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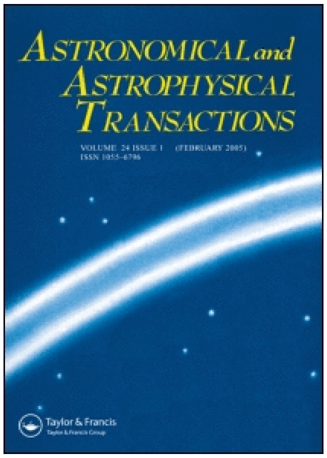

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An Analysis of the energy balance in the solar wind formation region

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The non-thermal broadening of coronal lines observed within short distances from the Sun was analysed and analysis revealed that near the Sun this broadening is caused by Alfven waves. Within the magnetohydrodynamic (MHD) approximation, the wave energy flux required for solar wind formation, and also the plasma velocity and temperature were calculated. Electron density distributions and flow geometry were used as input data. It is shown that the energy flux required for solar wind formation enters the solar corona in the form of Alfven waves and the dissipation of these waves provides the heating of the solar wind plasma near the Sun. The transformation of Alfven waves to acoustic waves in this region is less effective than their dissipation. The dissipation of the Alfven waves falls off with distance from the Sun, and the heating of the solar wind plasma is determined by the coefficient of transformation of the Alfven waves to acoustic waves. Subsequently, the dissipation effectiveness of the acoustic waves decreases, and the absorption coefficient of acoustic waves becomes less than the transformation coefficient of the Alfven waves to acoustic waves; plasma heating is now determined by the absorption of acoustic waves.

Keywords: Sun; Corona (Sun); Solar wind

1. Introduction

One of the key problems in the solar wind theory is the question of the energy source for solar wind acceleration. A theoretical treatment of this issue is made considerably difficult by the fact that the Sun's corona is characterized by a relatively rarefied plasma and that the height scale is comparable with the wavelength of the waves, which can supply the necessary energy for solar wind formation.

This issue becomes still more challenging in the case of the origin of quasi-stationary high speed solar wind streams because the amount of energy required for their formation is by factors of 2–3 larger than that for a quiet solar wind. On the basis of experimental investigations [1–3] and the theoretical model proposed in paper [4], it was shown that high speed solar wind streams (HS) have their origins in coronal holes (CH), which are characterized by decreased temperatures and densities and by a low radiative energy flux. Consequently, the additional

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energy source for solar wind formation must have a non-thermal character. This source is essential since it is responsible for solar wind formation. However, the physical nature of this source and the dependence of the heating power on plasma parameters are still not understood completely [5]. The source of the energy required for solar wind formation might be provided either by the dissipation of waves arriving at the corona from lower-lying layers of the solar atmosphere [6] or by the dissipation of coronal currents [7]. The wave origin of heating sources appears to be the most probable candidate; however, results of theoretical calculations [8–12] do not suggest any unambiguous conclusion about the type of dissipating waves and their dissipation mechanism. An analysis of the energy balance of the solar corona made on the basis of observational data showed that in the lower corona the 'additional' energy flux required for solar wind formation is an energy flux of Alfven waves, and the coefficient of absorption of these waves within small distances from the Sun ($r < 1.5R_\odot$) varies in proportion to electron density [13]. The HS and CH model, which was suggested previously [4], was based on the assumptions about the constancy of energy and mass flows entering the corona. Qualitatively, these assumptions have been supported by many experimental results [2]. Solar interplanetary-modelling problems, however, call both for a quantitative treatment of the energy balance of open coronal regions and for the elucidation of the mode of the waves that ensure an extra energy flux of the solar wind.

