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The Effects of Induced Scattering of Alfvén Waves for the Solar Wind Acceleration

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Abstract. The analysis of energy balance of coronal holes gives that to accelerate the fast solar wind streams the energy flux of the order of $800 \text{ erg/cm}^2 \text{ s}$ is needed. Axford and McKenzie suggested that the energy source, necessary to accelerate fast solar wind, is in the regions of strong magnetic field that define the boundaries of chromospheric supergranules. If the magnetic field is not strictly unipolar in these regions, the necessary energy is released in the processes of impulsive reconnection events. For the plasma parameters appropriate for the coronal base such processes of impulsive reconnection are accompanied by the generation of Alfvén and fast magnetosonic waves with the period of the order of 1 s. On the basis of kinetic equation the model for the evolution of Alfvén waves in solar wind is suggested. The induced scattering of these waves by plasma ions is considered as the dominant mechanism of dissipation of Alfvén waves. The description of the evolution of the wave spectra in the process in the processes of their propagation till the distance of 187 solar radii was found.

1. Introduction

The solar wind which is formed by the gas-dynamic expansion of solar corona into the interplanetary space can be divided into two states: the fast (> 700 km/s) and slow (≈ 400 km/s) streams. The fast solar wind originates in the polar coronal holes, where electron temperature $T \approx 10^6$ K, plasma density $n = 10^8$ cm $^{-3}$ and magnetic field at the coronal base $B_0 \approx 10$ G [1], [15]. Variations of the velocity of this fast solar wind streams are insignificant (700–800 km/s). The slow solar wind is associated with transient openings of closed field regions in the corona. The streams of slow wind are limited by the range $\pm 13^\circ$ near the equator and the fast solar wind streams can be found at the latitude $> \pm 20^\circ$. The transition zone between this regions has the width $\pm 13^\circ - \pm 20^\circ$ on the north and south latitudes in the solar minimum [17]. The radiation balance analysis in the coronal holes [22] shows that to accelerate solar wind it is necessary to dissipate the energy flux of radiationless origin $\approx 8 \cdot 10^5$ erg/cm 2 ·s within the distance of one–two solar radii above the Sun’s surface in order to maintain the observed temperature $1,5 \cdot 10^5$ K of slowly rising expanding gas.

Axford and McKenzie [1] suggested that the energy source, necessary to accelerate the fast solar wind streams, is in the regions of strong magnetic field that define the boundaries of chromospheric supergranules. If the magnetic field is not strictly unipolar in this regions, then the necessary energy is released in the processes of impulsive reconnection of magnetic field lines on the characteristic spatial scale of network activity $l = 100$ km. Such processes of impulsive reconnection should be accompanied by the generation of Alfvén and fast magnetosonic waves. Using the parameters of plasma at the coronal base described above we can find the Alfvén wave velocity $V_A = B/\sqrt{4\pi nm_i} = 2 \cdot 10^8$ cm/s, the ion’s thermal velocity $V_{Ti} = 2 \cdot 10^7$ cm/s, and the characteristic time of magnetic field lines reconnection [16]:

$$\tau_R = \frac{\pi V_A}{4l \ln \text{Re}_m} = \frac{\pi \cdot 2 \cdot 10^8 \text{ cm/s}}{4 \cdot 10^7 \text{ cm} \cdot \ln 3.5 \cdot 10^{11}} \sim 0.6 \text{ s}, \quad (1)$$

where: $\text{Re}_m = 4\pi n e^2 V_A l / m_e \nu_{ei} c^2 = 3.5 \cdot 10^{11}$ is the magnetic Reinold’s number, $\nu_{ei} = 20n / (T^\circ)^{3/2} = 2.3 \text{ s}^{-1}$ is the collision frequency. It is evident that the characteristic period of Alfvén waves is of the order of obtained reconnection time. The total energy flux necessary to accelerate fast solar wind is estimated as $8 \cdot 10^5$ erg/cm 2 ·s [1] and the major part of the energy of generated waves should be dissipated within one-two solar radii above the solar surface.

