THE ASTROPHYSICAL JOURNAL, 601:L107–L110, 2004 January 20

THE NONLINEAR ALFVÉN WAVE MODEL FOR SOLAR CORONAL HEATING AND NANOFLARES

SATOSHI MORIYASU,[1] TAKAHIRO KUDOH,[2] TAKAAKI YOKOYAMA,[3] AND KAZUNARI SHIBATA[1]
Received 2003 October 30; accepted 2003 December 3; published 2004 January 16

ABSTRACT

The mechanism of solar coronal heating has been unknown since the discovery that the coronal plasma temperature is a few million degrees. There are two promising mechanisms, the Alfvén wave model and the nanoflare-reconnection model. Recent observations favor the nanoflare model since it readily explains the ubiquitous small-scale brightenings all over the Sun. We have performed magnetohydrodynamic (MHD) simulations of the nonlinear Alfvén wave coronal heating model that include both heat 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 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.

Subject headings: MHD — Sun: corona — Sun: flares — waves

1. INTRODUCTION

The corona is the outer atmosphere of the Sun, the temperature of which is a few million degrees. Its heating mechanism, however, is not yet known. This is one of the most important unsolved problems in astrophysics. X-ray observations have revealed that the corona consists of various magnetic structures such as coronal loops (Poletto et al. 1975) and have established that the coronal heating mechanism is associated with magnetic activity. There are two promising models for coronal heating: one is that Alfvén waves in the magnetic field transport energy into the corona (Alfvén 1947; Axford et al. 1999; Ulmschneider, Priest, & Rosner 1991; Narain & Ulmschneider 1996), and the other is that the corona is heated by the accumulation of numerous small flares (Lin et al. 1984; Dennis 1985) because of magnetic reconnection (i.e., nanoflare heating; Parker 1988). The Alfvén wave heating model has a weakness in that Alfvén waves themselves are difficult to dissipate in the corona because of the very low resistivity of the coronal plasma. Therefore, it is difficult to convert the energy of these waves into thermal energy. In addition, recent X-ray and extreme-ultraviolet (EUV) observations with the soft X-ray telescope (SXT) on board the *Yohkoh* satellite, the EUV Imaging Telescope (EIT) on board the *Solar and Heliospheric Observatory* (*SOHO*) satellite, and the *Transition Region and Coronal Explorer* (*TRACE*) have revealed ubiquitous rapid and localized dynamic events in the corona and the chromosphere that favor nanoflare heating. Hence many coronal heating studies are now based on the nanoflare heating scenario. However, some studies have also suggested that the Alfvén wave model is more likely (Hollweg, Jackson, & Galloway 1982; Mariska & Hollweg 1985; Hollweg 1992; Kudoh & Shibata 1999).

Kudoh & Shibata (1999) performed 1.5-dimensional magnetohydrodynamic (MHD) numerical simulations of torsional Alfvén waves (which represent torsional fluctuations of the magnetic field that propagate along the magnetic flux tube) in the case of vertical open magnetic flux in the solar atmosphere. In their simulations, Alfvén waves are excited by random motions in the photosphere, and they found that if the amplitude of the photospheric velocity fields is greater than ~1 km s^{-1}, an energy flux is transported into the corona by torsional Alfvén waves that is sufficient to heat it (~3.0×10^5 ergs s^{-1} cm^{-2}; Withbroe & Noyes 1977). 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 Letter, we report the results of 1.5-dimensional MHD numerical simulations of coronal heating dynamics that include the nonlinear propagation of Alfvén waves, heat conduction, and radiative cooling in an emerging flux loop. The simulations suggest that the corona is episodically heated by nonlinear Alfvén waves and also that the simulated EUV and X-ray intensities are similar to what one actually observes.