Using observational data, this paper investigates the character of the heating source to heights $\approx 5R_\odot$. In section 2, an analysis of the non-thermal broadening of observed coronal lines is made to determine the wave modes arriving at the solar corona. In section 3, the MHD approximation is applied to calculate the 'additional' energy flux (the energy flux of the waves), which is required for solar wind formation, as well as macroscopic characteristics of plasma (velocity and temperature). Input data are represented by electron density distributions and by the flow geometry in two homogeneous, large-scale regions of the solar corona with an essentially different flow geometry. Thereupon, we determine the dependence of absorption coefficients of this flux on plasma parameters and compare it with known dependencies for different wave modes.

2. General properties of the solar wind energy source

Generally, the energy flux entering the corona goes into the corona's emission and the solar wind formation, and some part of the flux can come down (to the transition region) due to heat conduction. Taking into consideration that at $1.02R_\odot$ ($R_\odot$ – being the solar radius) the radial temperature gradient is small, we suppose, the role played by the heat-conducting flux at this distance can be neglected. In this case, the energy balance of the corona may be represented as:

$$\begin{aligned}(F_\mathrm{k} + F_\mathrm{t} + F_\mathrm{g}) + F_\nu + F_\mathrm{w} &= n v_r r^2 s\left(\frac{mv^2}{2} + \frac{5}{2}kT + \frac{M_\odot G m}{r}\right)\\ &\quad + \int_{r_0}^{r} A(T) n_e^2 x^2 s(x)\mathrm{d}x + F_w\\ &= F_0, \end{aligned} \tag{1}$$

where F_k, F_t and F_g are the kinetic, thermal and gravitational energy fluxes, respectively; F_ν the radiation losses of coronal plasma; F_w the 'additional' (wave) energy flux; $n = \nu n_e$ particle density; v the mean velocity of the particles; v_r the radial velocity component; k the Boltzmann's constant; $T = T_e = T_i$ the temperature; $M_\odot$ the mass of the Sun; G the gravitational constant; $m = \mu m_p$ the effective mass; ν and μ the coefficients representing

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the ion composition ($\nu = 1.9545$, $\mu = 0.555$); s the degree of non-adiality and $A(T)$ the emissivity of coronal plasma that only has a weak dependence on temperature ($A = 1.4 \times 10^{-22}\,\mathrm{erg\,cm^3\,c^{-1}}$ at $T = 1.4 \times 10^6\,\mathrm{K}$).

For quantitative calculations of the wave energy flux and velocity amplitudes of different wave modes, we used results reported in [15], where the mean values of n, T and of the non-thermal velocity amplitudes ($\triangle V_{nt}$) in the corona ($r = 1.02R_\odot$) for different heliolatitudes were obtained. In our opinion, their data are sufficiently comprehensive and reliable. According to measurements [24], the particle flux of a quiet solar wind is $C = nv(r/R_\odot)^2 = 1.8 \cdot 10^{13}\mathrm{cm^{-2}} \cdot \mathrm{c^{-1}}$. The net energy flux at $r \simeq 1\,\mathrm{AU}$, provided that $v_{\max} = 800\,\mathrm{km\,c^{-1}}$, is determined from the expression

$$F_0 = F_k = mn\frac{v_{\max}^3}{2}\left(\frac{r}{R_\odot}\right)^2,$$

in view of the fact that at $r = 1\,\mathrm{AU}$, $F_\mathrm{k} \gg F_\mathrm{g} + F_\mathrm{t} + F_\mathrm{w} + F_\nu$.

An ‘additional’ energy flux in the corona ($r = 1.02R_\odot$) can be realized in the form of acoustic, magnetosonic and Alfven waves. In accordance with equation (1) and the results of [15], it is possible to calculate the amplitude of the above-mentioned wave modes required for ensuring the energy balance of the corona and the solar wind.

For Alfven waves, we have

$$F_\mathrm{w} = v_\mathrm{a}\rho(\triangle V_\mathrm{a})^2 r^2 s, \tag{2}$$

where $v_\mathrm{a} = H_r(4\pi\rho)^{-1/2}$, $\rho = mn$ and $\triangle V_\mathrm{a}$ is the amplitude of the wave.