As the dominant mechanism of dissipation of Alfvén waves generated by the processes of impulsive reconnection of magnetic field lines, we will consider the induced scattering of Alfvén waves by plasma ions [11]. The great part of this model was developed in paper by Galeev and Sadvovskii [7] For the sake of simplicity we limit ourselves by the case of the circularly polarized Alfvén waves propagating along the radial magnetic field $\mathbf{B}_0 = B_0(r)\mathbf{z}$ from the polar coronal holes (the wave vector $\mathbf{k} = (0, 0, k)$, where r is the radial distance from the center of the Sun). For the solar wind we can fix the following ordering of the ion cyclotron ω_{ci} , Alfvén ω_k and ion

Doppler kv_{Ti} frequencies:

$$\omega_{ci} \gg \omega_k \gg kV_{Ti}, \quad (2)$$

where $\omega_{ci} = eB_0(r)/m_i c$, $\omega_k = kV_A$. Under this conditions plasma is magnetized and the resonant condition describing the interaction of Alfvén waves with the different polarization propagating in the opposite directions along the magnetic field lines can be written as:

$$\omega_k + \omega_{k'} - (k + k') v_z = 0, \quad (3)$$

where $\omega_k = kV_A > 0$, $\omega_{k'} = -k'V_A < 0$, $k, k' > 0$ and v_z is the velocity along the magnetic field.

In the next section we will describe the evolution of the Alfvén waves spectrum in the processes of their propagation and show that the wave energy flux necessary to accelerate the fast solar wind can be dissipated at the heights of 1-2 solar radii above the solar surface that is required by the Withbroe [22] analysis.

2. Evolution of Alfvén wave spectrum in the processes of their propagation

Evolution of Alfvén wave amplitudes in the processes of their propagation into the interplanetary space we calculated theoretically assuming that the interplanetary magnetic field $B_0(r)$ and the solar wind velocity u are radial and spherically symmetric, the Alfvén waves are circularly polarized, the wave amplitudes are small $|B_k^\pm(r)|^2 k \ll B_0^2(r)$.

In this approximation we find the equation for the spectral energy density of waves [7] (see also [12], [18]):

$$[u(r) + V_A(r)] \frac{\partial |B_k^+(r)|^2 k}{\partial r} = -\kappa k^2 V_A(r) \frac{|B_k^+(r)|^2 k}{B_0^2(r)} \frac{\partial |B_k^+(r)|^2 k}{\partial k}, \quad (4)$$

Here unlike to previous paper [7] we took bi-Maxwellian distribution for ions and Maxwellian distribution for electrons.

Integrating equation (4) we find the general solution [9] for the spectral energy density:

$$|B_k^+(r)|^2 k = \Phi \left[\kappa I \int_{R_\odot}^r \frac{V_A(r) dr}{u + V_A(r)} + \frac{1}{k(R_\odot)} - \frac{1}{k} \right]. \quad (5)$$

Here: Φ is an arbitrary function; $V_A(r) = V_A(R_\odot)R_\odot/r$; $k(R_\odot)V_A(R_\odot)/2\pi = 1.7$ Hz; $R_\odot = 6.96 \cdot 10^{10}$ cm; $\kappa = |B_k^-(r)|^2/|B_k^+(r)|^2$ is the ratio of the spectral energy density of Alfvén waves, propagating to the Sun and from the Sun respectively, that is the constant because both waves have the same spectral index $\alpha = -1$ and radial profiles. The ratio of the wave energy density to the energy of the magnetic field $I = |B_k^+(r)|^2 k/B_0^2(r)$ happens to be the constant too due to the identical radial profiles of the energy density of Alfvén waves and the energy of magnetic field and very weak dependence of the wave energy density $|B_k^+(r)|^2 k$ on wave vector k due to the very small left-hand side of the

equation (4). Numerical value for I can be found by equating the energy flux of Alfvén waves generated at the base of the corona to the energy flux of the radiationless nature with the value $8 \cdot 10^5$ erg/cm²·s, necessary for the acceleration of the fast solar wind from polar coronal holes:

$$V_A(r) \frac{|B_k^+|^2 k}{4\pi} = 8 \cdot 10^5 \text{ erg/cm}^2 \cdot \text{s}. \quad (6)$$

As the result we find that: $I = 5 \cdot 10^{-4}$.

