CONNECTION THE SUN AND THE SOLAR WIND: THE FIRST 2.5-DIMENSIONAL SELF-CONSISTENT MHD SIMULATION UNDER THE ALFVÉN WAVE SCENARIO

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ABSTRACT
The solar wind emanates from the hot and tenuous solar corona. Earlier studies using 1.5-dimensional simulations show that Alfvén waves generated in the photosphere play an important role in coronal heating through the process of nonlinear mode conversion. In order to understand the physics of coronal heating and solar wind acceleration together, it is important to consider the regions from photosphere to interplanetary space as a single system. We performed 2.5-dimensional, self-consistent magnetohydrodynamic simulations, covering from the photosphere to the interplanetary space for the first time. We carefully set up the grid points with spherical coordinates to treat the Alfvén waves in the atmosphere with huge density contrast and successfully simulate the solar wind streaming out from the hot solar corona as a result of the surface convective motion. The footpoint motion excites Alfvén waves along an open magnetic flux tube, and these waves traveling upward in the non-uniform medium undergo wave reflection, nonlinear mode conversion from Alfvén mode to slow mode, and turbulent cascade. These processes lead to the dissipation of Alfvén waves and acceleration of the solar wind. It is found that the shock heating by the dissipation of the slow-mode wave plays a fundamental role in the coronal heating process, whereas the turbulent cascade and shock heating drive the solar wind.

Key words: stars: mass-loss – Sun: chromosphere – Sun: corona – Sun: photosphere Online-only material: color figure

1. INTRODUCTION
The coronal heating and solar wind acceleration are fundamental problems in solar physics. Although various physical mechanisms have been proposed for coronal heating, it remains unclear why the hot corona exists above the cool photosphere and the high-speed solar wind emanates from there. The main difficulty arises due to the rapid decrease of the density, amounting to more than 15 orders of magnitude in the interplanetary space compared to the photospheric value. The huge density contrast between the photosphere and interplanetary space has made it difficult to understand the energy transfer from the Sun to the solar wind as a single system even within the magnetohydrodynamic (MHD) framework. Alfvén waves are believed to be a primary candidate that drives the solar wind (e.g., McIntosh et al. 2011). Direct observations of propagating Alfvén waves have been reported after the launch of the Hinode satellite (De Pontieu et al. 2007; Nishizuka et al. 2008; Okamoto & De Pontieu 2011). Since Alfvén waves are notoriously difficult to dissipate, various physical processes have been proposed. The dissipation of Alfvén waves is the key behind the acceleration of solar wind, and the essential problem is to dissipate the Alfvén wave that eventually will transfer the energy to accelerate the solar wind. Recently, the mechanism of turbulent cascade has been proposed in which the downward wave that is generated due to the reflection of the Alfvén wave in the gravitationally stratified atmosphere interacts with the upward propagating Alfvén wave and develops Alfvénic turbulence. Once the Alfvénic turbulence is generated, the energy cascade of the turbulence to smaller spatial scales finally heats the corona and drives the solar wind (Matthaeus et al. 1999). Various phenomenological approaches have been considered to avoid the complexities of the turbulence (Cranmer et al. 2007; Verdini & Velli 2007; Bigot et al. 2008). In numerical simulations an incompressible approximation is usually adopted (Einaudi et al. 1996; Dmitruk & Matthaeus 2003; Van Ballegooijen et al. 2011), although the mode conversion from Alfvén to slow mode seems to play an important role (Kudoh & Shibata 1999; Suzuki & Inutsuka 2005, 2006; Antolini & Shibata 2010; Matsumoto & Shibata 2010). One of the major challenges in numerical simulation is to consider the huge density contrast between the solar photosphere and interplanetary space. In this paper, we show results of two-dimensional MHD simulations, considering the region from the solar photosphere and solar wind as a single system, and include the details of wave reflection from the transition region, nonlinear mode conversion, and the turbulent cascade for the first time.

