Reconnection, Alfvén Wave, and Coronal Heating

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Abstract. We discuss the following subjects: 1) the generation of Alfvén waves via reconnection, 2) the propagation of nonlinear Alfvén waves and associated production of spicules and coronal heating, 3) the dissipation of Alfvén waves through the mode coupling with slow and fast mode MHD waves.

1. Introduction

Recent space observations revealed that the solar corona is much more dynamic than had been thought, and that most of dynamic phenomena (such as flares and jets) are more or less related to magnetic reconnection. Hence heating due to small scale reconnection (i.e. nanoflare) (Parker 1991) has been discussed as promising mechanism for coronal heating. Nevertheless, the nanoflare heating is still controversial. For example, the occurrence frequency of microflares and nanoflares has been found to be \( \frac{dN}{dW} \propto W^{-\alpha} \) with the power-law index \( \alpha \approx 1.5 - 1.6 < 2 \) (Shimizu 1995; Shimojo & Shibata 1999; Aschwanden et al. 2002), suggesting that the total energy released by nanoflares is not dominant for heating the corona. (Here, \( N \) is the number of events (micro/nanoflares) and \( W \) is the energy per event.) However, Krucker & Benz (1998) found \( \alpha > 2 \) from SOHO/EIT data (Benz & Krucker 2002), and Parnell & Jupp (2000) also found \( \alpha > 2 \) using TRACE data. There is another approach to the coronal heating problem. Yashiro & Shibata (2001) analyzed Yohkoh/SXT data to find the relation between average gas pressure \( p \) and magnetic field strength \( B \) of active regions, and obtained \( p \propto B^{3.78} \). This supports Alfvén wave model rather than nanoflare model if a simple situation is assumed. (But see Sturrock (1999) for more elaborate nanoflare model which seems to be consistent with these observations.) It is clear that more work is needed to settle the coronal heating problem.

In this paper, we first note that magnetic reconnection can generate Alfvén waves (Yokoyama & Shibata 1996; Yokoyama 1998; Takeuchi & Shibata 2001a,b) and hence nanoflare model may be unified with Alfvén wave model. With this in mind, we next explore the generation of spicules and coronal heating by Alfvén waves (Kudoh & Shibata 1999; Saito et al. 2001). The results are quite encouraging: if Alfvén waves with amplitude of more than 1 km/s are generated in the photospheric level, spicule generation, nonthermal line width in the transition region and corona, and coronal heating are all explained consistently. Finally, we examine the heating of a loop by Alfvén waves, using the self-consistent MHD...
Figure 1. Time variation of spatial distributions of density ($\rho$) (left) and velocity along the flux tube ($V_s$) (right). In both figures, the horizontal axis is the height from the photosphere (along the vertical flux tube) in unit of 1000 km, and the vertical axis is either log $\rho$ (left) or $V_s$ (right). The plots at various time are stacked with time increasing upward in uniform increments of 7.2 s, and the numbers attached to the vertical axis are time in unit of minutes (from Kudoh & Shibata 1999). Note that the transition regions are lifted up quasi-periodically by the effect of slow and fast mode MHD shocks (seen as large amplitude velocity $V_s$) which are generated by nonlinear Alfvén waves.

Simulations of nonlinear Alfvén wave propagation in a loop with heat conduction and radiative cooling (Moriyasu et al. 2002), and apply the results to the generation of a coronal loop in emerging flux regions. The results show that the heating is due to both slow and fast mode MHD shocks which are generated by nonlinear mode coupling with Alfvén waves, and also that the time scale of appearance of a hot coronal loop in emerging flux is roughly consistent with TRACE observations of emerging flux regions.

2. Generation of Alfvén Waves by Reconnection

It has often been thought that the nanoflare model is very different from the Alfvén wave model. Actually, however, if reconnection occurs, Alfvén waves are generated, and hence the difference between the nanoflare model and the Alfvén wave model may be smaller than had usually been thought. Parker (1991)
already argued that Alfven waves are generated via nanoflare reconnection in the corona, and such Alfven waves could be the source of heating and acceleration of high speed solar wind. Axford et al. (1999) and McKenzie & Axford (1997) also proposed that the picoflare in the chromosphere can be the source of Alfven waves which eventually accelerate high speed solar wind (also see Hu & Habbal 1999; Sturrock 1999; Sturrock et al. 1999). Both ideas are consistent with the observations of Alfven waves in the solar wind.

