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ABOUT HEATING OF THE SOLAR CORONA BY MHD WAVES

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In the scientific literature, the heating of the solar corona by magnetohydrodynamic waves, especially Alfven and slow acoustic waves, is widely discussed. The calculations of different authors of the energy flux density vary greatly: namely, the energy flux values by Alfven waves by 6 orders of magnitude, slowwaves by 4 orders of magnitude. Some effects affecting the calculated values of the energy flux of these waves are examined in this work. It is shown that the main reason for this is that the value of non-thermal velocities from observations is not accurately determined since the inclination of movements is not unknown to the direction of the line of sight.

Keywords: MHD waves – Solar corona

1. INTRODUCTION

The solar corona is a high-temperature layer of the solar atmosphere. The temperature in calm areas of the corona is 106 K but on active regions (1-5) 106 K. To compensate for energy loss of the corona due to radiation, by the heat conduction mechanism, as well as on the solar wind acceleration, is required constant heating with energy flux of 105 erg cm– 2s^{-1} at calm regions and 107 erg cm^{-2}s^{-1} at active regions [36]. The source of heating energy of the solar corona (as well as the acceleration of the solar wind) is the convective motion that moves the magnetic fields of coronal structural formations. In this case, depending on the velocity of magnetic field movement, two types of motion are distinguished: with a timeline, more and less than the time scale of the Alfven wave from one end of the magnetic tube to the other end. In the first case, the magnetic fields are compressing, the magnetic lines of force are reconnecting, resulting in current sheets are forming; these currents are named direct currents; in the second case, waves

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with alternating currents are generating. These processes are two fundamental mechanisms for heating the solar corona. In 1972, Parker put forward an idea of a possible mechanism for heating the corona with numerous Nano-flares with the energy of 1024–1027 erg occurring in the corona [31]. Some researchers had investigated this mechanism widely. More detailed information on the mechanisms of heating of the corona and the observational waves in the corona could be found in review articles [1] [11–15, 29]. In heating of the corona by MHD waves, the most perspective is considered Alfven and slowmagneto-acoustic waves. It should be noted, that obtained values of the energy flux density by different authors vary significantly (see the attached table). This work aims to understand this problem.

2. EXPRESSIONS FOR DETERMINING THE ENERGY FLUX DENSITY TRANSFERRING BY MHD WAVES.

Authors are using various expressions to calculate the energy flux density transferring by MHD waves, depending on methods and results of observation. Below we give these expressions and show their conclusions. 1) We output the main expression for the energy flux density, transferring by MHD waves (see example [2]). This expression is main, because of the output of all other expressions is based on this expression as we see below.

The kinetic energy density of gases is determining by the expression:

$$\epsilon_k = 1/2 - \rho \upsilon \tag{1}$$

Here ρ- density, ν - (we espetially emphsase)- the root mean square value of the particle velocity of the medium. In the case of MHD waves, ν - is the root mean square velocities of the particles excited by the propagation of MHD wave. The amount of kinetic energy in the elementary volume dV is:

$$d\upsilon_k = 1/2 \cdot \nu^2 dV$$

Here, dV is the elementary volume, occupied by propagating with phase velocity ν_{ph} wave, through elemental area dA during time dA, i.e.

$$dV = dAdt\nu_{ph}$$

Putting this in (1) and dividing both parts on dAdt, we obtain the desired expression for the kinetic energy flux density of the propagating MHD wave:

$$F = 1/2 \cdot \rho \nu^2 \nu_{ph} \tag{2}$$

This expression is the main one for calculating the quantity of kinetic energy flux density in MHD waves; therefore, we stay on the derivation of this expression in more detail.

2) For Determining the flux density of the kinetic energy of the acoustic wave, exist an expression, in which using the variation in the intensity of the spectral line of emission on the wave related with a change in density. The intensity of the emission line is proportional to the square of the density: $I\ \rho^2$; differentiating this and applying the known expression $\nu_a/\nu_{ph} = d\rho/\rho$, [1]; - here ν_a and $d\rho$ - are the amplitudes, obtain:

$$\frac{\nu_a}{\nu_{ph}}\frac{1}{2}\frac{dI}{I}.$$

Taking into account, that there is a ratio between the root-mean-square value of the velocities ν and velocity amplitude $\nu^2 = \nu_a^2/2$ (note that this expression is obtaining when calculating the root-mean-square values of the velocities for the full period of the sinusoidal wave) and putting this in (2), we obtain:

$$F = \frac{1}{8}\rho\nu_{ph}^3\left(\frac{dI}{I}\right)^2 \tag{3}$$

We underline, that here dI/I - is the amplitude of the intensity variation, therefore, this expression gives the maximum value of the flux density.