In the process of wave propagation the position of the spectral break is shifted to the low frequencies [20]. The position of spectral break frequency is defined by the particular solution of the equation (5) which can be construct from the general solution.

We can find the exact position of the spectral break frequency as a function of radial distance by dividing both sides of this equation by the Alfvén wave velocity [7]:

$$f_{br}(r) = \left[0.6 + 2\pi\kappa I \int_{R_\odot}^r \frac{V_A(r) dr}{u + V_A(r)} \right]^{-1} \frac{R_\odot}{r}. \quad (7)$$

Assuming that the acceleration of fast solar wind is terminated at $r = 3R_\odot$ [2] we find that $f_{br}(3R_\odot) \approx 0.28$ Hz. At this stage most of the heating has been deposited within $(1 - 2)R_\odot$ above the surface as required by Withbroe [22] analysis. We can simplify this expression at the distance $r > 10R_\odot$ assuming that the velocity of the fast solar wind $u = 7.5 \cdot 10^7$ cm/s $\gg V_A(r)$. As a result we reduce the expression (7) to the form:

$$f_{br}(r) = \left[0.6 + \pi\kappa \ln \frac{r}{R_\odot} \right]^{-1} \frac{R_\odot}{r}. \quad (8)$$

Taking the numerical value of the spectral break $6 \cdot 10^{-2}$ Hz at the distance $r = 60R_\odot$ [20], separating the domain of Alfvén wave turbulence with the spectral indexes $\alpha = -1$ and domain with $\alpha = -5/3$ and equating it to the theoretical value obtained from the equation (8) we find the ratio of the spectral energy density of Alfvén waves propagating to the Sun and from the Sun respectively that is equal to $\kappa = 0.17$. This means that the intensity of waves propagating to the Sun is six times lower than those for the waves propagating from the Sun.

Experimental observations show that above the spectral break a wave spectrum with a slope near $-5/3$ [4] is established [7]:

$$|B_k^+(r)|^2 = |B_{k_{br}}^+(r)|^2 k_{br}^{5/3} / k^{5/3}. \quad (9)$$

The equation for the spectral energy density of waves in this case should inherit the structure of the equation (4) with the continuous transition across the spectral break [7]:

$$\begin{aligned} [u(r) + V_A(r)] \frac{\partial}{\partial r} \frac{|B_k^+(r)|^2 k^{5/3}}{4\pi} \\ = -\kappa k^{5/3} V_A(r) k_{br}^{-0.2} \frac{|B_k^+(r)|^2 k^{5/3}}{B_0^2(r)} \frac{\partial}{\partial k} \frac{|B_k^+(r)|^2 k^{5/3}}{4\pi}, \end{aligned} \quad (10)$$

Equation for characteristics of (10) take a form:

$$\frac{1}{k^{5/3}} \frac{dk}{dr} = \kappa I \frac{[2\pi f_{br}(r)]^{2/5} V_A(r)^{3/5}}{u + V_A(r)}, \quad (11)$$

where $I = |B_{k_{br}}^+(r)|^2 k_{br} / B_0^2(r) = 5 \cdot 10^{-4}$, $u \gg V_A(r)$. Beyond the $187.5R_\odot$ (0.87 astronomical units — AU) the collisional hydromagnetic turbulence spectrum of Kraichnan [10] with the spectral index $\alpha = -1.5$ [20] replace the collisionless spectra with the spectral indexes $\alpha = -1$ and $\alpha = -5/3$.

Integrating (11) and transforming the result to the frequency dependence on the radial distance we obtain:

$$f = \left[C \left(\frac{r}{R_\odot} \right)^{3/5} - \left(\frac{1}{f_{br}(r)} \right)^{3/5} \right]^{-5/3}, \quad (12)$$

where C is an arbitrary constant.

Figure 1 shows the characteristics of the equation (10) between the curves of the spectral break frequency f_{br} and the ion cyclotron frequency $f_{ci} = 1.6 \cdot 10^4 (R_\odot/r)^2$, where the wave energy is totally absorbed in the ion cyclotron resonance.

