NONLINEAR ALFVÉN WAVE MODEL FOR SOLAR CORONAL HEATING AND NANOFLARES

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ABSTRACT

We have performed magnetohydrodynamic (MHD) simulations of the nonlinear Alfvén wave coronal heating model that include both thermal conduction and radiative cooling in an emerging flux loop and found that the corona is episodically heated by fast- and slow-mode MHD shocks generated by nonlinear Alfvén waves via nonlinear mode-coupling. We also found that a cool unstable loop is formed if the amplitude of Alfvén waves is not sufficient to heat the corona. Moreover, it is shown that the time variation of the simulated extreme-ultraviolet and X-ray intensities of these loops, on the basis of the Alfvén wave model, is quite similar to the observed one, which is usually attributed to nanoflare or picoflare heating. This suggests that the observed nanoflares may not be a result of reconnection but in fact may be due to nonlinear Alfvén waves, contrary to current widespread opinion.

1. INTRODUCTION

To unveil the solar coronal heating mechanism has been a challenging subject through over half a century. Numerous ideas have been proposed to try to solve the problem. They are agreed that magnetic fields on the solar surface are distorted by the photospheric turbulence and that the magnetic energy stored through such a process would be released by some dissipation mechanism(s) to heat the coronal plasma towards the temperature of million degrees. How does such release of magnetic energy take place? This is the most essential topic of today. According to the energy release mechanism, the recent proposed theories are divided in two groups, one the magnetohydrodynamic (MHD) wave model and the other the magnetic reconnection model. The studies for the MHD wave model have been variously developed mainly through numerical modelling approach. In particular, Alfvén waves are promising media to heat the corona (Hollweg, 1992; Kudoh & Shibata, 1999). Kudoh & Shibata (1999) investigated the Alfvén wave model of spicules and coronal heating. They performed 1.5-dimensional MHD numerical simulation of torsional Alfvén waves propagating along an open magnetic flux tube. In their simulations, Alfvén waves are excited by random motions in the photosphere, and it was shown that if the amplitude of the photospheric motions is greater than \( \sim 1 \text{ km s}^{-1} \), an energy flux enough for heating the quiet corona (\( \sim 3.0 \times 10^{16} \text{ ergs s}^{-1} \text{ cm}^{-2} \); Withbroe & Noyes, 1977) is transported into the corona by torsional Alfvén waves. Furthermore, the nonlinearity of the Alfvén waves produces shocks. This suggests that Alfvén waves may heat the corona via shock dissipation. However, they did not study whether all of the energy of the Alfvén waves is actually dissipated in the corona via shock dissipation or whether such shock heating balances conduction and radiative cooling and creates a corona, since their calculation did not include the effects of conduction and radiative cooling.

In this proceeding, we report the results of 1.5-dimensional MHD numerical simulations of coronal heating dynamics that include the nonlinear propagation of Alfvén waves, thermal conduction, and radiative cooling in an emerging flux loop. The simulations show that the corona is episodically heated by nonlinear Alfvén waves and that, if the amplitude of the photospheric motions is not sufficient to heat the plasma towards coronal temperatures, a cool unstable loop of several \( 10^{5} \) K is formed. Our results also suggest that the simulated EUV and X-ray intensities are similar to what one actually observes.

2. NUMERICAL SIMULATIONS

We consider an emerging flux loop with a length of \( 10^{5} \) km and a nonconstant cross-sectional area in the solar atmosphere. The loop is assumed to be at rest for simplicity. The configuration of the flux loop is shown in Fig.1. Since the pressure ratio \( P_{\text{gas}}/P_{\text{mag}} \approx 1 \) near the photosphere and \( P_{\text{mag}} \) dominates with increasing height, where \( P \) is the pressure, the emerging flux tube is slim near the photosphere and expands above. We take the ratio of the cross section between the loop top and the foot of the loop to be \( \sim 1000 \). The resultant magnetic field is \( \sim 1000 \) gauss at the footpoints and \( \sim 1 \) gauss at the loop top. Our simulations are calculated along a single field line (drawn with a thick solid line and denoted by
“s” in Fig.1) along which azimuthal motions (φ components of velocity and magnetic fields) are allowed. This is meaning of 1.5-dimensional approximation.