The magnitude of the magnetic field of open coronal regions can be deduced from data on the interplanetary magnetic field (IMF) near the Earth’s orbit (reduced to the Sun by Parker’s spiral), $H_{r0} = H_r(r/R_\odot)^2$. The mean value of $H_r = 4.4\gamma$ at 1 AU [16], and $H_{r0} = 2\,\mathrm{G}$ (H_{r0} is taken to be independent of the heliolatitude). It is interesting to note that measurement of the mean field of the Sun as a star [14] gives a maximum value of $H_\odot = 2\,\mathrm{G}$, and the magnitude of the large-scale field $H_{r0} \geq H_\odot$ is in accordance with the scheme in [17], which is in reasonably good agreement with the above estimate of H_{r0} obtained from IMF data.

For magnetosonic waves propagating at small angles to a radial direction (fast mode), we have

$$F_\mathrm{w} = v_\mathrm{a}\rho\frac{(\triangle V_\mathrm{ms})^2}{2} r^2 s. \tag{3}$$

For acoustic waves, we have

$$F_\mathrm{w} = v_\mathrm{s}\rho\frac{(\triangle V_\mathrm{s})^2}{2} r^2 s, \tag{4}$$

where v_s the sound velocity.

On substituting equation (2)–(4) into equation (1) and taking into consideration that at $r = 1.02R_\odot F_\mathrm{k} \ll F_\mathrm{g}, F_\mathrm{t}, F_\mathrm{w}, F_\nu$, we determine the amplitudes of different types of waves

$$(\triangle V_\mathrm{a})^2 = \frac{F_0 - F_\mathrm{t} - F_\mathrm{g} - F_\nu}{r^2 s\rho v_\mathrm{a}}, \tag{5}$$

$$(\triangle V_\mathrm{ms})^2 = \frac{2(F_0 - F_\mathrm{t} - F_\mathrm{g} - F_\nu)}{r^2 s\rho v_\mathrm{a}}, \tag{6}$$

$$(\triangle V_\mathrm{s})^2 = \frac{2(F_0 - F_\mathrm{t} - F_\mathrm{g} - F_\nu)}{r^2 s\rho v_\mathrm{s}}. \tag{7}$$

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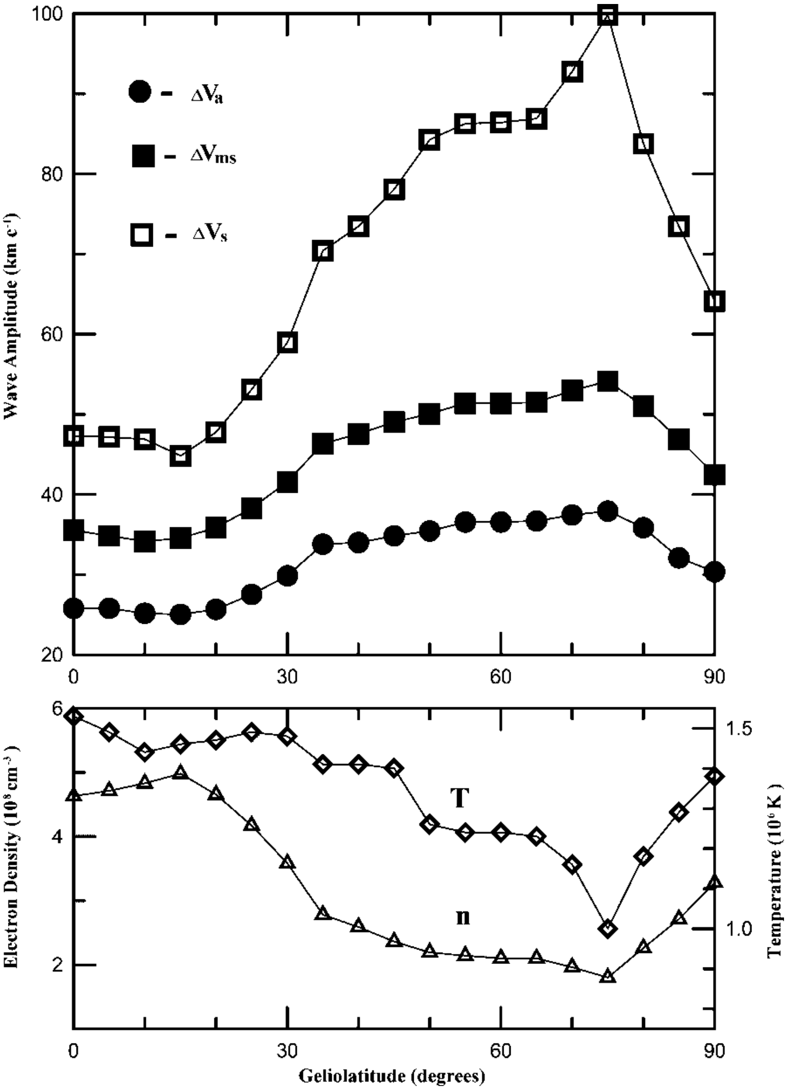