3) Let us determine expression from above described:

$$\nu_a = \nu_{ph}\frac{d\rho}{\rho}$$

and using the ratio $\nu = \nu_a/2$; applying this ratio in (2), we obtain:

$$F = \frac{1}{8}\rho\nu_{ph}^3\left(\frac{d\rho}{\rho}\right)^2 \qquad (3")$$

In [33], the fractional factor in this expression has written as 1/2.

4) By applying the ratio $\nu^2 = \nu_a^2/2$ in (2) we obtain

$$F = \frac{1}{4}\rho\nu_a^2\nu_{ph} \tag{4}$$

5) Usually, between the root-mean-square values of the velocities ν and most probable velocity ξ, obtained from the Doppler width of the spectral lines, the authors take the ratio $\nu^2 = 2\xi^2$. Then, applying this in (2) we obtain

$$F = \rho\xi^2\nu_{ph} \tag{5}$$

The ratio between the root-mean-square ν and the most probable values of the velocities ξ should be $\nu^2 = 1,5\xi^2$. İndeed, under the Maxwellian distribution of non-thermal velocities (the distribution of non-thermal velocities accepted such) $= \sqrt{\frac{3kT}{m}}$, $\xi\sqrt{\frac{2kT}{m}}$

Hence, come out the above ratio. Here, T - is determined temperature value, characterizing the Maxwellian distribution of non-thermal motions by velocities.

For determining F, are using root-mean-square values of velocities of Doppler shifts of the spectrum lines, caused by the propagating wave.

Additionally, expression of the form (4) and (5) are using for F (see, example, [7]). In this regard, note the following: Doppler shift velocities are only part of motions on the wave; the fact is that, under slant observation, the spectral lines expand and shift simultaneously. In our opinion, it is unknown how to determine the value of non-thermal velocities with such a "bifurcation" of these velocities. The phase velocity of the Alfven wave: $\nu_{ph} = \frac{B}{\sqrt{4\pi\rho}}$

Where B - is the magnetic field intensity

When calculating F of Alfven wave, with using amplitude and most probable value of velocity, obtained from Doppler width, is using the following expressions:

$$F = \frac{1}{4}\sqrt{\frac{\rho}{4\pi}}\nu_a^2 B \qquad (6)$$

$$F = \sqrt{\frac{\rho}{4\pi}}\xi^2 B \qquad (7)$$

In attached table had shown energy-flux density values by MHD waves in the direction of the corona, calculated by the authors who used various expressions. Results of calculations of the most typical works on this problem had shown. Observational data about the wave, wave velocity (ν in km s^{-1}), source of determination of velocity, using lines, the phase velocity of wave ν_{ph}, name of the region of solar atmosphere for which determined the value F, have given in notes. Frequently, the authors used the expression that did not correspond to observational data for calculating F, in this case, in note column is indicated which expression should be used. The value table of F (erg sm-2 s-1) which had calculated by various expressions. The value of the magnetic field B has expressed in gauss (Gs). If in notes there is the value of B, then the wave is Alfven if the value of B is missing, then the wave is the slowmagneto-acoustical wave.

3. DISCUSSION.

As can be seen, the energy flux in the Corona, transferred by Alfven waves, according to different researchers, varies on six orders of magnitude ([33,34]:(10 erg $sm^{-2}s^{-1}$); [19]: (1.85 107erg $sm^{-2}s^{-1}$)), the flux transferred by slow magneto-acoustic waves differs on four orders of magnitude ([26]: (3.13 102 erg $sm^{-2}s{-}1$);

