A Model for Solar Wind Structure and Dynamics Based on Alfvén Wave Turbulence

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Abstract. We present a 3D reduced magnetohydrodynamic (RMHD) model of reflection-driven Alfvén wave turbulence in an open magnetic field at the center of a coronal hole. The non-linear interactions between outward (dominant) and inward (minority) propagating waves generate turbulence. The RMHD equations describing the turbulence include the effects of solar wind outflow velocity on the dissipation of waves. The Alfvén wave turbulence results in the transfer of energy to small perpendicular scales (“direct cascade”) or to larger scales (“inverse cascade”). We first show the result of our calculation for a model where there is smooth variation of plasma parameters such as Alfvén speed and density with height along the flux tube. However, this model does not produce the required energy to heat the plasma and accelerate the fast solar wind. Therefore, we introduce our second model, where we include additional density fluctuation along the open field. These density variations simulate the effects of compressive MHD waves in the solar wind. We find that these variations in density enhance the turbulence dissipation rates, and thereby increase the heating rate and the acceleration of the solar wind.

1. Introduction
The fast solar wind at 1 AU has velocities in the range of 500-800 km s$^{-1}$, and originates from coronal holes on the Sun. It has long been known that Alfvén waves are present in the solar wind [1, 2], and in situ measurements have demonstrated that turbulent fluctuations in the magnetic field and plasma velocity are ubiquitous [3–7]. The turbulent waves are characterized by a broad spectrum of wavenumbers and frequencies. Transverse magneto-hydrodynamic (MHD) waves such as Alfvén waves likely originate in the solar photosphere, where they may be produced by interactions of the open magnetic field with subsurface convective flows. As the waves travel outward, they reflect due to spatial variations in Alfvén speed, which generates inward propagating waves [8, 9]. The nonlinear interactions between the inward and outward propagating waves can distort the wave fronts and produce turbulence [10–12]. Even though the outward propagating Alfvén waves are modified by turbulent interactions, they are capable of transporting energy and momentum over large distances before giving up their energy. Therefore, Alfvén wave turbulence (AWT) is believed to play an important role in the heating and acceleration of the fast wind [13–22]. Remote-sensing observations of the Sun further support the idea that Alfvén waves are present in the solar atmosphere [23–27].

Alfvén waves can affect the solar wind in two ways: they can heat the coronal plasma and provide a wave-pressure force [28, 29]. Turbulent cascade of the waves is considered to be responsible for transferring wave energy to small spatial scales, where the waves are dissipated.
and the energy is converted into heat of the plasma [11]. The nature of these collisionless dissipation processes is not well understood, but likely involves wave-particle interactions on the scale of the ion gyroradius or smaller [30]. Since the dissipation scale is so much smaller than the energy injection scale of the turbulence, it is generally assumed that the turbulent dissipation rate is not strongly dependent on the details of the dissipation process. Therefore, to estimate the plasma heating rate it is sufficient to simulate only the largest scales of the turbulence and to establish the energy cascade rates at those scales. The wave pressure force is caused by the spatial variation of the wave energy density along the open field lines [29], and plays an important role in driving the fast solar wind to the observed high velocity. Therefore, models of the acceleration of the fast solar wind by AWT should take into account the wave pressure forces.

Matthaeus and collaborators were the first to develop RMHD models of AWT in an open flux tube [11, 31, 32]. They demonstrated that a turbulent state can develop in the corona despite the fact that the waves can escape into the heliosphere. In a recent paper, Zank and co-authors introduced results of a model describing the transport and evolution of turbulence in open magnetic field regions [33]. In their model, a quasi-2D turbulence is generated in closed loops of the magnetic carpet, and interchange reconnection between the carpet loops and the open magnetic field causes the turbulence to be injected into the solar wind, where it is advected upward by subsonic, sub-Alfvénic flow. The turbulence has an Alfvénic component referred to as minority slab component and is evolved through the coupling between the majority quasi-2D and minority slab component. More recently, the effects of the wind outflow on the waves have been included in RMHD models [34–36]. In contrast to the model by Zank and collaborators [33], the RMHD picture provides only an Alfvén wave perspective.