Figure 1. Dependence of the density, temperature and wave amplitude in the solar corona on the heliographic latitude.

The results of these calculations are presented in figure 1, where n and T are given for $r = 1.02R_{\odot}$ [15]. It can be seen from figure 1 that the largest values of the calculated amplitudes of all wave modes correspond to regions with decreased values of n and T. The measurement of $\triangle V_{nt}$ was made at the limb, and this implies that for a quantitative comparison of the calculated amplitudes with $\triangle V_{nt}$, it is necessary to average along the line of sight the contribution from elements having different phases, a different direction of the oscillation vector (for Alfven waves) and different latitudes, longitudes and distances from the Sun. The mean value along the line of sight can be obtained from the formulas

$$\langle(\triangle V_{\mathrm{a}})^2\rangle = \frac{\int_{-\infty}^{\infty}\int_0^{2\pi}\int_0^{2\pi}\sin^2(\omega t+\alpha)\sin^2\varphi(r^2/(r^2+x^2))n^2(\triangle V_a)^2\,\mathrm{d}\varphi\,\mathrm{d}\alpha\,\mathrm{d}x}{4\pi^2\int_{-\infty}^{\infty}n^2\,\mathrm{d}x} \tag{8}$$

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$$\langle(\triangle V_{\rm ms})^2\rangle = \frac{\int_{-\infty}^{\infty}\int_0^{2\pi}\sin^2(\omega t+\alpha)(x^2/(r^2+x^2))n^2(\triangle V_{\rm ms})^2\,{\rm d}\alpha\,{\rm d}x}{2\pi\int_{-\infty}^{\infty}n^2\,{\rm d}x} \qquad (9)$$

$$\langle(\triangle V_{\rm s})^2\rangle = \frac{\int_{-\infty}^{\infty}\int_0^{2\pi}\sin^2(\omega t+\alpha)(x^2/(r^2+x^2))n^2(\triangle V_{\rm s})^2\,{\rm d}\alpha\,{\rm d}x}{2\pi\int_{-\infty}^{\infty}n^2\,{\rm d}x}, \qquad (10)$$

where α is the oscillation phase, x the distance along the line of sight and averaging over φ is averaging along the direction of the oscillation vector.

Results of calculations of $\triangle\tilde{V} = \langle(\triangle V)^2\rangle^{1/2}$ in accordance with equation (8)–(10) and the experimentally observed non-thermal velocity ($\triangle V_{\rm nt}$) and intensity of the red coronal line (Fe × λ6374) are presented in figure 2. Note that increased values of non-thermal velocities and the decreased intensity of the red coronal line correspond to regions with decreased electron

