This is an article published in *Astrophysical Journal*.

Citation for the published paper:

**Kristof Stasiewicz; Jonas Ekeberg**

*Electric potentials and energy fluxes available for particle acceleration by alfvenons in the solar corona*


DOI: 10.1086/589878
ELECTRIC POTENTIALS AND ENERGY FLUXES AVAILABLE FOR PARTICLE ACCELERATION BY ALFVENONS IN THE SOLAR CORONA

K. STASIEWICZ 1,2 AND J. EKEBERG 1

Received 2008 January 15; accepted 2008 May 6; published 2008 May 28

ABSTRACT

We show that solitary wave solutions of the one- and two-fluid MHD equations, here called alfvenons, represent two types of electric field structures with negative or positive potentials that can explain the acceleration of particles in the solar corona. Negative potentials are created self-consistently by fast alfvenons and can reach hundreds of kilovolts, which could accelerate the electrons that produce X-ray emissions during flares. Slow alfvenons create positive potential structures of a few kV that accelerate solar wind ions. These alfvenons can be powered by irregular plasma flows in the photosphere and chromosphere, as well as by time-varying magnetic fields during reconnection events at the tops of coronal loops. Similar alfvenon structures are observed in the terrestrial magnetosphere, where they accelerate particles related to aurorae.

Subject headings: acceleration of particles — MHD — Sun: corona — Sun: flares — Sun: X-rays, gamma rays

1 Swedish Institute of Space Physics, Uppsala and Kiruna, Sweden; k.stasiewicz@irfu.se, jonas.ekeberg@irfu.se.

2 Space Research Centre, Polish Academy of Sciences, Warsaw, Poland.

1. INTRODUCTION

The generation of solar wind with protons streaming at 300–800 km s⁻¹, after acquiring first the gravitational escape speed of 600 km s⁻¹, implies the presence of positive acceleration potentials of 2–5 kV in the corona. Scattering a fraction (∼0.5 keV) of the ion kinetic energy would produce particles with high coronal temperatures: ∼5 MK. The active Sun emits X-rays corresponding to electron energies of tens of hundreds of keV, which requires the presence of accelerating potentials of hundreds of kV in active regions. Furthermore, the energy spectrum of particles accelerated in the solar corona extends to tens of MeV (Miller 1998; Aschwanden 2004), suggesting the presence of correspondingly high effective potentials. Thus, the major problem of solar physics consists of finding explanations for the emergence of electric field structures with sufficiently high voltages, capable of accelerating solar wind ions to ∼3 kV and electrons in flares to ∼100 kV. The highly publicized problem of “the heating of the corona” requires only the scattering of a small portion of the beam energy of solar wind ions or of accelerated electrons.

Recently, it has been demonstrated that structures with large electric potentials can be spontaneously created by nonlinear magnetohydrodynamic waves (alfvenons) in the solar corona (Stasiewicz 2006) and in the magnetosphere (Stasiewicz 2007). Although it is well known that one- or two-fluid MHD equations describe various branches of sinusoidal waves (Stringer 1963), it is less known that these equations also describe exponentially varying solutions that form solitons (McKenzie et al. 2004). Concepts of flare energy transport by Alfven waves were invoked by many authors, and recently by Fletcher & Hudson (2008). Large-amplitude nonlinear solitary structures are not theoretical speculations, but phenomena observed by the Cluster and other spacecraft at the bow shock, at the magnetosheath, and in the magnetosphere, which have been quantitatively modeled as solutions of two-fluid, or Hall-MHD, equations for collisionless plasmas (Stasiewicz 2004a, 2004b, 2005).

Three relevant questions arise: (1) What is the role of alfvenons in the generation of solar wind and in the acceleration of particles in flares? (2) What are the electric fluxes that can be transmitted along magnetic field lines by these nonlinear structures. (3) How large are the electric potentials available for acceleration of plasma in the solar corona? Answers to these questions are provided below.