2. METHOD
We have performed two-dimensional MHD simulation with radiative cooling, thermal conduction, and gravity. Our numerical model includes a single flux tube extended from a kilogauss (kG) patch in the polar region (Tsuneta et al. 2008) to the interplanetary space (~20 Rs). Our basic equations are

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0,$$  

$$\frac{\partial \rho \mathbf{V}}{\partial t} + \nabla \cdot \left( \rho \mathbf{V} \mathbf{V} + P_{\text{T}} - \frac{\mathbf{B} \mathbf{B}}{8 \pi} \right) = \rho \mathbf{g},$$  

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{V} \mathbf{B} - \mathbf{B} \mathbf{V}) = 0,$$  

$$\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot \left[ (\mathcal{E} + P_{\text{T}}) \mathbf{V} - \frac{1}{4 \pi} (\mathbf{V} \cdot \mathbf{B}) \mathbf{B} + \kappa \nabla T \right] = \rho \mathbf{g} \cdot \mathbf{V} - R,$$

where \( \rho \), \( \mathbf{V} \), \( \mathbf{B} \), and \( T \) are mass density, velocity, magnetic field, and temperature, respectively. \( P_{\text{T}} \) indicates total pressure, \( P_g + B^2/8\pi \), where \( P_g \) is gas pressure. Total energy per unit volume
Initially, we set an isothermal (10^4 K) atmosphere. We input extended from a kG strength to 10 G at the height of 2000 km. Conduction tensor and solar mass, respectively. We adopt anisotropic thermal conduction tensor $\kappa$ along magnetic field lines (Yokoyama & Shibata 2001). Radiative cooling term $R$ is assumed to be a function of local density and temperature (Suzuki & Inutsuka 2005). Note that no other ad hoc source terms for heating are included in the energy equation.

The vector form of our basic equations is appropriately transformed into a spherical coordinate system with $(r, \theta, \phi)$ and $\theta = \pi/2$, $\phi = 0$. Initial magnetic field is extrapolated using a potential field approximation so that the open field lines are extended from a kG strength to 10 G at the height of 2000 km. Initially, we set an isothermal (10^4 K) atmosphere. We input velocity disturbance in the $\theta$ direction at the footpoint of the flux tube in order to generate Alfvén waves. We assume a white-noise power spectrum with $(1 \text{ km s}^{-1})^2$ in total power, which is rather a good approximation to the observed spectrum (Matsumoto & Kitai 2010). Since the velocity disturbances are pre-determined, any feedback effects (Grappin et al. 2008) of the coronal disturbances on the photospheric motions are ignored. The periodical boundary condition is posed in the $\phi$ direction. Our numerical simulation is based on an HLLD scheme (Miyoshi & Kusano 2005) that is robust and efficient among the various kinds of approximate Riemann solvers. The solenoidal condition, $\nabla \cdot \vec{B} = 0$, is satisfied within a round-off error by using the flux-CT method (Tóth 2000). The TVD-MUSCL scheme enables us to archive the second-order accuracy in space, while the Runge–Kutta method gives the second-order accuracy in time. We use a min-mod limiter in order to suppress the numerical oscillation around shocks, which is one of the standard techniques in the TVD scheme. Our numerical domain extends from the photosphere to $R = 20 \text{ Rs}$ radially. The spatial resolution is 25 km at the surface and increasing with radius. The horizontal length is 3000 km at the photosphere with spatial resolution of $\sim 100$ km. Total grid points in our simulation are 8198 in the radial direction and 32 in the horizontal direction.