MHD simulations of turbulent flows are difficult because they require high spatial resolution. To reach the required resolution, many authors focus on “homogeneous” turbulence in a box (often with periodic boundary conditions). This simulation domain may represent a small part of a much larger turbulent system such as the solar wind far from the Sun. This approach is not valid for the acceleration region of the solar wind (say, 1 – 20 \( R_\odot \)) because the wavelengths \( \lambda_\parallel \) of the waves are expected to be comparable to the solar radius, so the large-scale gradients in the magnetic field and plasma density are expected to have important effects on the waves. The AWT model predicts that the waves in this region are highly anisotropic in the sense that the magnetic and velocity fluctuations are nearly perpendicular to the mean magnetic field. Also, the amplitude of the inward waves is likely to be much smaller than that of the outward waves, so the turbulence is highly imbalanced. It is not yet fully understood how imbalanced turbulence behaves in an inhomogeneous plasma.

In this paper we use a 3D RMHD model [35, 36] to study how reflection-driven AWT can heat and accelerate the fast solar wind emerging from an open magnetic field based at a coronal hole. The modeling includes the effects of the wind velocity on the waves. Also, the simulations take into account the inhomogeneity and non-local nature of the turbulence. We first show that the nonlinear interactions between the dominant \( z_+ \) waves and minority \( z_- \) waves is responsible for the transfer of wave energy either to smaller perpendicular scales (“direct cascade”) or to larger scales (“inverse cascade”). We then introduce density fluctuations in the open field and show that in a model with density variation, the wave reflection is increased significantly, thereby enhancing wave dissipations rates and turbulence and as a result increasing the heating rates.

2. Reduced MHD Model
We consider a thin magnetic flux tube inside a polar coronal hole at solar minimum. The tube extends radially outward from the Sun to a distance \( r = 20 \ R_\odot \). Alfvén waves are launched inside this tube by imposing incompressible “footpoint” motions at the coronal base (\( r \approx 1.003 \ R_\odot \)). The assumed motions have a velocity amplitude \( v_{\text{rms}} \approx 40 \text{ km s}^{-1} \), consistent with observed
non-thermal velocities in coronal holes [37], and a transverse length scale comparable to that of the solar granulation (\(\sim 1\) Mm). The waves are modeled using the RMHD approximation [38, 39], and are described in terms of Elsasser variables:

\[
z_{\pm} \equiv v_1 \mp B_1 / \sqrt{4\pi \rho_0},
\]

(1)

where \(B_1(r, t)\) and \(v_1(r, t)\) are the magnetic- and velocity perturbations of the waves, and \(\rho_0(r)\) is the mean plasma density. Here \(z_+\) describes the “dominant” waves, which always propagate radially outward, and \(z_−\) describes the “minority” waves, which can propagate inward or outward depending on how they are produced [40]. The form of the RMHD equations used here include the effects of a radially expanding magnetic field, density variations along the flux tube, and the solar wind outflow [34, 35]:

\[
\frac{\partial \omega_\pm}{\partial t} = -(u_0 \pm v_A) \frac{\partial \omega_\pm}{\partial r} + \frac{1}{2} \left( \frac{dv_A}{dr} \pm \frac{u_0}{2H_\rho} \right) (\omega_+ - \omega_-) + \frac{u_0}{2H_B} (\omega_+ + \omega_-) \\
\cdot \cdot \cdot - \frac{1}{2} [\omega_+, f_-] - \frac{1}{2} [\omega_-, f_+] \pm \nabla_\perp^2 \left( \frac{1}{2} [f_+, f_-] \right),
\]