2. ELECTRIC FIELD AND POYNTING FLUX

Consider an MHD wave in the plasma rest frame of reference, with speed ωk in the x-direction at an angle α to the background magnetic field \( B_0 = B_0 \left( \cos \alpha, 0, \sin \alpha \right) \). We assume that plasma parameters vary mainly along x, so that \( \partial \delta B / \partial t \propto \partial \delta \alpha / \partial t \), and transverse gradients can be neglected. Under such an assumption, the electric and magnetic fields are \( E = (\delta E_\alpha, \delta E_\beta, \delta E_\gamma) \) and \( B = (B_\alpha, \delta B, B_\gamma + \delta B) \), where delta quantities represent wave perturbations of arbitrary amplitude. The power available for acceleration of plasma by waves is related to the electromagnetic energy (Poynting) flux, \( S = \mu_0 (E \times B) \). The component of this flux along the \( B_0 \) direction is given by

\[
\mu_0 S_\parallel = (\sin \alpha \delta E_\alpha - \cos \alpha \delta E_\gamma) B_0 + \cos \alpha \delta B \delta E_\gamma, \tag{1}
\]

where \( \delta B \) and \( \delta B \) correspond to Alfvenic and magnetosonic polarizations, respectively. In the case of sinusoidal waves, \( \cos \alpha \exp (ikx - i\omega t) \), the Maxwell’s equation \( \nabla \times E = -\partial B / \partial t \) implies

\[
\delta E_\gamma = (\omega k) \delta B_\gamma, \quad \delta E_\beta = - (\omega k) \delta B_\beta, \tag{2}
\]

while the x-component can be obtained from the generalized Ohm’s law as

\[
\frac{\delta E_\alpha}{V_\beta} \approx M \frac{\delta B_\gamma}{B_0} \tan \alpha - \frac{\beta \lambda}{2n} \frac{\partial}{\partial x} \left( \frac{p_\gamma}{p_\beta} \right). \tag{3}
\]

Here, \( n = N/N_0 \), \( V_\beta = B_\beta (\mu_0 N_0 n_0)^{-1/2} \) is the Alfven speed, \( M = \omega k V_\beta \) is the Alfven Mach number, \( p_\gamma = p_\alpha n^2 \) is the electron pressure, \( \beta, \lambda \) is the ratio of electron and magnetic field pressures, and \( \lambda = V_\beta / V_\alpha \) is the ion inertial length. A small term proportional to \( m_e / m_i \), the electron to ion mass ratio, is neglected in equation (3). It is easily verified that the parallel electric field, \( E \cdot B / B_0 \), contains only the electron pressure term,
consistent with equation (7). The Poynting flux in the plasma frame is then

$$\frac{S_n}{S_p} = M_i \frac{\delta B_n^2}{B_0^2} + M \cos \alpha \frac{\delta B_p^2}{B_0^2} - \sin \alpha \frac{\beta \lambda_i}{2n} \frac{\partial}{\partial x} \left( \frac{p_n}{p_w} \right) \frac{\delta B_n}{B_0},$$  \hspace{1cm} (4)

in units of $S_n = V_e B_0^2 \mu_o$, with $M_i = M \cos \alpha$. Replacing magnetic perturbations by velocity perturbations as implied by the momentum equations, $\delta B_n, B_0^2 \rightarrow M_i \delta V_n, V^2 - 1$, we find an equivalent form

$$\frac{S_1}{N_e m V_n^3} = M_i \left( \delta V_p^2 \frac{\cos \alpha}{V_n^2} + \cos \beta \frac{\delta V_n^2}{V_n^2} \right) - M_i \sin \alpha \frac{\beta \lambda_i}{2n} \frac{\partial}{\partial x} \left( \frac{p_n}{p_w} \right) \frac{\delta V_n}{V_n},$$  \hspace{1cm} (5)

which implies that there are ion flows $\delta V_p, \delta V_n$ that by shaking magnetic field lines $\delta B_p, \delta B_n$ create parallel Poynting flux $S_1$.

For a particular mode, one has to use a suitable Mach number: $M = \cos \alpha$ for Alfvén modes, $M = 1$ for fast magnetosonic waves, $M = (\gamma \beta^2)^{1/2} \cos \alpha$ for slow magnetosonic waves, and $M = (\gamma \beta^2)^{1/2}$ for acoustic waves, with $\beta = \lambda_i + \beta_s$.