The turbulent heating rate is estimated by dimensional analysis since viscosity and resistivity are not included explicitly in our basic equations. First, we derive the Fourier component, $\vec{v}_\phi$, of the Alfvénic disturbance $(v_\phi)$ as follows:

$$\vec{v}_\phi(r, k_\phi) = \int v_\phi(r, \phi)e^{-ik_\phi r}d\phi.$$ (5)

Then, the energy spectral density, $E(r, k_\phi)$, becomes

$$E(r, k_\phi) = \frac{1}{2\pi r^2 k_\phi} [\vec{v}_\phi(r, k_\phi)^2 + \vec{v}_\phi(r, -k_\phi)^2],$$ (6)

where $\Delta \phi$ indicates the angular system size in the $\phi$ direction. By using $k_\phi$ and $E(r, k_\phi)$, we can estimate the energy exchanging rate, $\epsilon(r, k_\phi)$, for a certain wavenumber, $k_\phi$, with neighboring Fourier modes. Then $\epsilon(r, k_\phi)$ becomes

$$\epsilon(r, k_\phi) \sim \bar{\rho}E(r, k_\phi)^{1/2}/k_\phi^{5/2},$$ (7)

where $\bar{\rho}$ denotes the mean density averaged over time and $\phi$ direction. As a turbulent heating rate, we use $\epsilon(r, k_\phi)$, whose wavenumber is larger than a critical wavenumber that is determined by numerical resolution. We choose $k_\phi \Delta \phi = 4$ as the critical wavenumber that corresponds to the spatial resolution covering one wavelength by eight grid points in our simulation.

3. RESULTS AND DISCUSSIONS

The coupling between the magnetic field and the surface convection excites an upward-propagating Alfvén waves (Steiner et al. 1998), and it could be an efficient energy carrier in the solar atmosphere. Considering such a scenario, we performed 2.5-dimensional MHD simulations covering regions directly from the photosphere to the interplanetary space. Once the Alfvén wave is forced to excite, the numerical system attains a quasi-steady state within 1800 minutes. Due to the dissipation of the Alfvén wave, the initially static and isothermal (10^4 K) atmospheres eventually develops a hot corona (10^6 K) and a high-speed (500 km s^{-1}) solar wind (Figures 1 and 2). The radial

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**Figure 1.** Results of MHD simulation of Alfvén wave propagation from the solar photosphere to the interplanetary space. (a) Normalized density fluctuation and (b) region that is magnified five times. The red squared region in (a) is equivalent to (b). (c) Temperature distribution and (d) density distribution; the regions shown are magnified 100 times from (b). The red squared region in (b) is equivalent to (c) and (d). The white solid lines in each panel represent the magnetic field lines. Lengths are shown in units of Rs = 6.96 $\times$ 10^6 km.
profiles of velocity, temperature, and density are quite consistent with the spectroscopic and interplanetary scintillation observations (Figure 2). Even though previous one-dimensional simulations (Suzuki & Inutsuka 2005, 2006) show similar radial variations, the coronal heating and solar wind acceleration mechanism in our two-dimensional simulation are essentially different from the previous ones.

The energy losses such as radiative cooling, thermal conduction, and adiabatic cooling due to the solar wind are the main cooling processes in the solar atmosphere. In order to maintain the solar corona, heating processes are necessary to balance the cooling processes. As shown in panel (a) of Figure 3, the energy flux of the Alfvén wave decreases monotonically, a part of which is transferred to the solar wind. Although a sizable fraction of energy flux is decreased in the chromosphere by the reflection and dissipation processes, the energy flux that is supplied to the corona is well above $10^5$ erg cm$^{-2}$ s$^{-1}$, a typical number that is required to maintain the corona and the solar wind (Hansteen & Leer 1995). The dissipation mechanism of the Alfvén wave should be different in various regions depending on the background medium.

Panel (b) of Figure 3 shows the comparison of each component of the heating and cooling rates. The heating is separated into the compressive (dilatational) and incompressible (shearing) parts. The green solid line shows the compressive component; compressive waves are generated due to the non-linear mode conversion from the Alfvén wave to compressive (or slow mode) wave (Kudoh & Shibata 1999), and these compressive waves eventually steepen into shocks. We estimate the heating rate by counting the entropy jumps at shock fronts in the simulations. The red-hatched area shows the incompressible heating, which is done by the dissipation of Alfvénic turbulence owing to strong shearing motion at small scales. We estimate the turbulent heating rate from the Fourier component of Alfvénic disturbances.

