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Invited Comment

Solar coronal electron heating by short-wavelength dispersive shear Alfvén waves

R Bingham[1,2], P K Shukla[3,5], B Eliasson[2] and A Cairns[4]

[1] STFC, Rutherford-Appleton Laboratory, Chilton Didcot 0X11 OQX, UK
[2] SUPA, Department of Physics, University of Strathclyde, Glasgow G4 ONG, Scotland, UK
[3] Institute for Theoretical Physics, Faculty of Physics and Astronomy, Ruhr University Bochum, D-44780 Bochum, Germany
[4] School of Mathematics and Statistics, University of St. Andrews, St. Andrews, Fife, KY16 9SS, UK

E-mail: bob.bingham@stfc.ac.uk, bengt.eliasson@strath.ac.uk and rac@st-andrews.ac.uk

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Abstract

The electron heating of the solar coronal plasma has remained one of the most important problems in solar physics. An explanation of the electron heating rests on the identification of the energy source and appropriate physical mechanisms via which the energy can be channelled to the electrons. Our objective here is to present an estimate for the electron heating rate in the presence of finite amplitude short-wavelength (in comparison with the ion gyroradius) dispersive shear Alfvén (SWDSA) waves that propagate obliquely to the ambient magnetic field direction in the solar corona. Specifically, it is demonstrated that SWDSA waves can significantly contribute to the solar coronal electron heating via collisionless heating involving SWDSA wave-electron interactions.

1. Introduction

A challenging problem in solar physics is to identify appropriate mechanisms responsible for heating charged particles in the solar coronal plasma [1, 2]. Here one requires an input of non-thermal energy to sustain the solar coronal electron temperature at multi-million degrees Kelvin, i.e. much higher than the photosphere temperature of about 10^4 K. The coronal plasma is tenuous, hot, and collisionless, contrary to the photospheric plasma which is dense, comparatively cool, and collisional. The temperature continues to rise slowly throughout the chromosphere, followed in the transition region by a steep rise to around 1.5–5 million degrees Kelvin

[5] Deceased.

in the corona. The energy content of the coronal plasma is approximately 1.6 J m^{-3} with an x-ray brightness of 1 W cm^{-2}, which is much smaller than that of the photospheric plasma with an energy content of about 3 kJ m^{-3} and a brightness of 6.4 kW cm^{-3}, which radiates at a temperature of about 6000 K. Detailed measurements of the x-ray emitting corona by past and present satellite missions, such as Skylab [3], SMM [4] and SOHO [5, 6], have significantly contributed to our knowledge of the solar corona, which can be seen only during solar eclipses, when the main radiation from the Sun's surface is blocked by the passage of the Moon, or with special instruments. From the soft x-ray observations, the solar corona is seen as a highly filamentary, inhomogeneous structure consisting of a complex myriad of magnetic loop-like structures. With the hottest plasmas found in regions of high magnetic field activity, which also contain the largest magnetic fields, thousands of x-ray bright points or blinkers [7] are also seen bubbling on the surface and are associated with cancelation of opposing magnetic fluxes. In closed magnetic field structures, for example, the temperatures in active

regions may reach up to ten million degrees Kelvin, while in open magnetic field regions such as coronal holes, the temperatures are about 1–2 million degrees Kelvin. The forthcoming Solar Orbiter [8] will study fundamental physical processes in the Sun's heliosphere, including what drives the solar wind and the origin of the coronal magnetic field, the production of energetic particles by solar eruptions, and the solar dynamo.

A number of mechanisms for heating electrons in the solar coronal and solar wind plasmas has been proposed [9–23], involving acoustic, Alfvén and cyclotron wave heating, as well as those associated with microstructures and nanoflares. In deciding which particular model is relevant for explaining observations, it is important to understand the plasma conditions where the heating processes are taking place, as well as to identify the free energy sources available for the plasma heating, how the energy is transported into the region, and how the transported electromagnetic wave energy is dissipated efficiently [24]. In the highly tenuous solar coronal plasma with temperatures of the order of several millions of Kelvin and densities of the order of $10^{10}\,\mathrm{cm}^{-3}$, the plasma $\beta = 8\pi n_0 k_B (T_e + T_i)/B_0^2$ ranges between 0.1–0.01, where n_0 is the equilibrium plasma number density, k_B is Boltzmann's constant, T_e (T_i) is the electron (ion) temperature, and B_0 is the magnitude of the ambient magnetic field. Hence, the wave magnetic field pressure dominates in this region and there is a strong indication that the heating is correlated with intense magnetic field activities (e.g. associated with the Alfvénic waves) in the filamentary structures. This is supported by the inhomogeneities in the temperature and magnetic field structures; the strength of the magnetic field also correlates well with the coronal temperatures [23] in other stars [25]. Alfvén waves can be excited in the solar corona and solar wind by charged particle beams and ion temperature anisotropy [26]. Given the high temperature and low density, the solar coronal plasma is collisionless and lends support to kinetic wave heating processes.

