Eur. Phys. J. D 44, 533–536 (2007)
DOI: 10.1140/epjd/e2007-00222-6

THE EUROPEAN PHYSICAL JOURNAL D

On the origin of solar wind. Alfvén waves induced jump of coronal temperature

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Received 1st February 2007 / Received in final form 13 April 2007
Published online 29 June 2007 –

Abstract. Absorption of Alfvén waves is considered to be the main mechanism of heating in the solar corona. It is concluded that the sharp increase of the plasma temperature by two orders of magnitude is related to a self-induced opacity with respect to Alfvén waves. The maximal frequency for propagation of Alfvén waves is determined by the strongly temperature dependent kinematic viscosity. In such a way the temperature jump is due to absorption of high frequency Alfvén waves in a narrow layer above the solar surface. It is calculated the power per unit area dissipated in this layer due to damping of Alfvén waves that blows up the plasma and gives birth to the solar wind. A model short wave-length (WKB) evaluation takes into account the $1/f^2$ frequency dependence of the transversal magnetic field and velocity spectral densities. Such spectral densities agree with old magnetometric data taken by Voyager 1 and recent theoretical calculations in the framework of Langevin-Burgers MHD. The presented theory predicts existence of intensive high frequency MHD Alfvén waves in the cold layer beneath the corona. It is briefly discussed how this statement can be checked experimentally. It is demonstrated that the magnitude of the Alfvén waves generating random noise and the solar wind velocity can be expressed only in terms of satellite experimental data. It is advocated that investigation of properties of the solar surface as a random driver by optical methods is an important task for future solar physics.

PACS. 52.35.Bj Magnetohydrodynamic waves (e.g., Alfven waves) – 52.50.Sw Plasma heating by microwaves; ECR, LH, collisional heating – 96.60.P- Corona – 94.30.cq MHD waves, plasma waves, and instabilities

1 Introduction

The coronal heating mechanism [1,2] is one of the most perplexing longstanding unresolved problems of contemporary physics [3]. This is the reason why even some condensed matter theorists are involved in the revealing of this mystery. The lack of experimental data makes distinguishing between the various theoretical models difficult. In such a situation it is possible to apply purely esthetic criteria for a natural description of some well-known facts. One such fact is that the increase of plasma temperature in the transition region by two orders of magnitude [4] occurs very rapidly — there is a smeared jump, which serves as a starting point for creation of the solar wind. We wish to emphasize that complete magneto-hydrodynamic (MHD) simulations of Alfvén waves generated by a random driver also give a sudden increase of the temperature as a function of height [5]. The purpose of the current work is to give a qualitative explanation of the observed temperature jump and to perform a model evaluation of its order of magnitude. Finally, we will analyze some possible future experimental observations described by the presented theoretical scenario. For example, the model predicts existence of intensive high frequency Alfvén waves beneath the coronal temperature jump.

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2 Scenario

In order to make a proper assessment for the magnetic field spectrum comparable with magnetometric data taken by Voyager 1 [6] we need to switch to a frequency-dependent regime and perform a time averaging of the Fourier transformed wave component $\mathbf{B}(t) \approx B_x\hat{x} + B_y\hat{y}$ perpendicular to the constant magnetic field $\mathbf{B}_0 = B_{0,z}\hat{z}$ along which the z-axis is chosen

$$\mathbf{B}(t) = \sum_{\omega_n} \exp(-i\omega_n t)\mathbf{B}_{\omega_n}, \quad \omega_n = \frac{2\pi}{\Delta t}n, \tag{1}$$

$$\mathbf{B}_{\omega_n} = \frac{1}{\Delta t}\int_0^{\Delta t} \exp(i\omega_n t)\mathbf{B}(t)\,\mathrm{d}t, \quad n = 0, \pm1, \pm2, \ldots$$

As our purpose is to present a model evaluation, from now on we will consider only one of the fluctuating wave components, so the plane magnetic field indices will be omitted. Fourier analysis of the signal accumulated for a time interval $\varDelta t$ gives us the opportunity to observe the magnetic field spectral density $\varPhi(t)$, which is tightly bound to the time averaged square of the wave magnetic component

$$\langle B^2(t)\rangle = \frac{1}{\varDelta t}\int_0^{\varDelta t} B^2(t)\,\mathrm{d}t = \sum_{\omega_n} |B_{\omega_n}|^2 = \int \varPhi(f)\,\mathrm{d}f. \quad (2)$$

