbar\omega_k = \Delta p_{||} v_{||} + n\hbar\omega_\mathrm{c}, \quad \Delta p_{||} = \hbar k_{||}. \tag{3}$$

For $n = 0$ (Cherenkov resonance) the oscillator energy does not change. For $n = 1, 2\ldots$ (Normal Doppler resonance) emission of the quantum is accompanied by transition of the oscillator to a lower energy level. For $n = -1, -2\ldots$ (Anomalous Doppler resonance) the oscillator energy increases and emission occurs at the expense of the parallel motion.

We would like to stress that this is just what takes place in the problem under investigation – the energy source for this instability is parallel energy of the anisotropic strahl electron distribution function. The electron distribution function with high-energy tail is unstable with respect to excitation of LH waves on anomalous Doppler resonance (Shapiro and Shevchenko, 1968, 1988; Omel'chenko et al., 1992):

$$k_{||} v_{||} = \omega_k + \omega_\mathrm{ce} \tag{4}$$

Here ω_k is the frequency of the lower hybrid waves.

The lower hybrid waves are dominantly electrostatic oscillations of plasma in magnetic field propagating obliquely to the magnetic field with frequencies in the interval $\omega_\mathrm{cp} \ll \omega \ll \omega_\mathrm{ce}$ (ω_ce, ω_cp are electron and proton cyclotron frequencies). The dispersion relation for these waves has the form

$$\omega_k^2 = \omega_\mathrm{LH}^2 \left(1 + \frac{m_\mathrm{p}}{m_\mathrm{e}} \frac{k_{||}^2}{k^2}\right) \tag{5}$$

Here $\omega_\mathrm{LH} = \omega_\mathrm{pi} / \left(1 + \omega_\mathrm{pe}^2 / \omega_\mathrm{ce}^2\right)^{1/2}$ is the frequency of the lower-hybrid resonance, ω_pe, ω_ce are the electron plasma and cyclotron frequencies, $k_{||}$ and $k_\perp$ are the wave vector components along and transverse to the magnetic field.

As a result of the "fan" instability, the pitch angle diffusion of electrons takes place and their perpendicular velocity grows. Thus this mechanism can be an effective plausible candidate to explain the broadening the electron pitch angle distributions in strahls and in solar electron bursts. It is the natural mechanism, since the source of the oscillations is the instability of the anisotropic distribution function of the strahl electrons that leads to decrease of the anisotropy by pitch angle scattering of electrons.

As we discussed above, the energy source for the fan instability is an anisotropy of the energetic electrons distribution and a positive slope over parallel velocity distribution is not needed for its development. Instead, electrons having either a plateau or even a monotonically decreasing distribution function over the parallel velocity in the form of high-energy tail can generate waves through the fan instability (Shapiro and Shevchenko, 1988). In this sense the question of stability of strahl electron distribution in the solar wind is similar to the problem of stability of electron beam in magnetized plasma (Shapiro and Shevchenko, 1968) as well as stability of precipitating auroral electrons in magnetospheric plasma (Omelchenko et al., 1994).

3 Equations and solution

The instability leads to the LH wave generation that causes the electron diffusion over pitch angle and formation of the shell distribution function ("fan" distribution on the ($v_{||}$, $v_\perp$) plane). The diffusion lines are circles in velocity space with center at the point $(\omega / k_{||}, 0)$:

$$w = v_\perp^2 + \left(v_{||} - \omega / k_{||}\right)^2 = \mathrm{const} \tag{6}$$