How much are Alfven wave flux generated through the reconnection? Yokoyama (1998) first quantitatively estimated energy flux carried by Alfven waves in the reconnection associated with emerging flux, using the nonlinear, nonsteady 2.5D MHD numerical simulations (Yokoyama & Shibata 1996). He found that the fraction of Alfven wave energy flux is about 10-20% of the total energy flux released during the reconnection. More recently, Takeuchi & Shibata (2001a,b) measured energy flux of Alfven waves generated in the magnetic reconnection in the photosphere, confirming Yokoyama's results in a different geometry. They have also shown that the energy flux of Alfven waves is enough to explain both coronal heating and spicule production (Kudoh & Shibata 1999, see next section).

3. Alfven Wave Model of Spicules and Coronal Heating

Spicules are basic dynamic structure of the chromosphere in the quiet region of the Sun, especially in the magnetic network boundary (see Sterling 2000 for a
Figure 3. Mean value of the energy flux in the corona as a function of $<v^2_\phi>^{1/2}$ in the photosphere (upper panel), and $<v^2_\phi>^{1/2}$ in the corona as a function of $<v^2_\phi>^{1/2}$ in the photosphere (lower panel). The dashed line shows the result of the WKB approximation (from Kudoh & Shibata 1999).

review). Spicules and associated dynamical processes in the network boundary may be important not only in chromospheric heating but also in coronal heating, since almost all magnetic field lines in the quiet corona are coming from the magnetic network boundary in the chromosphere. Hollweg et al. (1982) first performed 1.5D MHD simulation of nonlinear propagation of Alfven wave (with initially sinusoidal single pulse) along vertical flux tubes extending from the photosphere to the corona, and have shown that the nonlinear effect of large amplitude Alfven waves excite both slow and fast mode MHD waves which can accelerate spicules and heat the corona via shock dissipation.

More recently, using the same approach (i.e., 1.5D MHD simulations) but with random torque perturbation in the photospheric footpoints of a flux tube, Kudoh & Shibata (1999) have performed longer numerical simulations as well as more comprehensive parameter survey of the nonlinear propagation of Alfven waves along the vertical flux tube in the solar atmosphere (see Fig. 1 and Fig.
2). They found that if the amplitude of the photospheric velocity fields is larger than 1 km/s, (1) spicules are formed (i.e. the height of the transition region accelerated by slow and fast mode shocks generated by Alfvén waves is more than 5000 km), (2) energy flux enough to heat the quiet corona (\(\sim 10^5\) erg cm\(^{-2}\) s\(^{-1}\)) can be transported into the corona by Alfvén waves, and (3) nonthermal line widths of transition region lines and coronal lines (\(\sim 10 - 20\) km/s) are also explained by the velocity fields associated with nonlinear Alfvén waves in the transition region and the corona (see Fig. 3). Saito, Kudoh & Shibata (2001) further extended this model and explained why spicules are tall in the coronal hole and absent (or short) over plages (see also Shibata & Suematsu (1982) for a basic idea).

4. Are Alfvén Waves Really Dissipated in the Corona?

All previous simulation studies of Alfvén wave model (Hollweg et al. 1982; Hollweg 1992; Kudoh & Shibata 1999; Saito et al. 2001) have shown that the energy flux enough to heat the corona can be transported by nonlinear Alfvén waves. They have shown promising mechanism of dissipation, i.e., shock formation, but this mechanism can work mainly in the upper chromosphere, not in the corona. Hence one may ask “Are Alfvén waves really dissipated in the corona in a realistic situation?”.

Recently, Moriyasu et al. (2002) challenged this question in the case of coronal loop heating, and obtained the successful results. They performed 1.5D MHD numerical simulations of coronal heating dynamics including nonlinear propagation of Alfvén waves, heat conduction, and radiative cooling (optically thin cooling in the corona and empirical cooling in the chromosphere), in a coronal loop with a length of 10\(^5\) km with non-constant cross-sectional area (the ratio of cross-section between the loop top and the loop foot is \(\sim 1000\)) (see Fig. 4). The treatment of the perturbation in the photosphere is basically the same as in Kudoh & Shibata (1999), i.e., random torque perturbation is given at both footpoints of the magnetic loop.