The thus-defined spectral density

$$\varPhi(f) = \frac{1}{f_2 - f_1}\sum_{\omega_n} |B_{\omega_n}|^2, \quad \omega_n \in (\omega_1, \omega_2),$$
$$f = \omega/2\pi, \quad (f_2 - f_1)\varDelta t \gg 1 \quad (3)$$

determines the magnetic field energy density w and the Alfvén waves energy flux S as a function of the circular ω or linear frequency f

$$w = \frac{B^2(t)}{2\mu_0}, \quad S = \frac{V_{\mathrm{A}}}{2\mu_0}\int \varPhi(f)\,\mathrm{d}f. \quad (4)$$

In interplanetary space the spectral density $\varPhi$ is measured in typical units $\mathrm{nT}^2/\mathrm{Hz}$. Alfvén waves energy density depends on the integrated spectral density and the Alfvén speed V_{A}. In general the integration should be taken over all possible wave frequencies $f \in (0, \infty)$ unless the given specific power spectrum imposes an introduction of a low or high frequency cut-off. In the suggested model we use the natural cut-off frequency set by the condition for waves existence $\omega_{\mathrm{A}}\tau_{\mathrm{A}} = 1$, when the Alfvén waves frequency ω_{A} exactly equals the attenuation coefficient ${\tau_{\mathrm{A}}}^{-1}$. Therefore in the investigation that follows we exclude the influence of any extremely high-frequency Alfvén waves that would be absorbed by the medium immediately after their generation under the solar surface. Hence for heating in the corona we only take into account those waves, whose characteristic life time exceeds the inverse value of the cut-off frequency ω_c

$$\omega_{\mathrm{A}}\tau_{\mathrm{A}} > 1, \quad \omega_{\mathrm{A}} = V_{\mathrm{A}}k_z, \quad 1/\tau_{\mathrm{A}} = \nu k^2,$$
$$\rho V_{\mathrm{A}}^2 = B_{0,z}^2/\mu_0, \quad \omega_c = 2\pi f_c = V_{\mathrm{A}}^2/\nu. \quad (5)$$

Molecular kinetic theory [7] determines the temperature-dependence of the cut-off frequency, being a function of the kinematic viscosity ν. A more detailed analysis shows that the sum of kinematic and magnetic viscosity is relevant in the damping of the Alfvén waves [8,9], but the magnetic viscosity is much smaller and negligible for sufficiently high plasma temperatures. This is because the kinematic viscosity is $\propto T^{5/2}$ while the resistivity is $\propto T^{-3/2}$. For more detailed discussion see, for example, the work by Erdélyi and Goosens [10] and reference [11]. For low density coronal plasmas, electromagnetic emission and thermal conduction are negligible for the energy balance close to the temperature jump. In our model we neglect the difference between the electron and ion temperatures which are of the same order $T_e \approx T_p$. However we wish to emphasize that heating is due to ion viscosity and our consideration gives a natural explanation why the proton temperature is higher than that of the electrons $T_p > T_e$. It is because viscous friction heats the ions. Since we pursue just a qualitative estimation, with a logarithmic accuracy in the final results for the solar wind velocity presented below, we can neglect the slight temperature variations in the protons' Coulomb logarithm L_p as well as the influence of the electron temperature dependence on the Debye radius a. Precise calculations including such a dependence would only lead to minor corrections that would not change the order of magnitude of the final outcome

$$\nu = c_\nu T_p^{5/2}, \quad c_\nu = \frac{0.4}{M^{1/2}e^4 n_p L_p}, \quad L_p = \ln\frac{T_p a}{e^2} \gg 1,$$
$$\frac{1}{a^2} = 4\pi e^2\left(\frac{n_e}{T_e} + \frac{n_p}{T_p}\right), \quad e^2 \equiv \frac{q_e^2}{4\pi\varepsilon_0}. \quad (6)$$

According to valuable analysis on the experimental data obtained by the Voyager 1 magnetometer [6], the magnetic field spectral density can be approximated by a single power law. Here we have taken into account that both magnetic and energy fluxes are almost constant along the magnetic field lines. In such a way the spectral parameter $\mathcal{D}$ on the solar surface can be evaluated by order of magnitude if we know the satellite spectral parameter $\mathcal{D}^{(\mathrm{sat})}$ and the ratio of the constant components of the magnetic field

$$\varPhi(f) \approx \frac{\mathcal{D}}{f^2}, \quad \mathcal{D} \simeq \frac{B_{0,z}}{B_{0,z}^{(\mathrm{sat})}}\mathcal{D}^{(\mathrm{sat})}. \quad (7)$$