In the chromosphere, both the shock and the turbulence contribute to the heating. The wave nonlinearity, which is defined as wave amplitude divided by phase speed, quickly increases in the chromosphere with the rapid expansion of the magnetic flux tube (Figure 4). As a result, compressive waves are generated effectively by the nonlinear mode conversion of Alfvén waves. The turbulent heating is also important in the chromosphere because the Alfvénic turbulence is developed efficiently due to both phase mixing (Heyvaerts & Priest 1983) and wave reflection (Matthaeus et al. 1999). Since the flux tube rapidly opens near the photosphere, the Alfvén speeds of the neighboring field lines are different from each other. Due to the difference in Alfvén speeds across the magnetic field, the Alfvén waves along the neighboring field lines gradually become out of

Figure 2. Comparison of the simulation and the observation is summarized below. Red solid lines in each panel represent results of the simulations; these values are averaged over distance and over 30 minutes. (a) The green crosses (Teriaca et al. 2003) and the blue triangles (Zangrilli et al. 2002) represent the proton outflow speeds in the polar region observed by Solar and Heliospheric Observatory (SOHO). The black circles with crossed error bars (Grall et al. 1996) are obtained by Very Long Baseline Array. The black circles with vertical error bars (Habbal et al. 1995) indicate measurements by Heliospheric Observatory (SOHO). The black crosses (Esser et al. 1999) are derived empirically from nonthermal broadening based on the UVCS/SOHO measurements. (c) The black circles (Fludra et al. 1999) and the blue stars (Teriaca et al. 2003) are data based on observations by SUMER/SOHO and CDS/SOHO, respectively. The green triangles (Teriaca et al. 2003) and orange squares (Lamy et al. 1997) are observed by LASCO/SOHO.

Figure 3. Alfvén wave energy flux and its dissipation processes. (a) Alfvén wave energy flux as a function of radius. (b) Heating and cooling rates as a function of radius. The green solid line shows the shock heating rate estimated by counting sudden entropy jumps. The red-hatched area indicates the turbulent heating rate estimated from Fourier and dimensional analysis. The black solid line and the blue solid line show radiative and adiabatic cooling rates, respectively. The black-hatched area represents the transition region.
phase, even though the waves are in phase at the photosphere, which creates strong shear to dissipate their wave energy. In addition to the phase mixing, the rapid decrease of the density in the chromosphere and the transition region causes an increase in the Alfvén speed that finally leads to the reflection of the Alfvén wave. The nonlinear wave–wave interaction between the preexisting outward component and the reflected component develops the turbulent cascade.

In the corona, the shock dissipation is the main contributor to the heating although the turbulence is also effective in the lower corona. Passing through the transition region, the wave nonlinearity decreases rapidly because of the large Alfvén speed in the corona, so the local shock formation in the corona is not significant. Instead, compressive waves are generated by the vertically fluctuating motion of the transition region; the nonlinearly excited longitudinal waves in the chromosphere continuously tap the transition region (Kudoh & Shibata 1999), which further excites upward-propagating compressive waves in the corona. The reflected wave component drops off significantly above the transition region (Figure 5) because the Alfvén speed does not change so much. As a result, the turbulent cascade is suppressed in the subsonic region (1.02 to 4 Rs). The power index of the energy spectral density of Alfvénic disturbance is significantly softer than $-5/3$, which indicates that the energy cascading to smaller scales is not effective in this region (Figure 6). The shock heating compensates for the absence of turbulent heating in order to balance the cooling there. Generally, heating below the sonic point controls mass loading to the solar wind, so we suggest that the shock heating mechanism works efficiently to determine the mass-loss rate from the Sun. In our simulation, the mass-loss rate is of the order of $10^{-15} M_\odot\text{yr}^{-1}$, which agrees reasonably well with the observed value.