(2)
where \( f_{\pm}(r,t) \) are the velocity stream functions of the Elsasser variables, \( \omega_{\pm} \equiv -\nabla^2 \cdot f_{\pm} \) are the vorticities, \( u_0(r) \) is the solar wind outflow velocity, \( v_A(r) \) is the Alfvén speed, \( H_B(r) \equiv B_0/(dB_0/dr) \) is the magnetic scale length, \( H_p(r) \equiv \rho_0/(d\rho_0/dr) \) is the density scale length, and \( B_0(r) \) is the magnetic field strength. Note that \( u_0 \) and the radial gradients of \( B_0 \) and \( \rho_0 \) cause linear coupling between the \( \omega_+ \) and \( \omega_- \) waves. The brackets \( [\cdots,\cdots] \) involve derivatives w.r.t. the perpendicular coordinates \( x \) and \( y \), and are the only nonlinear terms in the equations. In addition there are wave damping terms (not shown).

\[ \text{Figure 2.} \text{ Radial dependence of wave-related quantities for a RMHD model of the solar wind.} \]
\[ \text{(a) Velocity amplitude of the waves (black curve), and Elsasser variables for dominant waves (red curve) and minority waves (green curve). The dashed red and green curves are for a model with the nonlinear terms switched off.} \]
\[ \text{(b) Wave energy dissipation rates per unit mass: rate derived from turbulence simulation (solid black curve), rate assumed in the setup of background atmosphere (dashed curve), and rate predicted by a phenomenological model [35].} \]

In RMHD modeling, before the turbulence can be simulated we must first specify the quantities describing the background atmosphere. For the field strength \( B_0(r) \) we use a potential field model. Figure 1 shows some properties of the background atmosphere. The temperature \( T_0(r) \) is specified using a simple formula [35]. As shown in Figure 1(a), the temperature rises quickly at low heights and declines slowly at large height. The density \( \rho_0(r) \) and outflow velocity \( u_0(r) \) of the wind are determined by iteratively solving the mass, momentum and energy equations for the wind in a one-dimensional, time-steady approximation (for details see [35]). The heating rate \( Q_A(r) \) is computed from the energy equation, which includes the effects of solar wind expansion and radiative and conductive losses [16]. The wave energy density \( U_A(r) \) is computed by solving the wave action equation, where we use a boundary condition on the wave amplitude at the coronal base. The wave pressure force \( D_{wp}(r) \) is computed from the gradient of \( U_A(r) \). The momentum equation includes the wave pressure force.

Figure 1(b) shows the outflow velocity \( u_0(r) \) of the wind (black curve) and Alfvén speed \( v_A(r) \) (red curve). Note that the two curves cross at \( r \approx 7 R_\odot \), which is the Alfvén critical point. Panel (c) shows the acceleration associated with the wave pressure force (red curve) as well as the acceleration of gravity (black curve). Note that the wave pressure force is quite strong because \( D_{wp}(r) \) exceeds gravity already at \( r = 2.5 R_\odot \). Finally, panel (d) shows the heating rate \( Q_A(r) \) needed to maintain the temperature \( T_0(r) \) of the background atmosphere (black curve). Some of this heat is used to compensate for the adiabatic cooling associated with the expansion of the solar wind; this contribution \( Q_{adv}(r) \) is given by the green curve in Fig. 1(d). The blue and red
curves give the radiative and conductive energy losses, respectively. Note that at low heights most of the energy is used to heat the expanding wind, while at 3 – 5 $R_{\odot}$ conduction is the dominant cooling mechanism. The dashed red curves show regions where thermal conduction causes heating of the plasma.

After the background atmosphere has been specified, the waves are simulated for a period of 30,000 s, which is sufficient for the turbulence to reach a statistically stationary state at all heights. Figure 2(a) shows the velocity amplitudes of the dominant waves $z_+$ (solid red curve) and minority waves $z_-$ (solid green curve), as well as the total wave amplitude (black). These values are averages over the tube’s cross-section and over time. Note that the dominant waves are much stronger than the minority waves, so the turbulence is strongly imbalanced. Also, the minority waves have a minimum at $r \approx 1.4 R_{\odot}$ where the Alfvén speed $v_A(r)$ reaches its maximum. This indicates that the rate of production of minority waves depends strongly on the gradient of Alfvén speed, $dv_A/dr$ in equation (2). The dashed red and green curves in Figure 2(a) are for a model in which the nonlinear terms in equation (2) are omitted, so there is no turbulence in this case. Comparison of the solid and dashed green curves shows that the nonlinear effects further suppress the minority waves.