To study the nonlinear evolution of the strahl electrons distribution function we will use a self-consistent quasi-linear approach. We will study the problem in local approximation where we can neglect the mirror force. We assume that $m_p k_{||}^2 \big/ m_e k^2 \gg 1$ and $\omega_{pe} \gg \omega_{ce}$. Then it follows from (5) that the frequency of generated waves in this case is $\omega = \omega_{ce} k_{||} \big/ k$. The system of quasi-linear equations that describe the evolution of the electron distribution function and the spectrum of lower hybrid waves excited by strahl electrons at anomalous Doppler resonance has the form (Shapiro and Shevchenko, 1968):

$$\frac{\partial f_0}{\partial t} = \frac{1}{2\pi} \frac{e^2}{m_e^2} \int k_\perp dk_\perp \hat{L} \left\{ \frac{k_{||}^2}{k^2} \frac{J_1^2 \left(k_\perp v_\perp \big/ \omega_{ce} \right)}{\left| v_{||} - v_{g||} \right|} |E_k|^2 \hat{L} f_0 \right\} \Bigg|_{v_{||} = (\omega_{ce} + \omega_k) \big/ k_{||}} \qquad (7)$$

$$\frac{\partial |E_k|^2}{\partial t} = \frac{\pi}{n_0} \frac{k_\perp^2 k_{||}}{k^5} \omega_{ce}^3 \int d\boldsymbol{v}_\perp J_1^2 (k_\perp v_\perp / \omega_{ce}) \hat{L} f_0 \Big|_{v_{||} = (\omega_{ce} + \omega_k) / k_{||}} |E_k|^2 \qquad (8)$$

In these equations $\hat{L}\psi = \frac{\partial \psi}{\partial v_{||}} + \frac{\omega_k - k_{||} v_{||}}{v_\perp k_{||}} \frac{\partial \psi}{\partial v_\perp}$, f_0 is the distribution function of the electrons averaged over time that is large in comparison with the characteristic wave period (background distribution function), E_k, ω_k are the electric field and frequency of the lower hybrid waves excited by the instability, $v_{g||} = \partial \omega \big/ \partial k_{||}$ is the wave group velocity. $J_1(k_\perp v_\perp \big/ \omega_{ce})$ is Bessel function, subscripts $||$ and $\perp$ denote components parallel and perpendicular to the background magnetic field $\boldsymbol{B}_0$.

The initial distribution of the electrons consists of isotropic distribution of core electrons and anisotropic distribution of more tenuous strahl electrons with density $n_s \big/ n_c = 0.05$ with maxwellian distribution over perpendicular velocities with perpendicular temperature $T_{\perp,s} \big/ T_c = 0.5$ and with decreasing distribution over parallel velocity

$$f_s(t=0) = \frac{n_s}{T_\perp \big/ m_e} \frac{1}{\left(1 \big/ v_{min} - 1 \big/ v_{max} \right)} \frac{1}{v_z^2} e^{-m_e v_\perp^2 / 2T_\perp}$$

Here n, T and v_T are electron density, temperature and thermal velocity, subscripts c and s denote the core and strahl electrons. We solved Eqs. (7)–(8) for two sets of parameters

$$\mathrm{S1}: T_{\perp,s} \big/ T_c = 0.5, v_{min} = 2 v_{T,c} \quad \text{and} \quad v_{max} = 20 v_{T,c}$$

as well as

$$\mathrm{S2}: T_{\perp,s} \big/ T_c = 1, v_{min} = v_{T,c} \quad \text{and} \quad v_{max} = 20 v_{T,c}$$

Results of integration of Eqs. (7)–(8) with a very small level of initial wave amplitudes are shown in Figs. 1 and 2 (set S1) and (3)–(4) (S2). In the Figs. 1 and 3 the dynamics of the LH wave power density is shown. Reduction of the wave intensity at small wave numbers is due to decrease of the density of strahl electrons. A strong decline of the power spectrum at $k \approx \omega_{ce} \big/ v_{T,c}$ is a consequence of the damping on the core electrons. The temporal dynamics of the electron distribution function is shown in the Figs. 2 and 4. As one can see, there is no positive slope at the initial electron distribution function over parallel velocity, however the strahl electrons have an anisotropic distribution that is unstable with respect to excitation of lower hybrid waves that leads to effective pitch-angle diffusion of the strahl electrons.