Authors	Used expressions F			Notes
	$1/2\ \rho\nu^2\nu_{ph}$	$\rho\xi^2\nu_{ph}$	$1/8\rho(dI/I)2\nu^3_{ph}$ ν (km/s),	Source of definition ν; used lines; ν_{ph}(km/s); domain of definition of F; density n (sm^{-3})
[3]		$2{\cdot}10^5$		28.4, Doppler width, lines of ions SiII, SiIII;45; photosphere at the altitude of h=2500 km,n=4 10^9
[4]		$4.9\cdot10^5$		$\nu^2 = 2\cdot(43.9)^2, B = 5\cdot43.9$ – non-thermal velocity obtained by Doppler width of 1445.75ÅSiVIII, coronal hole. n=4,8 10^7. It should use (5) without a factor of 2.
[6]		$1.2\cdot10^6$		30 – Non-thermal velocity obtained by Doppler width B=30, coronal hole, lines: FeXII 186.88, FeXII 195.12, FeXIII 202.04, n=?
[6]		$1.2\cdot10^6$		30 – Non-thermal velocity obtained by Doppler width B=30, coronal hole, lines: FeXII 186.88, FeXII 195.12, FeXIII 202.04, n=?
[7]		$7\cdot10^4$		3, root-mean-square values of Doppler line shifts, $n = 10^{10}, \nu_{ph}$ =?The quiet region, transition region, line CIV1548. This velocity is inadequate to root mean square velocity obtained from the Doppler lines
		$(6-48)\cdot10^5$		B=300. The ratio between the RMS value of the velocities of non-thermal motions and the RMS value of the line shifts velocities is unknown, therefore, the values of F are doubtful
[8]		$5\cdot10^6$		21, Determined by Doppler width of ultraviolet coronal lines, B = 100, the active region, $n = 10^9$.
		$1.7\cdot10^5$		22, B=10, quiet region
[9]			$1,5-4\cdot10^5$	dI/I=5%. 171Å,ν_{ph} =75-150, coronal hole, $n_e = 10^9$
[10]	$3.5\cdot10^2$			3, oscillation amplitude, slow magneto-acoustic wave line FeIX 171, ν_{ph}= 150, active region, n = 3 10^8. Should use the expression (4)

[17]: (6.18 106 erg $sm^{-2}s^{-1}$)). Let us try to understand out why the values of the energy flux, calculated by different authors differ so much. The flux magnitude

[16]		$1.2 \cdot 10^8 - 1.2 \cdot 10^9$ line NaD$_1$		1.14-2.43 Root-mean-square velocities by Doppler width of lines, magneto-acoustic wave, ν_{ph}=7, the photosphere. Should use the expression (2)
		$7.7 \cdot 10^8$ line FeI 8383.38		
[11]	346			3, velocities amplitude, active region, ν_{ph}=150, FeIX 171, FeXII 195. n=8,35 10^8. Should use the expression (4)
[17]			$1.75 \cdot 10^7 -$ $4.74 \cdot 10^5$	ν_{ph}=dω/dk is obtained from the solution of the MHD equations for the conditions of coronal holes. The first line is the Alfvén wave, the second is acoustic. The value of B is unknown. Calculations are carried out for different periods of the wave.
			$6.18 \cdot 10^6 -$ $1.91 \cdot 10^5$	
[18]		$3.1 \cdot 10^5$		$\nu^2 = 228^2$, non-thermal velocities on the Doppler line widths SiVIII 1440.49, 1445.75, this is multiplied by 2 to take into account two degrees of freedom; in fact, factor 2 takes into account the ratio $\nu^2 = 2\xi^2$; B=5; n=1,8 10^8
[19]		$(0.86 - 1.85) \cdot 10^7$		30-32 non-thermal velocities, obtained from Doppler width; B=39, FeXII192, active region, $ne = 10^9$
[22]		$2.4 \cdot 10^5$		2.6 –amplitude of shifts H$_\alpha$, B=1000, chromosphere, n$_e$=6·10^{14}. Should use the expression (4)
[20]		$(0.92 - 5.4) \cdot 10^5$		42, non-thermal velocities, the authors are called the amplitude of the wave, which is incorrect; FeX190, FeX193, B=7, coronal hole; n=6·$10^7 - 9 \cdot 10^6$
[21]		$9 \cdot 10^4 - 4.3 \cdot 10^5$		26, non-thermal velocities. It is multiplied by 2 to take into account 2 polarizations of the Alfen wave, which is incorrect. B = 1-5, lines MgX 625, Mg X 609, n=5·10^8, calm corona
[25]			$(0.1 - 2.6) \cdot 10^5$	ν_{ph}=1600 1-5% intensity ne=10^8, accelerated magneto-acoustic waves
[26]	313			ν=? - amplitude oscillation, FeIX 171. ν_{ph}=150, ν_e=3·10^8, active region. Should use the expression (4)
[27]		$10^5 - 2 \cdot 10^5$		20-25-wave amplitude, ν_A=200-250c calm and active corona FeIX171, HeII304, n=(3-6) 10^8. Should use the expression (4)