Figure 2(b) shows the wave energy dissipation rate $Q_{\text{tot}}(r)$ predicted by the RMHD model (solid black curve). This rate is again computed by averaging the dissipation rates over the flux tube cross-section and over time in the simulation. Note that $Q_{\text{tot}}(r)$ is not necessarily the same as the heating rate $Q_A(r)$ assumed in the setup of the background atmosphere. The latter is given by the dashed black curve in Figure 2(b), which is the same as the solid black curve in Figure 1(d). The goal is of course to construct a model in which $Q_{\text{tot}} \approx Q_A$, but we find that this does not happen in the present case. We find that in the height range from 1.2 to 10 $R_{\odot}$ the wave dissipation rate $Q_{\text{tot}}$ is significantly smaller than $Q_A$, indicating that the simulated wave heating is not sufficient to maintain the temperature of the background atmosphere. Note that $Q_{\text{tot}}(r)$ has a dip at $r \approx 1.4 R_{\odot}$ where the Alfvén speed has its maximum and the production of minority waves is suppressed; this is part of the reason for the discrepancy with $Q_A$. The blue curve in Figure 2(b) shows results for a phenomenological turbulence model [35], but this model has only limited success in reproducing $Q_{\text{tot}}$.

It is often stated that turbulence is generated by “counter-propagating” Alfvén waves. However, in equation (2) the nonlinear “bracket” terms do not contain radial derivatives and therefore do not depend on the direction of wave propagation. We find that in the present model with a smooth background atmosphere both the dominant ($\omega_+$) and minority ($\omega_-$) waves travel radially outward. This is demonstrated in Figures 3(a) and 3(b), where we plot $\omega_{\perp,k}(r,t)$ for a wave mode $k$ with perpendicular wavenumbers $n_k = 8$ and $n_y = 4$ (see [36]). Note that both panels show patterns slanted to the right, indicating outward propagation. The reason that the minority waves travel outward is that they are produced by weak linear coupling with the dominant waves. This linear coupling is mainly due to the term with $dv_A/dr$ in equation (2). The weakness of the coupling causes the minority waves to travel outward with their source (the dominant waves), consistent with earlier predictions [40]. In other RMHD simulations a combination of inward and outward propagation of the minority waves has been found [34]. It is likely that the behavior of the minority waves depends on the correlation time of the footpoint motions, which is only about 48 s in our model.

In most turbulence models for the solar wind it is assumed that the energy is transferred from larger to smaller spatial scales in a “direct” cascade. However, we find that in the acceleration region of the wind both direct and inverse cascades can occur. We computed the cascade rate of the dominant and minority waves in a RMHD model for the fast solar wind [36]. Figure 4 shows the cascade rate $\epsilon_+ (a_\perp, r)$ for the dominant waves as a function of dimensionless perpendicular wavenumber $a_\perp$ and radial distance $r$ (the wavenumber is scaled with respect to the flux tube width). In this model the waves are injected at the coronal base with wavenumbers $a_\perp$ in the
Figure 3. Vorticities as functions of radial distance $r$ and time $t$ for a wave mode $k$ with perpendicular wavenumbers $n_x = 8$ and $n_y = 4$ in a RMHD model for the fast solar wind: (a) dominant wave $\omega_{+,k}$, (b) minority wave $\omega_{-,k}$. Note that both waves travel radially outward.

range 11 – 17, and the waves are dissipated at wavenumbers $a_\perp > 44$. The cascade rate $\epsilon_+$ is computed by adding contributions from all mode triplets $(a_1, a_2, a_3)$ that straddle a chosen wavenumber $a_\perp$ and transport energy from modes with $a_i < a_\perp$ to modes with $a_i > a_\perp$ (for details see [36]). Figure 4 shows that at low heights the dominant waves have a direct cascade (red region), but $\epsilon_+$ changes sign at $r = 1.4 R_\odot$ for wavenumbers in the range $15 < a_\perp < 44$, indicating an inverse cascade (blue triangular region). The inverse cascade continues up to $r = 2.5 R_\odot$, but in a narrowing wavenumber range. The cascade rate $\epsilon_-$ of the minority waves is positive at all height (not shown). The negative cascade rates $\epsilon_- < 0$ limit the amount of energy that can transported into the dissipation range ($a_\perp > 44$). Therefore, in the region between 1.4 and 2.5 $R_\odot$ the wave dissipation rate is reduced compared to what it would be if a direct cascade occurred at all heights and wavenumbers. This is part of the reason why the dissipation rates in our model are not sufficient to maintain the temperature of the background atmosphere.