### 3. NONLINEAR WAVES AND ACCELERATION

The location of linear and nonlinear waves in the phase space $(M, \alpha)$ is best studied by using a general dispersion equation for two-fluid waves (Stasiewicz 2007),

$$k^2 \lambda_i^2 = \frac{A (M_i^2 - D)}{(m_i/m_n)(2A - M_i^2 D)} - 1,$$  \hspace{1cm} (6)

where $A = M_i^2 - 1$ and $D = \sin^2 \alpha (M^2 - \gamma \beta/2)$. A quadratic term proportional to $(m_i/m_n)^2$ has been neglected. Note that when $\lambda_i = 0$, the factor $A = 0$ describes nondispersive Alfvén waves, and the second factor, $M_i^2 - D = 0$, the slow and fast magnetosonic waves. Equation (6) is applicable to Alfvén, kinetic Alfven (KAW), inertial electron Alfvén (IEAW), magnetosonic, acoustic, lower hybrid (LH), and whistler waves, as visualized in Figure 1. Regions in the parameter space which give positive $k^2 \lambda_i^2 > 0$ correspond to exponentially varying solutions (solitons; colored regions), while $k^2 \lambda_i^2 < 0$ correspond to linear, sinusoidal solutions (white regions). Both types of solutions represent normal modes of the system, which exactly conserve the number flux, the momentum, and the energy flux.

The nonlinear equations listed by Stasiewicz (2005, 2007) are solved numerically in order to find the spatial profiles of $\delta B_p, \delta B_n, \delta E_p, \delta E_n$, which are used to determine the Poynting flux (eq. [1]) and integrated potential $\Phi = -\int \delta E_p, \delta E_n$. Generally, these equilibrium solutions represent solitary, bipolar electric structures with either positive or negative potential. The sign of the potential is determined by the sign of $E_i$ in equation (3), which depends on the sense of polarization of the transverse magnetic field, or sign of $\delta B_p$. Left/right hand polarized structures correspond to slow/fast Alfvénons and produce positive/negative potentials.

The presence of a perpendicular potential implies the creation of a parallel potential difference of the same magnitude, and vice versa. The parallel potential is related to $E_i$ that can be obtained from the generalized Ohm’s law (e.g., Krall & Trivelpiece 1973) as

$$E_i = \eta J_i - \nabla \cdot \left( \frac{p_n p_e - (p_n - p_e)}{N_e} \frac{\nabla B_z}{B} \right) \frac{\nabla B_z}{B} + \frac{m_i}{N_e} \left[ \nabla \cdot (J_e + J_i) + \frac{\partial J_i}{\partial t} \right].$$  \hspace{1cm} (7)

Thus, there are four mechanisms supporting $E_i$ in two-fluid MHD: (1) classical or anomalous resistivity, $\eta$; (2) the electron pressure gradient along the magnetic field; (3) the magnetic mirror force acting on anisotropic electron pressures; and (4) electron inertial effects. The above equation is valid for all wave modes and structures in fluid approach. Yet another mechanism for the parallel electric field can be provided by double layers (e.g., Charles 2007) which are on smaller, Debye length scales and require kinetic description. Phenomenologically, they can be included in equation (7) as a sort of anomalous resistivity.

The electric potential $\Phi$ modifies particles trajectories in the phase space. Conservation of the total energy, $m v_i^2/2 + m v_n^2/2 + e \Phi + m \Phi_o = \text{const}$, where $\Phi_o$ is the gravitational potential, implies that particles entering the structure would change their kinetic energy by an amount corresponding to the difference of the potential energies. In a collisionless plasma the perpendicular velocity is constrained by conservation of the first adiabatic invariant, leading to an increase of $v^2$, lowering of the mirroring altitude of particles to denser regions where they can be subject to collisions. Particles will dissipate kinetic energy by instabilities related to pitch angle anisotropy, through X-ray emissions, heating of the ambient plasma, and ionization of the neutral atmosphere at low altitudes. Heating can be also accomplished by ion Landau damping of slow modes and electron Landau damping of fast modes. The dissipative processes are beyond the formalism of the present stationary model and their description would require a fully kinetic model supported by simulations.
the terrestrial magnetosphere, where earthward accelerated electrons (1–20 keV) producing aurorae are measured together with accelerated ion beams moving in the opposite direction (e.g., McFadden et al. 1999). Fast alfvenons represent a twist of magnetic field lines, where the transverse components $\delta B_x$ and $\delta B_y$ make helical rotations around the guide field. Because the structure propagates obliquely across the magnetic field it has continuous access to flux tubes with nondepleted electrons. Furthermore, some alfvenon solutions contain return field-aligned currents, and they are very thin structures surrounded by ambient plasma. This could provide a mechanism for recycling electrons involved in parallel acceleration, solving possibly the problem of number of electrons needed to maintain long-duration flare activity (Fletcher & Hudson 2008).