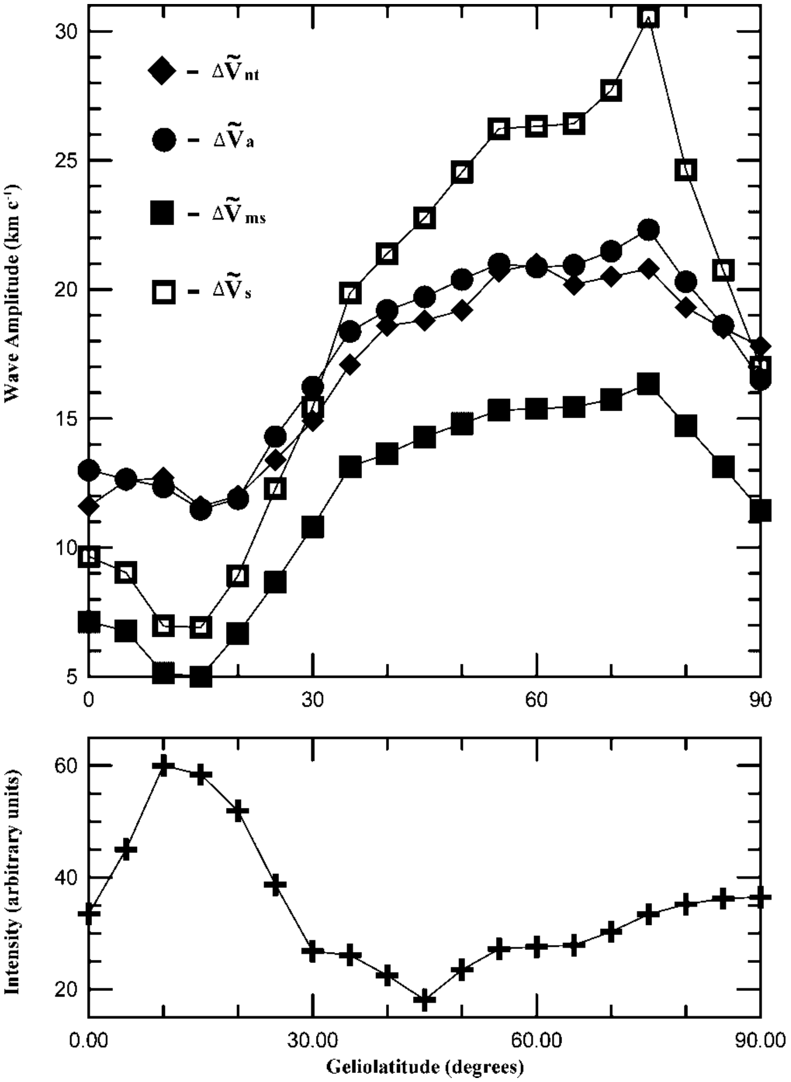

Figure 2. Comparison of calculated and observed non-thermal velocities, and intensity of the red coronal line (arbitrary units).

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density. This opposing behaviour of the non-thermal velocities and of the red coronal line intensity is attributable to the fact that the intensity of this line is proportional to the electron density squares, and hence a decrease in electron density leads to a decrease in the intensity of this line, but the observed decrease in temperature does not compensate for the electron density influence.

Clearly the best agreement of the observed and calculated amplitudes corresponds to Alfven waves. This suggests the conclusion that the energy flux entering the corona is indeed a constant for regions with an open field configuration, while the ‘additional’ energy flux ensuring the energy balance of the corona and the solar wind formation is basically an energy flux of Alfven waves.

We now attempt to elucidate the way in which the Alfven waves entering the solar corona convey their energy to the solar wind.

3. The dissipation of the wave energy flux

MHD equations with the presence of the waves [18] were used to calculate the energy flux and macroscopic characteristics of plasma in two open regions of the Sun’s corona with a different flow geometry. The distributions of $n(r)$ and $s(r)$ in these regions were discussed in paper [19]. The system of these equations was solved numerically, and integration was performed to the Sun. Results of the calculations of the temperature and of the energy flux required for solar wind formation, with such a sense of integration, only weakly depend on the boundary values of the temperature. The boundary value of the magnetic field strength H_{r_0}, the particle flux C and the total energy flux F_0 have already been discussed above.