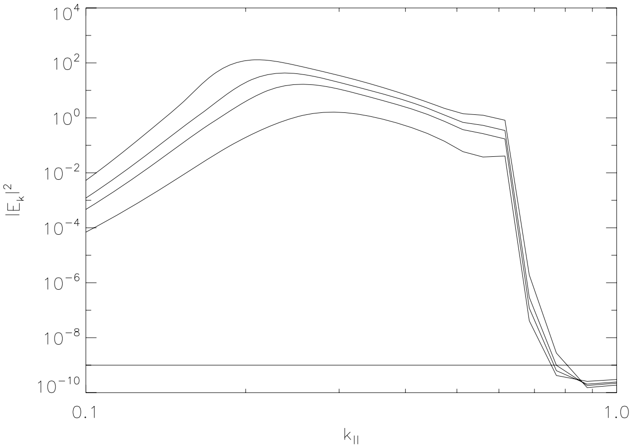

Fig. 1. Spectral density of the lower hybrid waves as function of the parallel wave number for S1 set of parameters at times $t = (0; 7.7 \times 10^2; 9 \times 10^2; 9.7 \times 10^2; 1.1 \times 10^3) \frac{1}{\omega_{ce}}$. The wave number is measured in $\omega_{ce} \big/ v_{T,c}$.

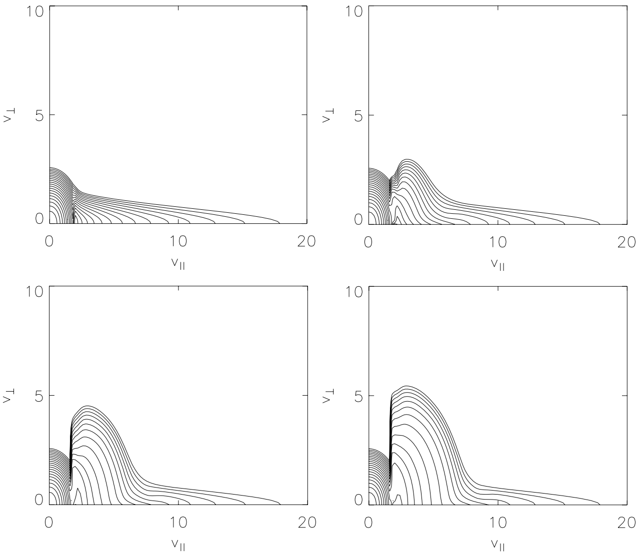

Fig. 2. Electron distribution function for S1 set of parameters at times $t = (0; 7.7 \times 10^2; 9.7 \times 10^2; 1.1 \times 10^3) \frac{1}{\omega_{ce}}$. Velocities are measured in $v_{T,c}$.

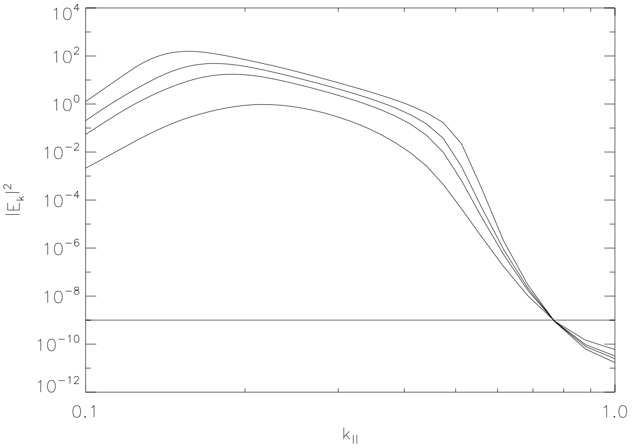

Fig. 3. Spectral density of the lower hybrid waves as function of the parallel wave number at times $t = (0; 2.2\times10^3; 2.7\times10^3; 2.9\times10^3; 3.2\times10^3)\frac{1}{\omega_{\rm ce}}$ for S2 set of parameters.