We assume an inviscid perfectly conducting plasma. The 1.5-dimensional expressions of MHD equations which we solve are as follows: the mass conservation,

$$\frac{\partial \rho}{\partial t} + v_s \frac{\partial \rho}{\partial s} = -\rho B_s \frac{\partial}{\partial s} \left( \frac{v_s}{B_s} \right) ; \quad (1)$$

the s component of the momentum equation,

$$\frac{\partial v_s}{\partial t} + v_s \frac{\partial v_s}{\partial s} = -\frac{1}{\rho} \frac{\partial P}{\partial s} - g_s + \frac{v_s^2}{r} \frac{\partial r}{\partial s} - \frac{1}{4\pi \rho} \frac{B_\phi}{r} \frac{\partial}{\partial s} (r B_\phi) ; \quad (2)$$

the φ component of the momentum equation,

$$\frac{\partial}{\partial t} (r v_\phi) + v_s \frac{\partial (r v_\phi)}{\partial s} = \frac{B_s}{4\pi \rho} \frac{\partial}{\partial s} (r B_\phi) + L(t, s) ; \quad (3)$$

the φ component of the induction equation,

$$\frac{\partial}{\partial t} \left( \frac{B_\phi}{r B_s} \right) + \frac{\partial}{\partial s} \left( \frac{B_\phi}{r B_s} v_s - \frac{v_\phi}{r} \right) = 0 ; \quad (4)$$

the energy equation,

$$\frac{\partial e}{\partial t} + v_s \frac{\partial e}{\partial s} = -\left( \gamma - 1 \right) e B_s \frac{\partial}{\partial s} \left( \frac{v_s}{B_s} \right) + \frac{1}{\rho r^2} \frac{\partial}{\partial s} \left( r^2 \kappa \frac{\partial T}{\partial s} \right) - \frac{R - S}{\rho} ; \quad (5)$$

and the equation of state, assumed to be that of ideal gas,

$$e = \frac{1}{\gamma - 1} \frac{P}{\rho} ; \quad (6)$$

where s is the distance measured along the poloidal field line, r is the distance from the axis of the flux loop, ρ is the density, e is the specific internal energy, T is the plasma temperature, v_s is the velocity along the poloidal magnetic field, v_φ is the azimuthal velocity, B_s and B_φ are the poloidal and toroidal components of the magnetic field, respectively, g_s is the gravitational acceleration parallel to the field line, and the ratio of specific heats, γ is assumed to be γ = 5/3. In our study, the effects of thermal conduction and radiative cooling, which were not considered by Kudoh & Shibata (1999), are now included as shown in Eq.5. For thermal conduction and radiative cooling, the same treatment as Hori et al. (1997) is used.

The Spitzer’s classical conductivity for a fully ionised hydrogen plasma is used for the thermal conduction;

$$\kappa = \kappa_0 T^{5/2} ,$$

where \( \kappa_0 = 9 \times 10^{-7} \) in cgs units. \( R \) is the radiative loss rate; optically thin cooling is assumed for the plasma with \( T > 4 \times 10^3 \) K (above the lower transition region), thus it forms

$$R = N_e N_p Q(T) = \frac{1}{4} N^2 Q(T) ,$$

where \( N_e \) and \( N_p \) are electron and proton number density, respectively, \( N \) is the total number density. \( N_e = N_p \) is assumed for plasma neutrality. \( Q(T) \) is the radiative loss function for an optically thin plasma. We use the radiative loss function, \( Q(T) \), simplified as shown in Fig.2 (Hori et al., 1997). For the plasma with \( T < 4 \times 10^4 \) K (chromosphere), we take the empirical cooling rate given as

$$R = 4.9 \times 10^9 \rho .$$

This expression is based on the empirical result of Anderson & Athay (1989) who found that the heating rate per gram is roughly constant at \( 4.9 \times 10^9 \) ergs g^{-1} s^{-1} over a large part of the chromosphere. \( S \) is the heating rate to maintain the initial temperature distribution. The function \( L \) in the RHS of Eq.3 is the artificial torque, which twists both footpoints of the loop at random, thus torsional Alfvén waves are generated in the photosphere. We impose this random perturbation through the calculation.

The initial temperature distribution along the loop is uniform at \( 10^4 \) K, i.e., a chromospheric temperature. This
temperature was assumed in order to investigate how the corona is created from a low-temperature chromospheric plasma. The initial density distribution along the loop is not in hydrostatic equilibrium but mimics the nonhydrostatic distribution seen in the case of emerging flux dynamics, \( \rho \propto H^{-4} \) (Shibata et al., 1989a, 1989b), where \( H \) is the height from the photosphere.

In our simulations, random motions in the photosphere twist both footpoints of the magnetic loop, which then generates torsional Alfvén waves. Random motions with amplitudes of \( 1 - 2 \) km s\(^{-1}\) are actually observed in the photospheric granulation (Tarbell et al., 1991). Magnetic reconnection in the photosphere and/or chromosphere is an alternative possibility for the generation of Alfvén waves (Axford & McKenzie, 1996; Yokoyama & Shibata, 1995; Takeuchi & Shibata, 2001). We have examined several cases with footpoint motions of various average amplitudes.