To estimate the fraction of Alfvén wave energy transferred to the protons of solar wind plasma in the process of induced scattering of waves we use, following Tu [19], the equation for the magnetic moment of protons. Doing this we take into account that due to the smallness of the left-hand side of the equation (10) the product $|B_k^+(r)|^2 k^{5/3}$ has a very weak dependence on the wave vector k . Therefore the right-hand side of (10) also depends weakly on k and we can rewrite it in form [7]:

$$[u(r) + V_A(r)] \frac{\partial}{\partial r} \frac{|B_k^+(r)|^2}{4\pi} = -\frac{\partial}{\partial k} 0.25\kappa f_{br}(r) I^2 B_0^2(r) \equiv -\frac{\partial}{\partial k} \Pi(r), \quad (13)$$

where $\Pi(r)$ is the volumetric energy flux.

The equation for the magnetic moment take a form:

$$u \frac{d}{dr} \ln \left(\frac{T_\perp}{B} \right) = \frac{\Pi(r)}{n(r) k_B T_\perp}, \quad (14)$$

where T_\perp is the perpendicular proton temperature in Kelvin, k_B Boltzmann's constant, $n(r) = 10^8 (R_\odot/r)^2 \text{ cm}^{-3}$ density of plasma.

We integrate the equation (14) from the three solar radii assuming that the acceleration of solar wind is already achieved. As a result we have:

$$\frac{T_\perp}{B_0} - \frac{T_\perp}{B_0} = \int_{3R_\odot}^r \frac{\Pi(r)}{n(r) k_B u B_0(r)} dr = 0.144 \ln \left[0.6 + \pi \kappa \ln \frac{r}{R_\odot} \right], \quad (15)$$

Non-adiabatic heating of the protons related to the presence of the volumetric energy flux $\Pi(r)$ reach only 0.16 K/nT in the range of radial distances $[3R_\odot, 200R_\odot]$. Therefore the source of energy for the acceleration of fast solar wind from the polar coronal holes must now be found in the solar corona itself [14].

Below the spectral brake frequency $f_{br}(r)$ we have the spectrum of Livshits-Tsyтович [12], [18] with the spectral index $\alpha = -1$. However this spectrum doesn't extend from f_{br} to the whole low frequency domain but truncated by the WKB solution.

Solving the stationary equation for Alfvén waves [21], [8], [3]:

$$\nabla \cdot \left((3\mathbf{u}(r) \pm 2\mathbf{V}_A(r)) \frac{|B_k^+(r)|^2 k}{8\pi} \right) - \mathbf{u}(r) \nabla \frac{|B_k^+(r)|^2 k}{8\pi} = 0, \quad (16)$$