2. NUMERICAL SIMULATION

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 Figure 1. Since the pressure ratio $P_{gas}/P_{mag} \approx 1$ near the photosphere and P_{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 ~1000. Our simulations are calculated along a single field line (drawn with a thick solid line and denoted by "p" in Fig. 1) along which azimuthal motions (ϕ components of velocity and magnetic fields) are allowed. This is named the 1.5-dimensional approximation. We assume an inviscid perfectly conducting plasma. In our study, the effects of conduction and radiative cooling, which were not considered by Kudoh & Shibata (1999), are now included. The classical conductivity for a fully ionized hydrogen plasma (Spitzer 1962) is used for

[1] Kwasan and Hida Observatories, Kyoto University, Yamashina-ku, Kyoto 607-8471, Japan; moriyasu@kusastro.kyoto-u.ac.jp, shibata@kwasan.kyoto-u.ac.jp.
[2] Department of Physics and Astronomy, University of Western Ontario, London, ON N6A 3K7, Canada; kudoh@astro.uwo.ca.
[3] Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; yokoyama.t@eps.s.u-tokyo.ac.jp.

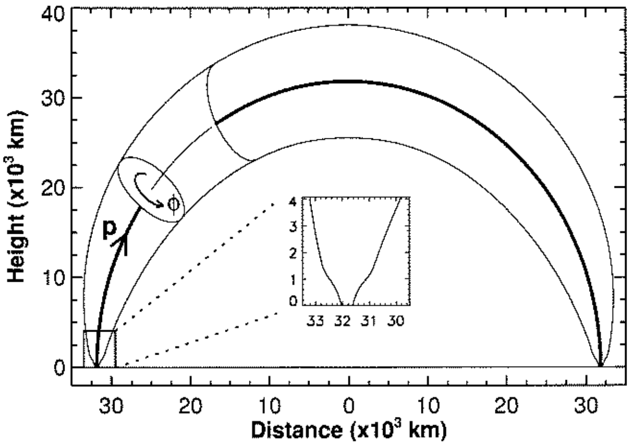

FIG. 1.—Schematic illustration of a model magnetic loop. Since the pressure ratio $P_{gas}/P_{mag} \approx 1$ near the photosphere and P_{mag} dominates with increasing height, the emerging flux tube is slim near the photosphere and expands above. Our simulations are calculated along a single field line (*thick solid line*; denoted by "p"). In addition, azimuthal motions (ϕ components of velocity and magnetic fields) are allowed.

the heat conduction. Optically thin cooling is assumed for the plasma with $T > 4 \times 10^4$ K (above the lower transition region), and the empirical cooling rate is $4.9 \times 10^9 \rho$ ergs cm^{-3} s^{-1} for the plasma with $T < 4 \times 10^4$ K (chromosphere). This value is based on the empirical result of Anderson & Athay (1989), who found that the heating rate per gram is roughly constant at 4.9×10^9 ergs g^{-1} s^{-1} over a large part of the chromosphere (see also Hori et al. 1997). Here, T is the plasma temperature and ρ the density.

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

Figure 2 shows results for a typical case in which the average amplitude of the photospheric velocity fields is ~2 km s^{-1}. The result shows that nonlinear Alfvén waves generate compres-