In this paper, we discuss the possibility of heating electrons by short-wavelength, in comparison with the ion thermal gyroradius $\rho_i = V_{Ti}/\omega_{ci}$, dispersive shear Alfvén (SWDSA) waves, that are supposed to pre-exist in the solar corona. Here, $V_{Ti} = (k_B T_i/m_i)^{1/2}$ is the ion thermal speed, $\omega_{ci} = eB_0/m_i c$ is the ion gyrofrequency, e the magnitude of the electron charge, m_i the ion mass, and c is the speed of light in vacuum. Nonthermal SWDSA waves with sheared wave magnetic field and finite density fluctuations could be excited by free energy sources contained in electron and proton beams, as well as in magnetic shear. The present investigation is thus complimentary to our previous model [13, 19, 27], which focused on the electron heating in the solar corona by long-wavelength (in comparison with ρ_i) dispersive shear Alfvén waves whose parallel wavelength is of the order of the ion-skin-depth $\lambda_i = c/\omega_{pi}$, where $\omega_{pi} = (4\pi n_0 e^2/m_i)^{1/2}$ is the ion plasma frequency.

The manuscript is organized in the following fashion. In section 2, we discuss the properties of the SWDSA waves and the associated parallel electron current which they carry due to the parallel wave electric field. The electron current is then dissipated on account of the SWDSA wave-electron interactions in the collisionless magnetoplasma of the solar corona. The rise of the electron temperature in the presence of a given electric field spectrum of the SWDSA waves is estimated for the plasma parameters that are representative of the solar corona. Our results are summarized in section 3, where we also highlight the potential of our theoretical model involving resonant interactions between Alfvén waves and electrons.

2. Solar coronal electron heating by finite amplitude short-wavelength dispersive shear Alfvén waves (SWDSA)

We consider the propagation of finite amplitude SWDSA waves in the solar coronal plasma composed of electrons and protons. The SWDSA wave is a mixed mode with a magnetic field-aligned electric field component, and consequently there are density perturbations associated with these waves, which also accompany sheared magnetic fields. To obtain the ion density perturbation n_{i1} as a function of the scalar potential ϕ of the SWDSA wave from kinetic theory in a collisionless plasma, we neglect the ion motion along the ambient magnetic field, as the parallel phase speed of the SWDSA waves is assumed to be much larger than the ion thermal and ion-sound speeds. This gives [28]

$$n_{i1} = -\frac{n_0 e\phi}{k_B T_i}\left[1 - \Gamma_0(b_i) - \frac{2\omega^2 \Gamma_1(b_i)}{\omega^2 - \omega_{ci}^2}\right], \qquad (1)$$

where $\Gamma_n = I_n \exp(-b_i)$, I_n is the modified Bessel function of order n, $b_i = k_\perp^2 \rho_i^2$, $k_\perp$ is the component of the wavevector $\mathbf{k}$ across the ambient magnetic field $\hat{\mathbf{z}}B_0$. The unit vector along the z-axis in a Cartesian coordinate-system is denoted by $\hat{\mathbf{z}}$.

The electron density perturbation n_{e1} is obtained by combining the linearized electron continuity equation with the inertialess electron momentum equation, supplemented by the parallel component of Ampère's law $v_{ez} = -(c/4\pi n_0 e)k_\perp^2 A_z$ and $E_z = -\partial\phi/\partial z - c^{-1}\partial A_z/\partial t$, where v_{ez} is the parallel component of the electron fluid velocity, E_z is the SWDSA wave electric field, and A_z is the parallel component of the vector potential. Furthermore, in view of the low-β approximation, we neglect the compressional magnetic field perturbation associated with the SWDSA waves. For $\omega \ll k_z V_{Te}$, where $V_{Te} = (k_B T_e/m_e)^{1/2}$ is the electron thermal speed, k_z is the wavevector component along the ambient magnetic field, and m_e the electron mass, the electron density perturbation is then obtained as

$$n_{e1} = \frac{n_0 e\phi}{k_B T_e}\frac{k_z^2 c^2 k_\perp^2 \lambda_{De}^2}{\left(k_z^2 c^2 k_\perp^2 \lambda_{De}^2 - \omega^2\right)}, \qquad (2)$$

where the wave frequency ω is much smaller than the electron gyrofrequency $\omega_{ce} = eB_0/m_e c$. Here, $\lambda_{De} = V_{Te}/\omega_{pe}$ is the electron Debye radius and $\omega_{pe} = (4\pi n_0 e^2/m_e)^{1/2}$ is the electron plasma frequency.