The development of an inverse cascade is due to the change of sign of $dv_A/dr$ at $r = 1.4 R_\odot$. As the dominant waves propagate outward they also cascade in wavenumber space, but the cascading is very slow because the amplitude of the minority waves is very small. Therefore, in the region between 1.4 and 2.5 $R_\odot$ the dominant waves are still in the process of gradually adjusting to the change in sign of $dv_A/dr$. In contrast, the minority waves have a much shorter cascade time scale and can immediately respond to this change. This leads to a situation where the minority waves produce an inverse cascade of the dominant waves. This shows that the turbulent cascade in the acceleration region of the fast wind cannot be treated as a local process: the cascade of the dominant waves occurs over a distance comparable to the variations in the background atmosphere, and the cascade rate $\epsilon_+$ is dependent on wavenumber.

3. Model with Density Variations
The difficulty with the solar wind model described in the previous section is that the energy produced by Alfvén wave turbulence is significantly less than the energy required to heat the
plasma. The energy dissipation rate $Q_{tot}(r)$ generated as a result of RMHD turbulence is less than the heating rate $Q_A(r)$ necessary to heat the background atmosphere and accelerate the solar wind. Therefore, we need to raise the heating rate $Q_{tot}$ without changing $Q_A$. In a system, where turbulence is generated by the nonlinear interactions between dominant and minority waves, the reflection of the waves creates the intermixing of the waves and thereby turbulence. Therefore, to enhance the rate of turbulence, we need to create more reflection of the dominant outward propagating waves. A way to achieve this is by introduction of density variations in the open field of our interest. The density fluctuations $\delta \rho(r,t)$ may be due to the sound waves coupling with Alfvén waves in the solar atmosphere. In the presence of sound waves, the Alfvén speed varies in time and space and Alfvén waves reflect as a result of these gradients in Alfvén speed. By imposing density variations in the open field, these gradients are increased and consequently the amplitude of the outward propagating waves are enlarged, creating more inward propagating waves by reflection and therefore increasing the turbulent propagation rate.

The existence of density fluctuations in the solar atmosphere and solar wind have been confirmed by observations. Intensity fluctuations corresponding to slow mode oscillating waves with periods of between 10 to 15 mins have been observed in polar plumes with the Extreme Ultraviolet Imaging Telescope (EIT) on the Solar and Heliospheric Observatory (SOHO) [41].

Figure 4. Energy cascade rate for the dominant waves in a model for the fast solar wind [36]. The rate $\epsilon_+(a_\perp, r)/\rho_0(r)$ is plotted as function of dimensionless perpendicular wavenumber $a_\perp$ and radial distance $r$ from Sun center. Direct and inverse cascades are indicated by red and blue colors (see color bar).
In coronal loops the intensity variations represent waves with periods of approximately 5 mins in the extreme ultraviolet [42, 43] and at visible wavelengths [44]. High-frequency intensity variations have been detected during the eclipses [45].

In solar wind, there is strong evidence of density fluctuations based on observations. In the past, a variety of radio observations were used to study the radial evolution of plasma at the distances of 4-6 \( R_\odot \) [46] or natural radio sources and spacecraft signals were employed to measure electron density fluctuations and solar wind speed [47]. Recent observations of solar wind adopting radio interferometry have confirmed the fluctuations in the amplitudes of density ranging from 6\%−15\% at heliocentric distances of 16-26 \( R_\odot \) [48]. [49] used the Extreme-Ultraviolet images of comet Lovejoy from the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). They studied the striations of magnetic field structure in both closed and open magnetic field regions. These striations indicate the presence of large density variations (at least a factor of 6) associated with contrast in brightness between neighboring coronal flux tubes over scales of a few thousand kilometers.