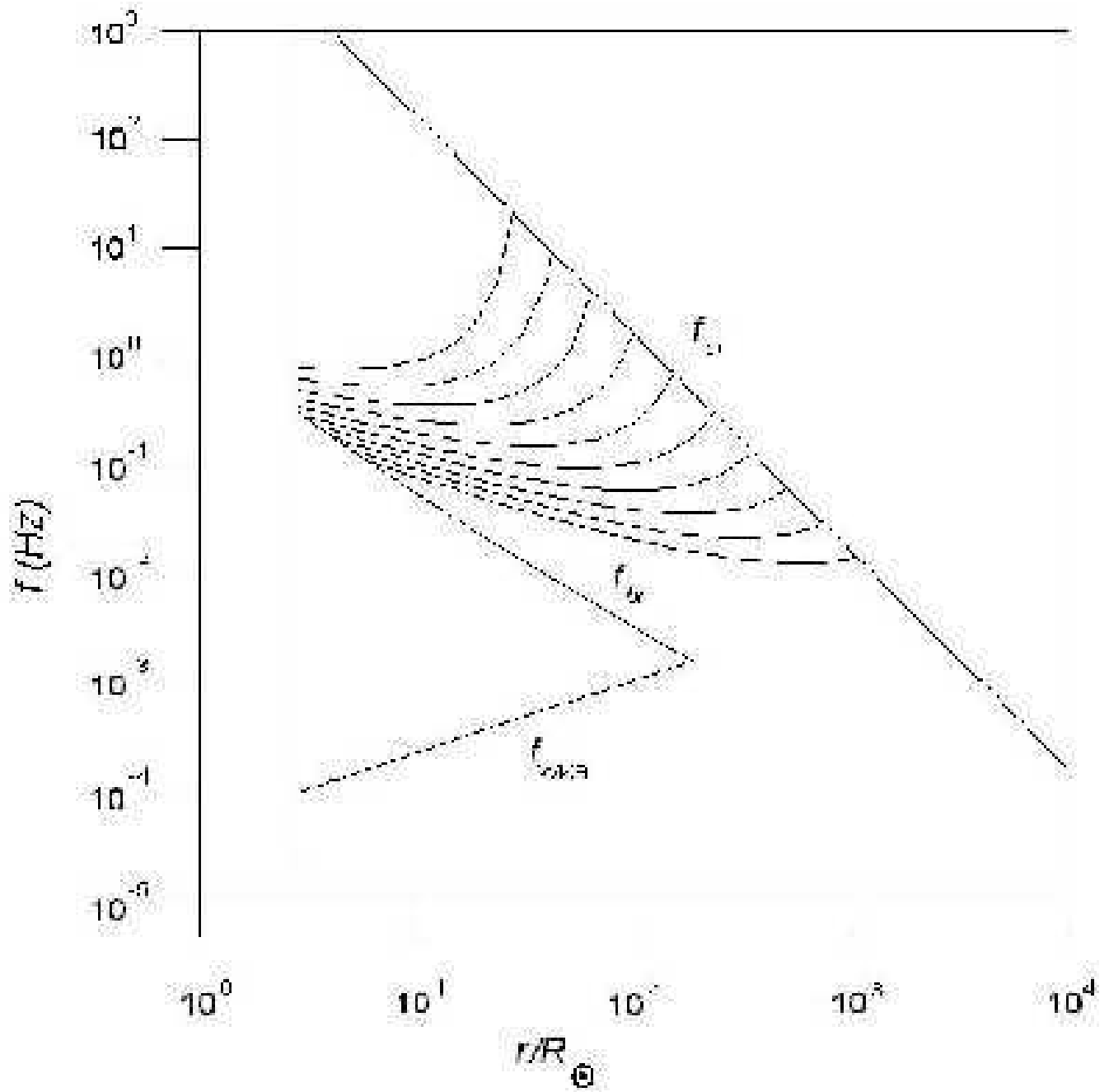


Figure 1. The characteristics of the equation (30) and the dependence of the spectral break frequency upon the distance from the Sun

the equation for the wave amplitude was found in the form:

$$\left[1 \pm \frac{V_A(r)}{u}\right]^2 n(r)^{-3/2} |B_k^+(r)|^2 k = \text{const.} \quad (17)$$

At the distances $r > 10R_\odot$ we can neglect the small parameter $V_A(r)/u \ll 1$ and rewrite it in the form defining the reduction of the wave amplitudes and their spectral index $\alpha = -2/3$ [20]:

$$\text{const} \cdot n(r) = (|B_k^+(r)|^2 k)^{2/3}. \quad (18)$$

Besides that, knowing from observations that the spectral break curve f_{br} and the WKB solution are merging at the distance 0.87 AU ($187.5 R_\odot$) we are able to find the form and position of WKB solution curve from the equation (18) in the form (fig. 1):

$$f_{WKB}(r) = 1.6 \cdot 10^{-3} \cdot \left(\frac{r}{187.5R_\odot}\right)^{2/3}. \quad (19)$$

3. Conclusion

Using the collisionless kinetic equation for interacting Alfvén waves in the random phase approximation we have followed analytically the evolution of these waves in the process of their propagation from the polar solar corona. As a result of such evolution the boundary of waves with the spectral index $\alpha = -1$ is shifted towards low frequencies due to induced scattering of waves by ions, which increase energy of ions by the recoil effect. However, this spectrum does not extend over the whole low frequency range but is truncated by WKB solution.

Above the frequency f_{br} the spectrum with the spectral index $\alpha = -5/3$ is obtained. Let us note that both in the polar solar corona and in the interplanetary space the approximation of collisionless plasma is valid at least up to the distance 0.87 AU.

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