Figure 3 presents the dependence of the absorption coefficient of the wave energy flux $\kappa_w = -(1/F_w)(\partial F_w/\partial r)$ – (of the ‘additional’ energy flux required for solar wind formation) on the heliocentric distance. Number 1 stands for the absorption coefficient in the quiet region

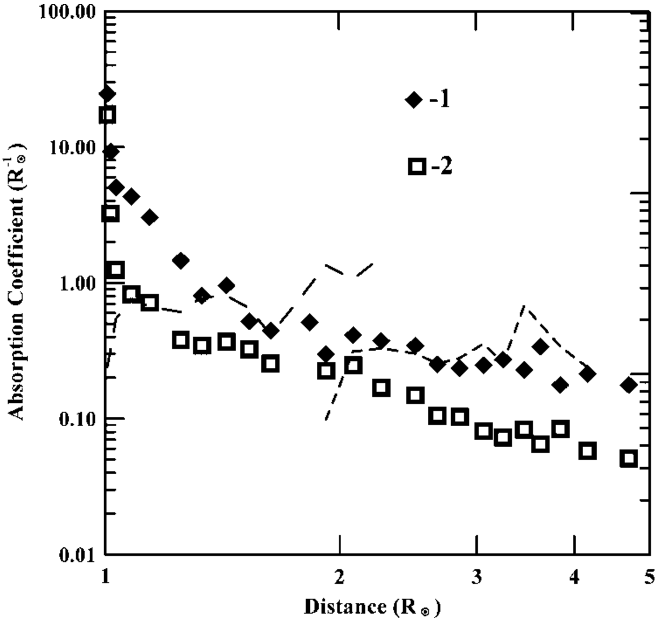

Figure 3. Dependence of the absorption coefficient of the wave energy flux on the heliocentric distance in the quiet region (1) and in the polar coronal hole (2).

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and number 2 corresponds to that in the coronal hole. It is apparent from figure 3 that in the quiet region the absorption coefficient is significantly higher than that in the coronal hole. Note that it is the weaker attenuation of the waves at small distances from the Sun in coronal holes that leads to the fact that most of this energy transforms to kinetic energy of the solar wind rather than being lost by radiation, as is the case in quiet regions.

3.1 *Dependence of the absorption of the wave energy flux on plasma parameters*

Particle density in the Sun's corona undergoes the most dramatic changes. A previous paper [20] considered the dependence of the calculated absorption coefficient of the waves κ_{w} on electron density. The authors showed that within the electron densities of $10^7 \leq n \leq 5 \times 10^8$ the dependence of κ_{w} on n_{e} is identical in regions with a different flow geometry, and this dependence fits the dependence of the attenuation of Alfven waves on n_{e} from [21]. However, at smaller n_{e}, *i.e.*, at longer distances from the Sun, the dependence $\kappa_{\mathrm{w}}(n_{\mathrm{e}})$ departs from that given in [21]; furthermore, it is different in coronal regions with a different flow geometry. This change in the dependence $\kappa_{\mathrm{w}}(n_{\mathrm{e}})$ can be due to the transformation of Alfven waves to acoustic waves.

Figure 4 presents the dependence of the calculated absorption coefficient κ_w on the one calculated theoretically in [21] ($\kappa_{\mathrm{a}} = (m_e/m_p)(\nu_{\mathrm{ep}}/v_a)$; ν_{ep} and ν_{pp} stand for the electron–proton and proton–proton collision frequencies, respectively) for little collision mode of different type wave with $\omega \gg (m_e/m_p)\nu_{\mathrm{ep}}$. Note that the dependence is identical in regions with a different flow geometry. Three typical portions are identifiable on this dependence: portion A, on which our calculated absorption coefficient corresponds to the absorption coefficient of Alfven waves $\kappa_{\mathrm{a}} = (m_e/m_p)(\nu_{\mathrm{ep}}/v_a)$, obtained in [21]; portion C may be interpreted as the absorption of acoustic waves because our calculated coefficient of energy absorption corresponds to the absorption coefficient of acoustic waves $\kappa_{\mathrm{s}} = (4/5)(\nu_{\mathrm{pp}}/v_{\mathrm{s}})$, as given in [21]. Portion B shows the transition of the calculated absorption coefficient from κ_{a} to κ_{s}, which is most likely to