The observed power law for the energy density $\propto 1/f^2$ is theoretically explained in the framework of Langevin-Burgers MHD model [12]. The 1D calculations for the time and noise averaged spectral density of Alfvén waves generated by a white noise random driver for the external force density, modeling the influence of the convective stochasticity

$$\langle F(t_1, z_1)F(t_2, z_2)\rangle = \tilde{\varGamma}\rho^2\delta(t_1 - t_2)\delta(z_1 - z_2) \quad (8)$$

reveal the same inverse proportionality to the second power of the Alfvén frequency

$$\overline{E}_f = \frac{\pi^2\rho V_{\mathrm{A}}^2\tilde{\varGamma}}{2\nu f^2 L}. \quad (9)$$

Comparison of the energy flux theoretically derived on the basis of the Langevin-Burgers approach applied for modeling the role of the turbulence for generation of Alfvén waves with the experimentally observed energy flux can give us a reliable assessment for the Burgers parameter $\tilde{\varGamma}$

$$S = L\int V_{\mathrm{A}}\overline{E}_f\,\mathrm{d}f = \int \frac{\pi^2\rho V_{\mathrm{A}}^2\tilde{\varGamma}}{2\nu f^2}\,\mathrm{d}f = \int \frac{V_{\mathrm{A}}\mathcal{D}}{2\mu_0 f^2}\,\mathrm{d}f. \quad (10)$$

Thus, if we consider Burgers approach as adequate for a turbulence model description, we can extract information for the turbulence spectrum in the photosphere, at the footpoints of the magnetic field lines

$$\tilde{\Gamma} = \mathcal{D}\nu/\pi^2\mu_0\rho V_{\mathrm{A}}. \qquad (11)$$

According to a recently proposed scenario [12,13] in the spirit of earlier ideas for wave heating [15,16] Alfvén waves serve as mediators, carriers of energy from the turbulent photosphere to the hot solar atmosphere, where in a small region the high-frequency waves attenuate intensively and heat the corona. Reference [12] treats the emission, while reference [13] considers the bulk absorption of Alfvén waves. In this work we present an evaluation for the absorbed in the transition zone energy flux, whose strong temperature dependence is determined by the temperature dependence of the cut-off frequency f_c and naturally results in a sharp temperature jump [13]

$$f_c = \frac{V_{\mathrm{A}}^2}{2\pi c_\nu T^{5/2}}. \qquad (12)$$

The absorbed energy flux is taken from Voyager 1 magnetometric data analysis, but it may also be obtained by a thermodynamical approach. If the comparatively small effects associated with radiative losses and compression are neglected, the absorption rate will be related only to the plasma internal energy density ε and the conducted work

$$S_{\mathrm{Abs}} = V_{\mathrm{A}} \int_{f_c}^{\infty} \frac{\mathcal{D}}{2\mu_0 f^2}\,\mathrm{d}f = \frac{V_{\mathrm{A}}\mathcal{D}}{2\mu_0 f_c} = \frac{\pi c_\nu \mathcal{D}}{\mu_0 V_{\mathrm{A}}} T_p^{5/2} \approx \varepsilon v + p v,$$
$$\varepsilon = \frac{3}{2}p, \quad p = n_e T_e + n_p T_p, \qquad (13)$$

where p and v are respectively the plasma pressure and velocity. In such a way we can derive the approximate rate for the velocity of the solar wind, driven by sharp coronal temperature increase due to absorption of intensive high frequency Alfvén waves, for which the transition region plasma is opaque

$$v_{\mathrm{wind}} \simeq \frac{0.08\,\pi \mathcal{D} T_p^{3/2}}{\mu_0 V_{\mathrm{A}} M^{1/2} e^4 n_p^2 L_p}, \quad T_p \sim T_e. \qquad (14)$$

As the shear viscous friction heats the heavy particles [10,14], the proton temperature T_p is significantly higher than that of the electrons T_e, however, for an order of magnitude evaluation here we suppose the electron temperature T_e to be similar to that of the protons T_p.