In the solar wind acceleration region ($R \gtrsim 4 R_\odot$), again, both the turbulent heating and shock heating are comparable. The wave nonlinearity, once dropped above the transition region, increases gradually with radius due to the decrease in Alfvén speed. Even though the nonlinearity is still small, Alfvén waves suffer nonlinear effects due to their long traveling distance. Then, compressive waves are locally excited by the mode conversion, and these waves finally get dissipated by the shocks. The turbulent heating works effectively in the solar wind. The signature of turbulent cascade can be seen clearly in the power spectra of Alfvén waves (Figure 7). Moreover, the turbulent cascade is not isotropic but anisotropic (Shebalin et al. 1983; Goldreich & Sridhar 1995); the direction of turbulent cascading is perpendicular to the background magnetic field. The energy cascading is triggered by the nonlinear wave–wave interaction between the outgoing and reflection waves (Matthaeus et al. 1999). The increase of the reflection component of Alfvén waves can be seen in Figure 7. The work done by the gas and the magnetic pressure from the turbulence is also of the same order and found to be sufficient to accelerate the solar wind. Figures 5 and 7 indicate that the critical balance state, $k_r v_A \sim k_\phi v_\phi$, of Alfvénic turbulence (Goldreich & Sridhar 1995) is attained as $R$ increases from the wave-like state, or weak turbulence state ($k_r v_A > k_\phi v_\phi$, at most), in the low corona (e.g., Perez & Boldyrev 2008).

Our two-dimensional MHD simulation shows that both the shock and the turbulence are important for the coronal heating and the solar wind acceleration. We showed that the
energy exchange between the Alfvén mode and slow mode is
effective, although previous MHD simulations of turbulence in
homogeneous media show the decoupling of Alfvén and com-
pressive modes (Cho & Lazarian 2003). The inhomogeneity of
the background medium due to the density stratification and
the rapidly expanding flux tube is essential to understand the
energy transfer processes in the solar atmosphere. In the pre-
vious one-dimensional MHD simulations (Suzuki & Inutsuka
2005, 2006), the shock heating is overestimated because the
geometrical expansion dilutes the shocks in a multidimensional
system. We showed that the shock dilution is not so signifi-
cant in a two-dimensional system. The turbulent cascading pro-
cess in our simulation results from two-dimensional nonlinear
terms, while previous studies (e.g., Dmitruk & Matthaeus 2003;
Van Ballegooijen et al. 2011) show the importance of nonlin-
erar terms originating in three-dimensional nature. Therefore,
three-dimensional MHD simulation is necessary not only to
completely rule out the possibility of shock dilution but also to
verify the turbulent cascading processes.

We showed that these changes in the main contributor
to the heating are the natural consequences of the strong
inhomogeneity, originated both in the photospheric magnetic
field and in the gravitational stratification. Although only the
Alfvénic disturbances are excited at the photosphere, in our
simulation, compressive waves are also important, especially
for the chromospheric heating (Bogdan et al. 2003; Hasan
et al. 2005; Fedun et al. 2011). It is possible to change the

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Figure 7. Evolution of power spectrum of Alfvén wave as a function of radius.
The four panels represent the power spectrum of Alfvén wave at (a) $R = 1.1$ Rs,
(b) $R = 6.0$ Rs, (c) $R = 11$ Rs, and (d) $R = 14$ Rs. The vertical and horizontal
axes represent the wavenumber in the $\phi$ direction, $k_\phi$, and in the $r$ direction, $k_r$,
respectively, normalized by $k_0 = 2\pi R_0 \phi$, where $\Delta \phi$ is the angular system size
in the $\phi$ direction. The color in each panel shows the power spectral density in
Fourier space normalized by the peak value.

(A color version of this figure is available in the online journal.)