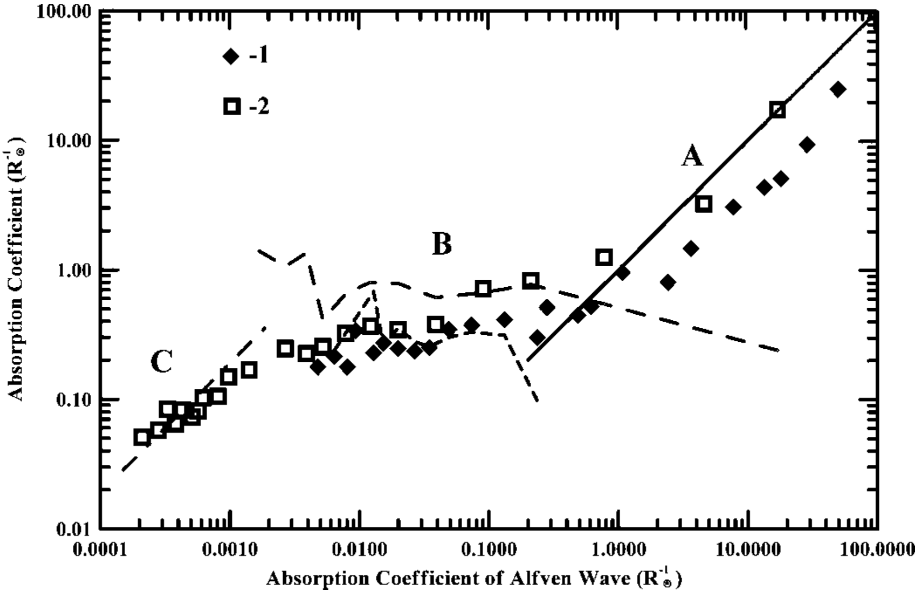

Figure 4. Dependence of the absorption coefficient on plasma parameters. The letters A, B and C label the portions of the dependence corresponding to different absorption mechanisms.

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correspond to the transformation of the Alfven waves to acoustic waves. We now turn to the determining of the corresponding transformation coefficient.

3.2 *Transformation of the wave energy flux*

The dissipation and transformation of the calculated wave energy flux are described by the equations:

$$F_{\mathrm{w}} = F_{\mathrm{a}} + F_{\mathrm{s}} \tag{11}$$

$$\kappa_{\mathrm{w}} = -\frac{1}{F_{\mathrm{w}}}\frac{\partial F_w}{\partial r} = \frac{\kappa_{\mathrm{a}} F_{\mathrm{a}} + \kappa_{\mathrm{s}} F_{\mathrm{s}}}{F_{\mathrm{a}} + F_{\mathrm{s}}} \tag{12}$$

$$\frac{\partial F_{\mathrm{a}}}{\partial r} = -\kappa_{\mathrm{a}} F_{\mathrm{a}} - \kappa_{\mathrm{as}} F_{\mathrm{a}} \tag{13}$$

$$\frac{\partial F_{\mathrm{s}}}{\partial r} = -\kappa_{\mathrm{s}} F_{\mathrm{s}} + \kappa_{\mathrm{as}} F_{\mathrm{a}}, \tag{14}$$