We have a rigid wall boundary condition at the photospheric level. The numerical schemes that we use are the cubic interpolated propagation (CIP) scheme (Yabe & Aoki, 1991) and the method of characteristic-constrained transport (MOC-CT; Evans & Hawley, 1988; Stone & Norman, 1992). The magnetic induction equations are solved by MOC-CT, and the other equations are solved by CIP. This is the same method as that of Kudoh & Shibata (1999). The successive overrelaxation method is used to solve the heat conduction equations.

3. RESULTS

3.1 Heating Mechanism and Properties of Resulting Corona for a Typical Case

Fig. 3 shows results for a typical case in which the average amplitude of the photospheric velocity fields is \( \sim 2 \) km s\(^{-1}\). Movie 1, 2, and 3 also show the typical results: Movie 1 shows propagation of torsion of the magnetic loop; Movie 2 shows the pressure distribution around the loop top; and Movie 3 shows the temperature distribution along the loop. The result shows that nonlinear Alfvén waves generate compressional slow- and fast-mode MHD waves and shocks in the chromosphere. The initially cool plasma (10\(^{4}\) K) is gradually heated by slow- and fast-mode MHD shocks towards coronal temperatures (Movie 3). However, because of conduction and radiative cooling the temperature distribution becomes quasi-steady (Fig. 3) after \( t \approx 156 \) minutes.

The temperature in Fig. 3 also shows a nearly flat profile for the coronal part of the entire loop as a result of thermal conduction. The density shows the typical structure of the solar atmosphere after reaching a quasi-steady state, i.e., a high value at the photospheric footpoints at the solar surface, a strong density decrease with height in the chromosphere, a contact discontinuity in the transition region, and a nearly constant density in the corona. There are several shocks in the velocity distribution (also seen in the density distribution). These propagate from both footpoints and dissipate one after another (Movie 2).

![Figure 3](image)

**Figure 3.** Results for a typical case, in which the average amplitude of the photospheric velocity fields is \( \sim 2 \) km s\(^{-1}\), are shown. From top to bottom, profiles are shown for the temperature, the density, the poloidal component of the velocity (i.e., the component parallel to the field lines), and the ratio of the azimuthal magnetic field to the poloidal one along the loop. The simulation times are 0 (black dashed line), 48 (blue dash-dotted line), and 156 minutes (red solid line).

Thus the heating is episodic and the nature of the coronal loop is highly dynamical. In the bottom panel, the ratio of the azimuthal magnetic field to the poloidal field indicates the torsion of the magnetic loop. The loop is highly twisted near the footpoints because the amplitude of the torsional Alfvén waves gets larger as they propagate upward (Movie 1). This causes compressional slow and fast MHD waves via nonlinear mode-coupling. These waves grow into shock waves, as seen in the velocity panel, and as they dissipate they heat the coronal plasma.

The average temperature and pressure at the loop apex in the quasi-steady state are \( 1.26 \times 10^6 \) K and \( 9.93 \times 10^{-2} \) dyne cm\(^{-2}\), respectively. These are typical values for the corona and fit the theoretical scaling law for a steady coronal loop (Rosner, Tucker, & Vaiana, 1978),

\[
T \approx 1.4 \times 10^8 (P_l)^{1/3},
\]  

(10)
where \( P \) is the pressure of the plasma and \( l \) the length of the coronal loop. In our case, \( l \approx 8 \times 10^4 \) km (not \( 10^5 \) km as suggested by the temperature distribution in Fig.3).

### 3.2 Hot Steady Loops and Cool Unstable Loops

We also examined several cases by changing the amplitude of the photospheric velocity fields (i.e., the strength of the torque that twists the footpoints of the loop). Fig.4 shows the average temperature of the resulting loop as a function of the amplitude of the photospheric velocity fields \( \langle v_\phi^2 \rangle^{1/2} \) in the photosphere. The red and blue circles indicate stable and unstable cases, respectively. It is shown that if \( \langle v_\phi^2 \rangle^{1/2} \) in the photosphere is greater than 1 km s\(^{-1}\), the plasma is heated towards coronal temperatures and the coronal plasma reaches a quasi-steady state as a result of the balance among shock heating, thermal conduction, and radiative cooling. In these cases, the energy flux transported above is sufficient to create a quasi-steady hot coronal loop. It is also shown that the average temperature tends upwards with increasing amplitude of the photospheric motions.