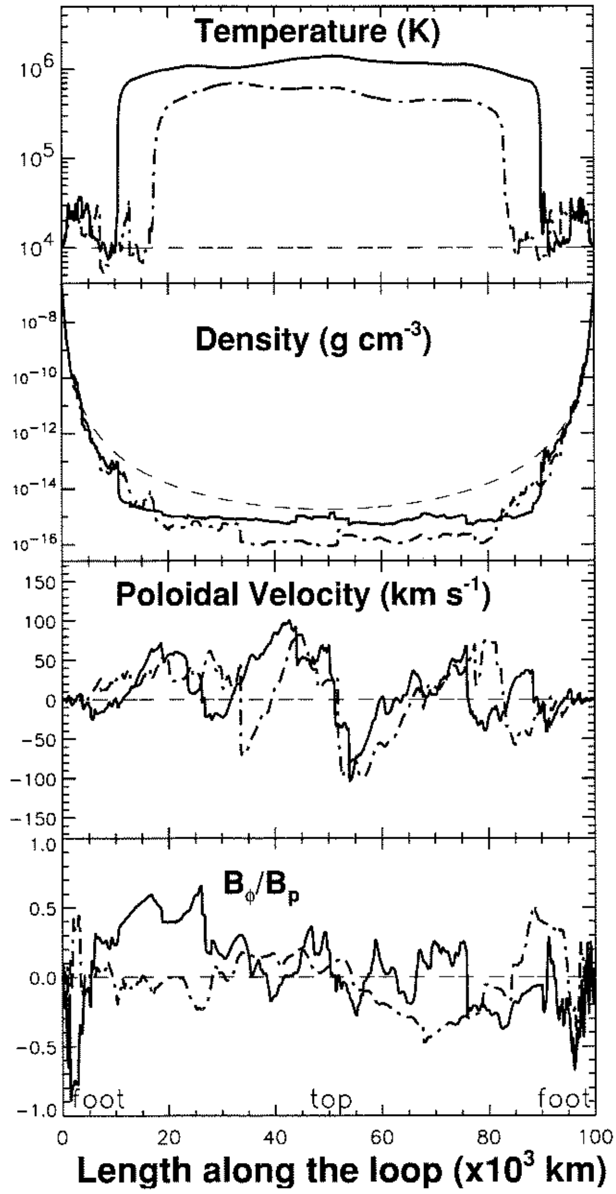

FIG. 2.—Results for a typical case, in which the average amplitude of the photospheric velocity fields is ~2 km s^{-1}, are shown. From top to bottom, profiles are shown for the temperature, the density, the poloidal component of the velocity (i.e., the component parallel to the field lines), and the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

sional 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 toward coronal temperatures (10^6 K). However, because of conduction and radiative cooling the temperature distribution becomes quasi-steady (Fig. 2) after t = 156 minutes.

The temperature in Figure 2 also shows a nearly flat profile for the coronal part of the entire loop as a result of heat 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 prop-

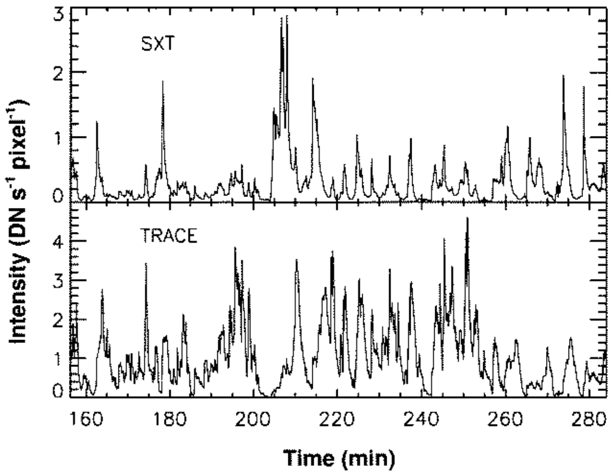

FIG. 3.—Simulated time variations of the SXT/X-ray (*top*) and *TRACE*/EUV (*bottom*) intensities at the apex of a coronal loop. These intensities are calculated using the results of the simulations in Fig. 2. There are many flarelike brightenings in intensity because of episodic heating by the MHD shocks. Furthermore, the time variations are very similar to those of the X-ray and EUV intensities actually observed by *Yohkoh*/SXT and *TRACE*, respectively.

agate from both footpoints and dissipate one after another. 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. 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 1.26×10^6 K and 9.93×10^{-2} dyne cm^{-2}, respectively. These are typical values for the corona and fit the theoretical scaling law for a steady coronal loop, $T \approx 1.4 \times 10^3 (Pl)^{1/3}$ (Rosner, Tucker, & Vaiana 1978), where P is the pressure of the plasma and l the length of the coronal loop. In our case, l is $\sim 8 \times 10^4$ km (not 10^5 km as suggested by the temperature distribution in Fig. 2). 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). As a result, it was found that if the amplitude of the photospheric velocity fields is greater than ~ 1 km s^{-1}, the plasma is heated to coronal temperatures ($\sim 10^6$ K), which agrees with the prediction of Kudoh & Shibata (1999).