The dispersion relation for SWDSA waves is obtained by inserting the expressions for the ion and electron density

fluctuations into Poisson's equation

$$k^2\phi = 4\pi e(n_{i1} - n_{e1}),\tag{3}$$

which gives

$$\left(\omega^2 - k_z^2 c^2 k_\perp^2 \lambda_{De}^2\right)\left(1 + k^2\lambda_{Di}^2 - \Gamma_0 - \frac{2\omega^2\Gamma_1}{\omega^2 - \omega_{ci}^2}\right)$$
$$- k_z^2 c^2 k_\perp^2 \lambda_{Di}^2 = 0,\tag{4}$$

where $\lambda_{Di} = (k_B T_i / 4\pi n_0 e^2)^{1/2}$ is the ion Debye radius. In the short-wavelength limit, viz $b_i \gg 1$, Γ_0 and Γ_1 vanish, and we have from equation (4)

$$\omega = k_z c k_\perp \left(\lambda_{De}^2 + \frac{\lambda_{Di}^2}{1 + k^2\lambda_{Di}^2}\right)^{1/2}.\tag{5}$$

In the following, we derive the parallel electron current density associated with the SWDSA waves, and discuss the associated electron heating rate arising from the dissipation of the electron current due to wave–particle interactions. By using the linearized drift kinetic equation [29] for the perturbed electron distribution function, we obtain an expression for the parallel component of the electron current density j_{ez} in a Maxwellian plasma. The result is [30]

$$j_{ez} = \mathrm{i}\frac{\omega E_z}{8\pi k_z^2 \lambda_{De}^2} Z'(\xi_e),\tag{6}$$

where Z' is the derivative of the standard plasma dispersion function [31] with the argument $\xi_e = \omega/\sqrt{2}\,k_z V_{Te}$. For $\xi_e \ll 1$ equation (6) yields

$$j_{ez} = -\frac{\mathrm{i}\omega E_z}{4\pi k_z^2 \lambda_{De}^2}\left[1 + \mathrm{i}\sqrt{\pi}\,\xi_e \exp\left(-\xi_e^2\right)\right],\tag{7}$$

which contains a reactive part.

The electron heating rate in the collisionless regime is governed by the dissipation of the magnetic field-aligned electron current, viz [13]

$$k_B \frac{\mathrm{d}T_e}{\mathrm{d}t} = \frac{1}{2n_0} Re\left(J_{ez}E_z^*\right)$$
$$= \frac{k_\perp^2 c^2}{8\sqrt{2\pi}\,k_z V_{Te}}\left(1 + \frac{T_i/T_e}{1 + k^2\lambda_{Di}^2}\right)\frac{|E_z|^2}{n_0},\tag{8}$$

where the asterisk denotes the complex conjugate. Equation (8) demonstrates that electrons are rapidly heated due to the dissipation of the parallel electron current associated with localized SWDSA waves. The localization of the latter could be caused by the self-modulation [19, 27, 32] of SWDSA wave packets by quasi-stationary density fluctuations in the solar coronal magnetoplasma. On the other hand, the localization of nonlinear short wavelength drift-Alfvén waves in the form of two-dimensional vortices has been described using a nonlinear model involving kinetic ions and fluid electrons [33, 34] in an inhomogeneous magnetoplasma, with applications to the magnetopause of the Earth's magnetosphere and to magnetically confined plasma. The effects of ion trapping in electron acoustic vortices [35, 36] also provides an alternative localization mechanism

which in good agreement with cavities observed in the auroral region.

We now apply the results of our theoretical model to the electron heating in the solar corona, where typical parameter values are $n_0 = 5 \times 10^9\,\mathrm{cm}^{-3}$, $T_e = 0.6 \times 10^6\,\mathrm{K}$, $B_0 = 10\,\mathrm{G}$, and $T_i \approx 0.01 T_e$. Thus, we have $\omega_{pe} = 4 \times 10^9\,\mathrm{s}^{-1}$, $\omega_{ci} = 1.8 \times 10^8\,\mathrm{s}^{-1}$, $V_{Te} = 3 \times 10^8\,\mathrm{cm\,s}^{-1}$, $\beta = 0.1$, and $\rho_i \approx 7\,\mathrm{cm}$. Assuming that the perpendicular (parallel) wavelength of the SWDSA waves is 5 (4×10^3) centimeters, we have $k_\perp \rho_i \gg 1$, and for $|E_z| = 10^{-4}\,\mathrm{V\,cm}^{-1}$ it follows from equation (8) the electron temperature will rise by a few million degrees Kelvin per second. This heating rate is large enough to dominate over cooling losses by conduction or radiation.

3. Summary and conclusions

Summing up, we have presented an investigation of the electron heating caused by short-wavelength SWDSA waves that are generated due to nano-flares in the solar corona and in fast solar wind. Specifically, we have shown that electron heating in collisionless solar coronal magnetoplasmas is caused by the SWDSA wave-electron interactions, since the SWDSA waves have parallel electric fields and finite density fluctuations. Thus, the present results are complementary to those reported earlier [13, 19, 27]. Our theoretical model suggests that the powerful Alfvén waves observed in the corona of the Sun [20, 23] play a very important role in heating solar coronal electrons and for producing the high speeds of the solar wind. Furthermore, we stress that besides the Alfvén wave-electron interaction model for heating electrons in the collisionless magnetoplasma of the solar corona, one has also to evaluate the potential of heating electrons by the magnetic field fluctuations associated by superposition of an infinite number of nanoflares that are triggered by magnetic field explosions.

Acknowledgments

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