where F_{a} and F_{s} are the energy fluxes of Alfven and acoustic waves; κ_{a} and κ_{s} the absorption coefficients of the energy flux of Alfven and acoustic waves; and κ_{as} the transformation coefficient of Alfven waves to acoustic waves. We neglected the inverse transformation of acoustic waves to Alfven waves, as acoustic waves are absorbed significantly more effectively than Alfven waves. The system of equations (11)–(14) permits us to infer the transformation coefficient of Alfven waves to acoustic waves from the calculated absorption coefficients of the wave energy flux κ_{w}, and κ_{a} and κ_{s} are determined from portions A and C of the dependence presented in figure 4. To do so, we solve equations (11)–(14) and get:

$$\kappa_{\mathrm{as}} = (\kappa_{\mathrm{w}} - \kappa_{\mathrm{a}}) - \frac{\mathrm{d}}{\mathrm{d}r}\left\{\ln\frac{\kappa_{\mathrm{s}} - \kappa_{\mathrm{w}}}{\kappa_{\mathrm{s}} - \kappa_{\mathrm{a}}}\right\}. \tag{15}$$

The transformation coefficient κ_{as}, calculated by formula (15), is shown in figures 3 and 4 by a dashed line (coronal hole) and short dashes (quiet region). As may be seen from figures 3 and 4, it is virtually unchanging in region B at different heliocentric distances for the coronal hole; however, it is larger for a quiet region. In our opinion, the transformation coefficient κ_{as} is conditioned by a non-linear transformation of the Alfven waves to sound waves, which is the result of an increase of the Alfven wave amplitude. In this case the transformation coefficient is possibly larger in those coronal regions where the Alfven wave amplitude is larger (coronal hole). But further investigation is needed to gain a better insight into the physical mechanism of the transformation.

4. Results and discussion

By analysing the non-thermal broadening of the coronal red line, it becomes apparent that the energy flux required for solar wind formation enters the Sun's corona in the form of Alfven waves.

Calculations of the dissipation of the wave energy flux have shown that solar wind plasma heating at small distances from the Sun is caused by the dissipation of Alfven waves (portion A in figure 4). Transformation of these waves to acoustic waves is less effective than the dissipation. The dissipation of Alfven waves is attenuated outward from the Sun and hence the absorption coefficient κ_w, together with the power of plasma heating, is determined by the

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transformation coefficient of Alfven waves to acoustic waves (portion B in Figure 4) because $\kappa_a < \kappa_{as} < \kappa_s$. Subsequently, the dissipation effectiveness of acoustic waves decreases, and when $\kappa_s < \kappa_{as}$ the absorption coefficient κ_w, inferred from observational data, corresponds to the dissipation of acoustic waves (portion C in figure 4). Also it should be noted that the transformation of Alfven waves to acoustic waves in solar wind was found in [22].

Our obtained dependence of the absorption coefficient of the wave energy flux on the collision frequency ($\kappa_a \sim \nu_{ep}$ – for Alfven waves and $\kappa_s \sim \nu_{pp}$ – for acoustic waves) is accounted for, we believe, by the fact that in the region of solar wind formation, the wave energy transforms to thermal energy of plasma and, in this case, the transfer of energy is determined by the corresponding collision frequencies.

Super-radial flow (in coronal holes) is accompanied by a decrease of n and T in the corona. This causes the absorption of Alfven waves to decrease at small distances from the Sun, and coronal emission to decrease too. In this case, most of the Alfven wave energy will transform to thermal and kinetic energy of the solar wind at large distances, thus supplying energy for the formation of a quasi-stationary HS solar wind stream.

The above-mentioned opposing behaviour of the red coronal line intensity and of non-thermal velocity is also characteristic for other coronal lines [23]. In our opinion, such behaviour of coronal lines has a natural explanation. In open regions of the Sun's corona, an increase in the flow divergence is accompanied by a decrease in electron density, which leads to a decrease in the coronal line intensity while the absorption of the waves, which ensure the formation of the solar wind, decreases; as a consequence, the amplitude of the waves in the corona, which makes a contribution to the non-thermal broadening of coronal lines, increases. This effect may be absent for those coronal lines that form in active regions.

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