[28]	$5.5 \cdot 10^3$			ν=33 - most probable velocity,ν_A=1000, SiXIII1445, $n_e = 6{\cdot}10^6$, coronal hole. Should use the expression (5)
[32]			$1.9 \cdot 10^3$	dI/I=1.15. ν_{ph}=300, n=$5 \cdot 10^8$, calm corona. Line is unkonwn
[23]		$2 \cdot 10^7$		0.027 Doppler shifts amplitude, ν_{ph}=5.4, photosphere, FeI 6301,5 n= $3{\cdot}10^{18}$. Should use the expression (4)
[33]		$10 - 100$		0.3, shift amplitude, $\nu_A = 549$ calm region, FeXIII 10747 FeXIII 10798; n=10^8-10^9 Should use the expression (4)
[34]		10		0.3, velocity amplitude, ν_A=2000 FeXIII 10745, calm.reg n=10^8. Should use the expression (4)
[35]	$6.4 \cdot 10^4$			4.3, velocity amplitude ν_{ph}=173, active region. FeXII 195, n= 2 10^9. Should use the expression (4)
[30]	$2 \cdot 10^3$			7,5 velocity amplitude ν_{ph}=150, coronal hole FeIX171, n=8 10^8. Should use the expression (4)
[36]		$4 - 1.5 \cdot 10^{11}$		3-60, non-thermal velocities on the Doppler widths of coronal lines, ν_{ph} = 5-104, magneto-acoustic and Alfven waves.

depends on the parameters ρ, ν_{ph}, ν and dI/I.

As can be seen from the table, in the calculation of F for coronal conditions, in the overwhelming majority of cases, n is in the range of $10^8 - 10^9 sm^{-3}$. Values of Alfven velocities are in the range about 200-6000 km/s (in some cases, the velocities have calculated by us according to values of B and n, obtained by authors).

The values of the phase velocities of the slowmagneto-acoustic waves are in the range about 75-300 km s^{-1}; in the overwhelming majority of cases, the phase velocity of these waves is 150 km s^{-1}. Changes in the intensities of these waves are (1-5). Let us see how the values of obtained parameters affecting on values of the energy flux density.

It can be said that due to difference in density of mass n, the values of F of slowmagneto-acoustic waves, can differ on order of magnitude, and because of difference in phase velocities, the values of F can differ most maximum 1.5 times; when determining the value of F over variation in the intensity of spectral lines dI/I (note that such definitions are very few) values of F can differ by several times.

Regarding Alfven waves, the phase velocity ν_{ph} depends both on the density and on the value of the magnetic field; thus, the combined effect of these two parameters can change F at most 20 times. Let us figure it out with the impact of ν on the value of F.

It should be said that authors often use the expression F, that does not correspond to the value of ν obtained from observations, but another. Let us explain aforementioned by example of two works [33, 34]; authors obtained from observations value of motion amplitude; when calculating value of F, expression (4) should be used, where the amplitude of value appears, but the authors used expression (5) in which the most probable value of velocity ξ, appears, which have located over the Doppler line width.

As a result, the authors obtained a value of F, four times greater than the true value. Such cases in the notes of the attached table have marked with the expression "should be used".

As can be seen in most cases, the authors used the expression F inappropriate to observational data. When calculating F for Alfven wave, some authors multiply the value of ν^2 by 2, explaining this by taking into account two degrees of polarization or two degrees of freedom of the wave (see, example, [18], [21]).

Surely, this is incorrect, since, independently of the number of degrees of freedom and polarization, the magnitude of shift velocity appears in the expression F.

On the magnitude of displacement is affecting slope of the direction of fluctuation of motion on a wave, as the slope of the magnetic field to the direction of the line of sight. It is impossible to obtain in observations, because of what; the calculated value of F can be far from the true one. In our opinion, when determining the value of ν from the Doppler width, for the case of slowmagneto-acoustic waves, but the slope of the magnetic field to the line of sight, both of interval of wave phase covered by the exposure time and the location of this interval on wave phase is significant: depending on magnitudes and locations on the phase of the interval, the values of non-thermal velocities expanding the spectrum line, would vary greatly, as a result of the values of F would vary significantly. The correct value of F will give only the root-mean-square value of the velocities, obtained from the full period of the wave, and the wave should be observed under its propagation. Unfortunately, there are no cases of such observations in the literature.

In our opinion, significant variations in estimates of the energy flux density of Alfven and slowmagneto-acoustic waves, analyzed as mechanisms of heating the solar corona, are in the effects, which indicated above. Our gratitude to N. Abdullaeva for technical support.

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