Although the average coronal plasma properties are well explained by a steady or static coronal heating model, it should be stressed that the plasma in the loop never reaches hydrostatic equilibrium. Instead, it stays in a very dynamic state (Fig. 2). In fact, Figure 3 shows simulated "observations" of a theoretical coronal loop observed by *Yohkoh*/SXT and *TRACE* at the loop apex, and it shows that the temporal variation is very similar to those of the X-ray and EUV intensities actually observed with SXT and *TRACE*, respectively. These intensities are calculated using the results of the simulations in Figure 2. There are many flarelike brightenings in intensity because of the episodic heating of the corona by the MHD shocks. 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 Figure 3, all "nanoflare-like events" are due to the MHD shocks

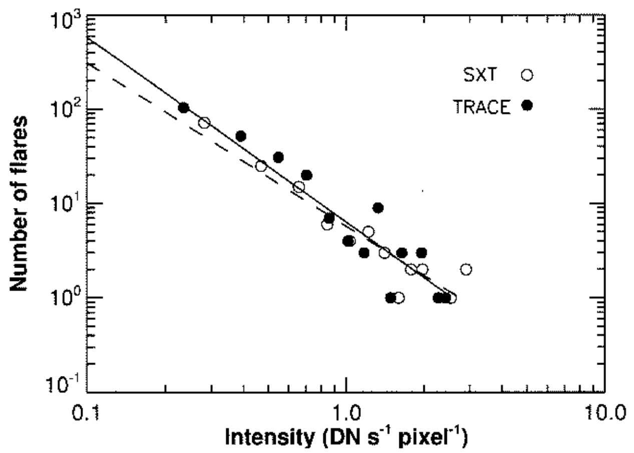

FIG. 4.—Occurrence frequency of X-ray and EUV "nanoflares" as a function of their peak intensity based on the same data as in Fig. 3 (*open circles*: SXT/X-ray; *filled circle s*: *TRACE*/EUV). This shows a power-law distribution with an index ~ -1.7 for SXT/X-ray and ~ -1.9 for *TRACE*/EUV (lines are fitted with a power law; *dashed line*: SXT/X-ray; *solid line*: *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 to -1.7 (Aschwanden & Parnell 2002), although an index $\lesssim -2.0$ has also been reported (Benz & Krucker 2002; Parnell & Jupp 2000). Thus, the Alfvén wave heating model reproduces the actual observed statistical property of micro/nanoflares rather well.

originally generated by the Alfvén waves. More interestingly, the histogram of the occurrence frequency of these "theoretical nanoflares" (Fig. 4) is also similar to that observed in the solar corona (Shimizu 1995; Hudson 1991; Aschwanden & Parnell 2002). Figure 4 shows a power-law distribution with an index ~ -1.7 for SXT/X-ray and ~ -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 the many "nanoflares" observed by recent space missions (*Yohkoh*, *SOHO*/EIT, and *TRACE*) are not in fact magnetic reconnection events but are actually MHD shock events originally generated from Alfvén waves.

4. CONCLUSION

We examined how a hot corona is created in an initially cool loop as a result of nonlinear Alfvén waves. It was demonstrated that the dissipation of Alfvén waves (via mode-coupling with slow- and fast-mode waves and shock dissipation) and the production of the coronal plasma as a result of the balance among shock heating, conduction, and radiative cooling can be self-consistently explained. Furthermore, the numerical simulations have revealed that the resulting corona is very dynamic and full of shocks, so that the temporal variation of the X-ray and EUV intensities shows many "nanoflare-type events," which is 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 actual observed time variation of the X-ray and/or EUV flux in the corona, and in the chromosphere, may not in fact be evidence of small-scale magnetic reconnections but could actually be due to Alfvén waves, contrary to current widespread opinion.

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*[4] mission that will be launched in 2006.

The authors would like to thank D. H. Brooks and the anonymous referee for many useful comments, especially concerning English improvement. This work was partially supported by the Japan Science and Technology Cooperation (ACT-JST), by a Grant-in-Aid for the 21st Century COE Center for Diversity and Universality in Physics, and also by the JSPS Japan-UK Cooperation Science Program (principal investigators: K. Shibata and N. O. Weiss). The numerical computations were carried out on VPP5000 at the Astronomical Data Analysis Center of the National Astronomical Observatory, Japan, which is an interuniversity research institute of astronomy operated by the Ministry of Education, Culture, Sports, Science, and Technology.

[4] More information about the *Solar-B* mission is available at the Institute of Space and Astronautical Science Web site, http://www.isas.ac.jp/e/enterp/missions/solar-b.

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