3 Discussion and conclusions

With a logarithmic accuracy we have derived an explicit formula for the initial velocity of the solar wind. This formula equation (14) is completely based on experimentally accessible parameters and can be easily rejected if it gives more than 3 orders of magnitude difference. But, if this model remains valid, let us briefly discuss what has to be done as a future perspective in order to finally solve the perplexing longstanding mystery for the origin of coronal heating and solar wind. First of all, numerical simulations on MHD with a white noise random driver [5] (Langevin-Burgers MHD) have to be repeated to reproduce a δ-like maximum of the energy dissipation density at the transition region. In other words all theoretical models qualitatively explaining the Voyager 1 data for the frequency dependent spectral density of the magnetic field have to be compared with random driver computer simulations of coronal heating. Confirmation of a narrow maximum of volume heating power due to self-induced plasma opacity is a routine task for further numerical investigations. The numerical analysis could improve the present analytical evaluation incorporating, for example, the reflection of Alfvén waves by the jump in plasma density.

Here we wish to insert a short historical remark. Stochastic mechanics in general was introduced by Langevin [17] in 1905 to explain the Brownian motion. Later, Burgers [18] in 1948 introduced the white noise random driver in the hydrodynamics of turbulence. Much later, in 1995, Polyakov [19] derived Kolmogorov power laws [20] using Langevin-Burgers approach, but his research remained unobserved in astrophysics, not to speak about heliophysics. That is why using random number generator in MHD simulations is simply called *random driver*, but the magnitude of the noise is almost never evaluated by comparison to real experimental data.

In the recent work we have only evaluated the area under the sharp maximum of dissipation and now it is time to perform state of the art calculations with a realistic random force, whose spectral density corresponds to the data taken by the satellites' magnetometers. For example, the turbulence spectrum can be treated with the based on the Langevin-Burgers model assessment equation (11). We propose that the physical mechanism for the origin of solar wind and coronal heating is already revealed and it is only a matter of honest numerical work to create a coherent picture. The results for the temperature jump and dissipation maximum have to be compared with the observations and other theoretical scenarios such as magnetic reconnections [21], for example. Each model unable to reproduce a sharp temperature increase in height has to be assigned to the waste basket. The same can be said for the models based on Ohmic heating which predict an electron temperature higher than that of the protons. Though the latter statement seems to be true for the X-ray bright points, it is definitely not valid for the corona as a whole. We are unaware, for example, how magnetic reconnection theory can explain why the proton temperature is higher than that of the electrons $T_p > T_e$. Analogously we have not found any reference explaining how turbulent cascade can lead to a very sharp increase of the coronal temperature.

Second, in order to evaluate the properties of the solar surface as a random driver, all the old data from Voyager 1 has to be meticulously analyzed and a detailed investigation by the forthcoming Solar Orbiter mission has to be planned.

Third, the Sun is a unique system for investigation of convective turbulence. It will be very interesting to compare the satellites' data for the magnetic field spectral density with results based on theoretical modeling of turbulence. The maturity of solar physics can stimulate significant development of the achievements in contemporary turbulence research. For instance, the $1/f^2$ power law by Burlaga and Mish [6] corresponds to one-dimensional $(k_x, k_y = 0)$ propagation of Alfvén waves in the framework of Langevin MHD [12], as the whole noise is created by the random motion of the funnel foot-points.

Next, absorption of Alfvén waves could be an important mechanism in many cases of space plasmas including accretion disks as well. In accretion disks the amplification of MHD waves by shear flow is the main mechanism of transformation of gravitational energy into heat; for references see the preprint [22]. The magnetized wind from an accretion disk should follow the magnetic force lines and plasma concentrated above the disk center will create an accumulative jet perpendicular to the disk. In such a way disk jets could be recognized as a wind coming from magnetized turbulent plasma.

Lastly, now we operate with a realistic 3D model for the distribution of the magnetic field from the solar surface to the satellite. The perturbation of magnetic field lines serves as a string of a harp to deliver the information about the solar turbulence from the photosphere to the magnetometer. Owing to the propagation of Alfvén waves we can "listen" to the sounds of the great solar symphony. Due to absorption of the high frequency modes, however, at the transition region where the temperature jump occurs we are able to hear only the basses, whereas for the ultra-violin band we remain absolutely deaf. A current problem which deserves to be put on the agenda is to observe the powerful high frequency Alfvén modes *under* the corona [23]. A kamikaze satellite could give some very important information, but for systematic research we need to learn how to extract the behavior of the solar surface as a random driver using optical data. We conclude that the first important step in this direction is to establish correspondence between satellite magnetometric data and Doppler shift spectra for some bright events on the solar surface. Only after a proper incorporation of these ingredients we can conclude that our understanding of heating mechanism of the solar corona is complete and we have disclosed a very important case of heating of space plasmas.

Support and fruitful discussions with D. Damianov, A. Rogava, T. Zakarashvili, and R. Erdélyi are highly appreciated.

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