When \( \langle v_\phi^2 \rangle^{1/2} \) in the photosphere is around 1 km s\(^{-1}\), the plasma is heated to no more than \( 6 \times 10^5 \) K and the temperature distribution exhibits unstable behaviour that a steady distribution is suddenly disturbed or broken down and then it turn back to a steady state. Contrary to the cases that \( \langle v_\phi^2 \rangle^{1/2} > 1 \) km s\(^{-1}\) in the photosphere, the energy flux is not enough for heating the plasma towards coronal temperatures in these cases, thus a cool loop of several \( 10^5 \) K is formed. Further, this cool loop is unstable due to the radiative cooling which has its peak at a few \( 10^5 \) K (see Fig.2). In this study, the case that \( \langle v_\phi^2 \rangle^{1/2} < 1 \) km s\(^{-1}\) in the photosphere is not investigated satisfactorily, because the calculations of that case stop before reaching to a steady state due to plasma properties to be too small values.

Although the criterion, which separates hot steady loops from cool unstable loops, is 1.15 km s\(^{-1}\) in this study, the value depends on the loop model (i.e., the length of a loop, the degree of expansion of cross-sectional area). Hence, the simulations for various loop model are needed.

### 3.3 Simulated Observations

In Sec.3.1, it is shown that the average coronal plasma properties are well explained by a steady or static coronal heating model. Nevertheless, the plasma in the loop never reaches hydrostatic equilibrium, instead, stays in a very dynamic state (Fig.3). In fact, Fig.5 exhibits “observations” of a theoretical coronal loop with Yohkoh/SXT and TRACE at the loop apex, which shows that the time variation is very similar to those of X-ray and EUV intensities actually observed with SXT and TRACE, respectively. These intensities are calculated using the results of the simulations in Fig.3. There are many flarelike brightenings of intensity because of the episodic heating of the corona by MHD shocks. Movie 4 shows the simulated observation of the entire loop by Yohkoh. Since the simulated X-ray intensity is very faint (Fig.5), observations such as Movie 4 are not actually obtained at present. The future missions may observe a coronal loop like this movie. On the other hand, the simulated EUV intensity is the same order of the actual observation of \( 10^5 \) km loops.

When such rapid time variations are observed, they are usually attributed to microflares or nanoflares produced by small-scale magnetic reconnection events. However, in the case of Fig.5, all “nanoflare-like events” are due to MHD shocks originally generated from Alfvén waves. More interestingly, the histogram of the occurrence frequency of these “theoretical nanoflares” (Fig.6) is also similar to that observed in the solar corona (Shimizu, 1995; Hudson, 1991; Aschwanden & Parnell, 2002).
Figure 6. Occurrence frequency of X-ray and EUV “nanoflares” as a function of their peak intensity based on the same data as in Fig.5 (red triangles: SXT/X-ray; blue circles: TRACE/EUV). This shows a power-law distribution with an index $\sim -1.7$ for SXT/X-ray and $\sim -1.9$ for TRACE/EUV (lines are fitted with a power law; red line: SXT/X-ray; blue line: TRACE/EUV).

Fig.6 shows a power-law distribution with an index $\sim -1.7$ for SXT/X-ray and $\sim -1.9$ for TRACE/EUV. It is well known that the occurrence frequency of microflares and nanoflares has been found to obey a power-law distribution with an index of around $-1.6 \sim -1.7$ (Aschwanden & Parnell, 2002). Thus, the Alfvén wave heating model reproduces the statistical property of actually observed micro/nanoflares rather well. Hence, there is a possibility that many “nanoflares” observed by recent space missions (Yohkoh, SOHO/EIT, and TRACE) are not magnetic reconnection events but are MHD shock events originally generated from Alfvén waves.

4. CONCLUSIONS

We examined how a hot corona is created in an initially cool loop as a result of nonlinear Alfvén waves. It was demonstrated that not only the dissipation of Alfvén waves (via mode-coupling with slow- and fast-mode waves and shock dissipation) but also the production of the coronal plasma as a result of the balance among shock heating, conduction, and radiative cooling can be self-consistently explained. We found that, if the amplitude of the photospheric motions is greater than 1 km s$^{-1}$, a steady coronal loop is created and that when the amplitude is around 1 km s$^{-1}$, an unstable loop of several $10^5$ K is formed. Furthermore, the numerical simulations have revealed that the resulting corona is very dynamic and full of shocks, so that the time variation of X-ray and EUV intensities shows many “nanoflare-type events,” quite similar to what is actually observed. Even the statistical properties of these “theoretical nanoflares” are similar to those observed in terms of the power-law distribution. This suggests that the actually observed time variation of X-ray and/or EUV flux in the corona and in the chromosphere may not be evidence of small-scale magnetic reconnections but could be due to Alfvén waves, contrary to the current belief.

Whether Alfvén waves are efficiently produced in the photosphere and/or chromosphere and whether the “nanoflare events” are actually MHD shocks will be tested by the Solar-B mission that will be launched in 2006.

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