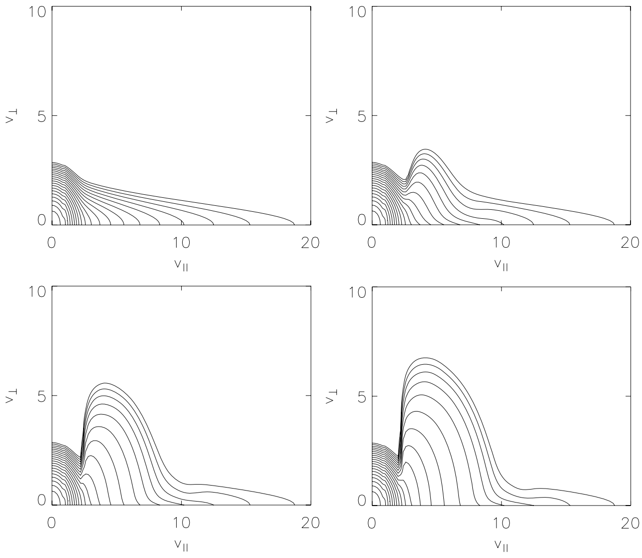

Fig. 4. Electron distribution function at times $t = (0; 2.2\times10^3; 2.9\times10^3; 3.2\times10^3)\frac{1}{\omega_{\rm ce}}$ for S2 set of parameters. Velocities are measured in $v_{T,{\rm c}}$.

4 Conclusions

As was discussed above, previous studies of the velocity diffusion mechanisms of the strahl electrons were based on their interaction with whistlers provided by interplanetary turbulence. The goal of this paper was to consider another potential mechanism of pitch angle diffusion of the strahl electrons. We studied here a natural mechanism where waves needed for the electron pitch angle diffusion are excited by the instability caused by anisotropy of the strahl electron velocity distribution. The strahl electrons have more energy in parallel motion because of their narrow pitch angle distribution along the magnetic field. This distribution is unstable with respect to excitation of waves at anomalous Doppler resonance. We studied in local approximation the lower hybrid waves (electrostatic whistlers) excitation and pitch angle diffusion of strahl electrons due to this instability.

We would like to note that we limited ourselves in this study by considering only resonant electron-particle interaction in quasi-linear approximation. The results of the pitch angle diffusion shown in the Fig. 2 indicate that halo can be formed as a result of diffusion of strahl electrons. However the dynamics of the halo creation cannot be described in this approximation. The numerical simulations will be used to study the halo formation from the scattered strahl electrons and results will be compared with a model by Gosling et al. (2001) that describes the formation of the halo by assuming that there is a source of an isotropic population of sunward directed electrons. We defer discussion of the halo formation to a subsequent paper.

Another unsolved problem is how mirror force will influence the width of the pitch angle distribution of the strahl electrons and how densities of halo and strahl electrons change as function of the distance from the sun. Analysis of observed radial evolution of a halo and a strahl (Maksimovich et al., 2005; Strevak et al., 2009) has shown that the halo and the strahl relative densities vary in an opposite way. With increasing distance from the sun, the density of the strahl electrons decreases while the number of the halo electrons increases. These results suggest as well that the halo is created by the strahl electrons and that there are some mechanisms in the solar wind that scatter the strahl electrons into the halo (Strevak et al., 2009). One can find from results of solution that characteristic scales at which instability develops is reasonable small. For example at distances on the order of 1 AU where $\omega_{ce} \approx 10^3\,{\rm s}^{-1}$, the characteristic time for the instability development is on the order of 3–4 s that gives a spatial scale of instability about $(5\div6)\times10^3$ km, that is much smaller than a characteristic scales of change of the solar wind parameters. Thus, the discussed above instability almost instantly will create a shell distribution of the strahl electrons at each distance from the sun that is reached by the strahl. Therefore, the quasi-linear terms in equations will become very small. In this case the macroscopic mirror forces will focus the strahl electrons and create the unstable distribution. A scale separation model (Galinsky and Shevchenko, 2000, 2007) should be used to study theoretically the radial evolution of the strahl and halo electrons. We will consider these questions in detail elsewhere.

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