Using observations from the Japanese Venus explorer Akatsuki [50] and applying radio occultation technique, [51] analyzed the frequency time series taken at heliocentric distances of 1.5-20.5 \( R_\odot \). They detected quasi-periodic density fluctuations with periods of 100 to 2000 seconds at all distances. We will be drawing a comparison between the observations from [51] and our modeling results in this section.

We present a model of density fluctuations in the solar wind. In our simulations, we include static density variations in our prescribed background atmosphere, i.e., the variations are random in position along the flux tube and constant in time. Also, for simplicity the density is assumed to be constant over the cross-section of the flux tube. To implement the effect of density fluctuations, we first define a Fourier-filtered random function

\[
\xi(r; \lambda) = \int dk \int dl \text{rand}(l) e^{-k^2\lambda^2} e^{2\pi i (r-l)};
\]

(3)

where \( \xi(r; \lambda) \) is a spatially randomly varying function with length scale larger than \( \lambda \) and \( \text{rand}(l) \) is a random function of \( l \). We normalize \( \xi(r; \lambda) \) as

\[
\bar{\xi}(r; \lambda) = \frac{\xi(r; \lambda)}{\langle \xi(r; \lambda) \rangle_{\text{rms}}},
\]

(4)

such that \( \langle X \rangle_{\text{rms}} \) denotes the root-mean-square value of \( X \). Therefore the root-mean-square value of \( \bar{\xi} \) is unity. The fractional density fluctuation \( \delta \rho/\rho \) is given by

\[
\delta \rho/\rho = n(r)\bar{\xi}(r; \lambda_\rho),
\]

(5)

where \( \lambda_\rho = 0.4R_\odot \) and \( n(r) \) represents an envelope of the fractional density fluctuation. A uniform density fluctuation with rms amplitude of 0.1 \( (n(r) = 0.1) \) was used in [35]. According to the radio wave observation by [51], the magnitude of density fluctuation is highly non-uniform and has a maximum around \( r \approx 5-6R_\odot \). In this study, we apply a nonuniform density variation based on this observation as

\[
n(r) = \frac{1}{2} \beta^{-1/4} \frac{\delta B}{B}, \quad \beta = \frac{c_s^2}{\nu_A^2},
\]

(6)

where \( \delta B \) is the rms value of the magnetic fluctuation \( B \) and \( c_s \) is the sound speed. The resulting time-independent, one-dimensional model with spatial density fluctuations is used as the background atmosphere for the three dimensional RMHD model of Alfvén waves turbulence along the expanding flux tube. The methodology for solving the RMHD equations in this case...
is identical to the case of Smooth model discussed in the previous section. Figure 5(a) shows the dissipation per unit mass for the simulated waves without density fluctuation (dashed blue curve) and with density fluctuation (solid blue curve). As the Figure clearly indicates for a model with density variation, the AWT produces enough heating to heat the background atmosphere. At all heights (1-20 \( R_\odot \)) the density variation has increased the heating rate per unit mass along the open flux tube, and at many positions this increase is by an order of magnitude. In Figure 5(b), we present the profile of \( n(r) \) given by Eq. (6) (solid line) together with the observational values from [51] shown by circles.

We demonstrated in this section how density fluctuation can increase the level of turbulence and heat the open field structure. The density variation introduced in our model is in agreement with the observation of [51]. However, to create a full picture of the influence of density fluctuation on wave turbulence, heating and acceleration of the solar wind, the density variation should be included in the cross section of the flux tube as well as along the flux tube. To simulate these effects, a full 3D MHD modeling is required and not a RMHD modeling of waves.

![Figure 5](image-url)

**Figure 5.** Figure on the left shows the heating rate for different correlation times. Figure on the right shows the amplitude of density fluctuations from our modeling (solid black line) and the observed values (circles) from [51].

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