5. SLOW ALFVENONS AND THE SOLAR WIND

For the acceleration of the solar wind, much smaller potentials, 2–5 kV, are needed. These potentials should be positive in order to drive ions out from the chromosphere. A natural candidate for such electric structures are the slow alfvenons shown in Figure 2. The slow alfvenons create positive potentials of $10^{-2} \Phi_0$. A combination of $B$, $N$ parameters that give $\Phi_0 \sim 5000$ kV in Table 1 would support electric field structures with a potential corresponding to the typical energy of solar wind ions. The Poynting flux (eq. [5]) driving slow alfvenons is most likely created by irregular plasma flows related to the universal convection granulation observed in the Sun’s photosphere.

A connection between slow mode waves and sources of solar wind has recently been confirmed with Hinode data by Cirtain et al. (2007) and Sakao et al. (2007). The presence of slow-mode structures on coronal loops has also been confirmed experimentally by De Moortel et al. (2000) and Robbrecht et al. (2001). The present model appears to be consistent also with observations (e.g., Woo & Habbal 2005), which indicate that slow wind is initially confined in closed loops at borders between active regions and coronal holes, while the fast wind is cooler, less dense, and emanates directly from coronal holes with steeper radial density gradients. Indeed, Table 1 shows that less dense plasma would support larger potentials, provided the magnetic field strengths are comparable in both cases.

<table>
<thead>
<tr>
<th>$N$ (cm$^{-3}$)</th>
<th>1000 G</th>
<th>100 G</th>
<th>10 G</th>
<th>1 G</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$ ......</td>
<td>5.5E+10</td>
<td>5.5E+9</td>
<td>5.5E+4</td>
<td>...</td>
</tr>
<tr>
<td>$10^5$ ......</td>
<td>1.7E+11</td>
<td>1.7E+10</td>
<td>1.7E+5</td>
<td>1.7E+2</td>
</tr>
<tr>
<td>$10^6$ ......</td>
<td>5.5E+11</td>
<td>5.5E+10</td>
<td>5.5E+5</td>
<td>5.5E+2</td>
</tr>
<tr>
<td>$10^7$ ......</td>
<td>...</td>
<td>1.7E+9</td>
<td>1.7E+6</td>
<td>1.7E+3</td>
</tr>
</tbody>
</table>

TABLE 1

<table>
<thead>
<tr>
<th>$B_0$</th>
<th>$N$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 G</td>
<td>100 G</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>5000</td>
<td>50</td>
</tr>
<tr>
<td>50000</td>
<td>500</td>
</tr>
<tr>
<td>...</td>
<td>5000</td>
</tr>
</tbody>
</table>

TABLE 2

<table>
<thead>
<tr>
<th>$B_0$</th>
<th>$N$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 G</td>
<td>100 G</td>
</tr>
<tr>
<td>5.5E+10</td>
<td>5.5E+9</td>
</tr>
<tr>
<td>1.7E+11</td>
<td>1.7E+10</td>
</tr>
<tr>
<td>5.5E+11</td>
<td>5.5E+10</td>
</tr>
<tr>
<td>...</td>
<td>1.7E+9</td>
</tr>
</tbody>
</table>
6. DISCUSSION