The initial temperature distribution along the loop is 10\(^4\) K, i.e., chromospheric temperature. This was assumed to see how the corona is created from the low temperature chromospheric plasmas. The initial density distribution along the loop is not in hydrostatic equilibrium, but is mimicking non-hydrostatic distribution seen in the case of emerging flux dynamics (Shibata et al. 1989).

Basic dynamics they found in the chromosphere are also basically the same as those in Kudoh & Shibata (1999): Nonlinear Alfvén waves generate compressional slow and fast mode MHD waves. The initially cool plasma (10\(^4\) K) is gradually heated by slow and fast mode MHD shocks to coronal temperature (10\(^6\) K), and after t = 156 min, the temperature distribution becomes quasi-steady. Though the average coronal plasma properties are well explained by steady or static coronal heating model, it should be stressed that the plasma in the loop never reaches hydrostatic equilibrium but instead in a very dynamic state. In fact, Figure 5 shows “observations” of theoretical coronal loop (by Moriyasu et al 2002) with TRACE, which shows that the time variation is very similar to that of EUV intensity observed with TRACE. If such time variation is observed, it is often considered that all time variation is due to microflares.
Figure 4. Schematic illustration of a model magnetic loop (from Moriyasu et al. 2002).

Figure 5. (Left) The predicted time variation of TRACE/EUV intensities at the top of a coronal loop heated by slow and fast mode MHD shocks generated from nonlinear Alfvén waves. (Right) The occurrence frequency of the EUV “nanoflares” as a function of their peak intensity (based on the same data shown in the Left). Both figures are made using the results of 1.5 MHD simulations (from Moriyasu et al. 2002).
or nanoflares. However, in the case of Figure 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 nanoflare” (see the right panel of Figure 5) is also similar to those observed in the solar corona (Shimizu 1995; Krucker & Benz 1998). Hence there is a possibility that many of various “nanoflares” observed by recent space missions (Yohkoh, SOHO/EIT, TRACE) may not be reconnection events, but may be MHD shock events originally generated from Alfvén waves.

5. Summary and Discussion

In this paper, we first emphasize that the reconnection can be a good source of Alfvén waves, and discuss how much Alfvén wave energy flux are generated in the reconnection process, based on numerical simulations (Yokoyama 1998; Takeuchi & Shibata 2001a,b). The simulation results show that the Alfvén wave energy flux is ~ 10 – 20% of total released energy during the reconnection. This is encouraging since recent SOHO and TRACE observations have revealed that magnetic reconnection is ubiquitous not only in the corona and the chromosphere but also in the photosphere (e.g., Schrijver et al. 1997).

On the other hand, the 1.5D numerical simulations of nonlinear Alfvén wave propagation in the solar atmosphere along a vertical flux tube have shown that spicules, coronal heating, and nonthermal line width in the transition region and corona are all explained by Alfvén waves if their amplitude is larger than 1 km/s in the photosphere. In the above, we discussed the possibility of Alfvén wave generation through reconnection, but there still remains other possibilities of Alfvén wave generation, e.g., by turbulent agitation of vertical flux tubes (e.g., van Ballegooijen 2002, private communication). Future high spatial resolution observations of the photosphere with Solar B and ATST would clarify this basic question on the generation of Alfvén waves.

We examined how a hot coronal is created in an initially cool loop as a result of nonlinear Alfvén waves (Moriyasu et al. 2002). It was found that not only the generation of compressional wave modes (slow and fast modes) but also dissipation of Alfvén waves (via mode coupling with slow and fast mode waves) 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 time variation of X-ray and EUV intensities show many “nanoflares”, quite similar to what is actually observed. Even the statistical properties of these “nanoflares” are similar to those observed; the power law distribution. This suggests that actually observed time variation of X-ray and/or EUV flux in the corona and the chromosphere may not be evidence of small scale reconnection but may be evidence of Alfvén waves, contrary to current belief.

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