The generic mechanism for parallel Poynting flux generation by magnetic footprint motions described by equation (5) would lead to a gradual buildup of magnetic and thermal energies of the loop until the system becomes unstable and ends up with eruptions such as flares or coronal mass ejections. Alfvénons carry large field-aligned currents, so they would contribute to the magnetic structure of coronal loops. The acceleration of particles by coherent electric field structures represents a one-step process, different from stochastic acceleration (e.g., Petrosian & Liu 2004), which is described by quasi-linear diffusion equation. However, particles trapped on closed loops could have multiple interactions with alfvénons and be accelerated to higher energies. Loop-top regions of hard X-ray emissions identified in Yohkoh data by Masuda et al. (1994) could correspond to such trapped particles accelerated by alfvénons. The scale of alfvénons propagating quasi-perpendicular is typically several ion inertial lengths (Stasiewicz & Ekeberg 2007), a tiny scale in the corona, where $\lambda = 7 \text{ m for } N \sim 10^{11} \text{ cm}^{-3}$. The parallel scale depends on the propagation angle, $L_\parallel = L_i \tan \alpha$, and for $\alpha = 90^\circ$ it corresponds to global field-line oscillations (e.g., Nakariakov 2007). An alfvénon with $L_i \sim 10^9 \text{ cm}$ propagating at $\alpha = 89.94^\circ$ would have length $L_\parallel \sim 100 \text{ km}$, which corresponds to the size of elementary acceleration structures inferred from high time resolution measurements of radio emissions generated by accelerated electron beams (Xie et al. 2000). Observations of drifting frequency patterns are commonly interpreted as related to electron beams produced in the reconnection region (Aschwanden & Benz 1997). However, bidirectional electron beams generating strong Langmuir waves ($\sim 1 \text{ V m}^{-1}$) are associated with alfvénons observed in auroral regions (e.g., Stasiewicz et al. 1997 [see Figs. 11–13]).

X-ray structures in the solar corona are likely caused by similar acceleration processes as auroral arcs, with appropriate scaling of thickness by $\lambda$ and potentials by $\Phi$ (Stasiewicz 2006, 2007). The large-scale auroral structures have thickness $L_\parallel \sim 100 \text{ km}$ and may extend horizontally to thousands of km in the $y$-direction. Because of the scaling properties, $\lambda \propto N^{-1/2}$, the alfvénons in the solar corona at $N \sim 10^4–10^9 \text{ cm}^{-3}$ are expected to be $10^{13}–10^4$ times thinner than the corresponding structures measured in the magnetosphere at $N \sim 10^2–10^9 \text{ cm}^{-3}$. Negative and positive potential structures are observed by many magnetospheric satellites in the auroral regions (e.g., Ergun et al. 1998), including the recent Cluster mission (Marklund et al. 2001).

The transverse horizontal extension of alfvénons (y-direction) can match the driver size of solar convection granulation, and the accelerated plasma will spread along $B$; both dimensions are of many Mm, which should be detectable by optical instruments. Thin threads and arcades of heated plasma seen in images from the TRACE spacecraft and Hinode (Cirtain et al. 2007) are possibly manifestations of remnants of alfvénons described above.

7. CONCLUSIONS

We have shown that the acceleration of the solar wind to the observed potentials 2–5 kV can be accomplished by electric structures of slow alfvénons driven by irregular plasma flows in the photospheric granulation. Slow alfvénons create positive potentials expelled ions into interplanetary space. Transferring some 15% of the ion energy to the electrons by collisions or plasma instabilities, viz., slowing down of the beam ions, could explain heating of the corona to $\sim 5 \text{ MK}$. Acceleration of particles in solar flares and additional electron heating can be attributed to fast alfvénons created by varying magnetic fields in coronal loops. Fast alfvénons are shown to support negative potentials of hundreds of kV, providing an explanation for the energies of X-rays and gamma rays created in the solar corona during flares. Similar structures (with sizes scaled by $\lambda$ and potentials by $\Phi = B/\lambda$) are observed in the terrestrial magnetosphere, which provides a strong argument in favor of their existence also in the solar corona and a motivation for further development of the present model.

J. Ekeberg is financed by the Swedish National Graduate School of Space Technology.

REFERENCES

Aschwanden, M. 2004, Physics of the Solar Corona (Berlin: Springer)
Charles, C. 2007, Plasma Sources Sci. Technol., 16, R1

Sakao, T. et al. 2007, Science, 318, 1585
———. 2007, Plasma Phys. Controlled Fusion, 49, B621