PROPA GATION OF NONLINEAR ALFVÉN WAVES IN THE SOLAR ATMOSPHERE: PRODUCTION OF SPI CULES AND CORONAL HEATING

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ABSTRACT

We present the results of 1.5-dimensional MHD simulations for solar spicule formation and heating of the corona. The MHD simulations are performed for toroidal Alfvén waves which propagate in an open magnetic flux tube in the solar atmosphere. The Alfvén waves are assumed to be generated by random motions in the photosphere. As the Alfvén wave propagate up in the solar atmosphere, a part of the Alfvén wave is reflected at the transition region and produces a slow mode magnetohydrodynamic wave. Then, the slow mode wave lift up the transition region and produces a spicule. The remaining Alfvén wave propagate up to the corona and will contribute to heating of the corona. Our simulation shows that the enough energy flux for heating the quiet corona ($\sim 3.0 \times 10^5$ erg/s/cm$^2$) is transported if the root mean square of the random motion in the photosphere is greater than $\sim 1$ km/s. Moreover, the transition region is lifted up to more than $\sim 5000$ km when the enough energy flux for coronal heating can be transported to the corona. We expect that the velocity fluctuation of $\sim 1$ km/s in the photosphere could be observed by the Solar B satellite.

Key words: spicules; coronal heating; MHD.

1. INTRODUCTION

Spicules are one of the dynamic phenomena in the quiet regions of the solar atmosphere (e.g., Beckers 1972, Nishikawa 1982, Suematsu, Wang, & Zirin 1995). They are the jets emanating from supergranulation boundaries which trace magnetic field lines. Suematsu et al. (1982), and subsequent authors (Shibata et al. 1982, Shibata 1982, Shibata & Suematsu 1982, Hollweg 1982, Suematsu 1985, Sterling & Mariska 1990, and Sterling, Shibata, & Mariska 1993) considered gasdynamic shocks which propagate along a magnetic flux tube (i.e., slow mode MHD shocks) and lift up the transition region and underlying chromosphere. They suggested that the elevated, upward-moving chromospheric material is observed as spicules. Hollweg, Jackson, & Galloway (1982), Mariska & Hollweg (1985), and Hollweg (1992) studied the dynamical effects of axisymmetric toroidal motions propagating in an axisymmetric vertical magnetic flux tube. Their numerical simulation shows that magnetohydrodynamic fast shock which is produced in the chromosphere also impel the transition region and underlying chromosphere upward. They also argued that the nonlinear Alfvén wave propagating along the flux tube could be the heating source of the solar corona.

In this paper, we considered the situation almost same as Hollweg et al. (1982). However, we imposed random perturbations in the photosphere instead of sinusoidal perturbations assumed by Hollweg et al. (1982). We will discuss the relation between the production of spicules and heating of corona quantitatively.

Figure 1. The shape of the flux tube we assumed. The initial plasma beta is $\beta = 1$ at the photosphere, and $\beta = 0.04$ at the corona.

2. THE MODEL

A shape of an open flux tube from the photosphere is assumed to be fixed in a solar atmosphere (Fig. 1), although the toroidal motion of the tube is allowed (1.5-dimensional approximation). Initially, the atmosphere is stratified in a constant gravity of the solar surface \( g = 2.74 \times 10^4 \text{ cm s}^{-2} \). The initial transition region is assumed at \( \sim 2250 \text{ km} \) from the photosphere. The strength of the magnetic field is assumed to be \( \sim 1600 \text{ Gauss} \) in the photosphere and \( \sim 7.8 \text{ Gauss} \) in the corona. The random perturbation of torque is continually imposed in the photosphere through a calculation. The calculation is performed from \( t=0 \) to \( t=25 \text{ minutes} \).

3. RESULTS

3.1. Production of Spicules

Fig. 2 shows that the time variation of the density structure along the flux tube. The plots at various time are stacked with time increasing upward in uniform increments of 7.2 second. The transition region is lifted up by nonlinear toroidal Alfvén waves, and fall down by the gravity. The maximum height is about 5000 km in this case. Fig. 3 shows the density (upper) and temperature (lower) at \( t = 17 \text{ minutes} \). The upward-moving chromospheric material is observed as spicules.

3.2. Coronal Heating

Fig. 4 shows the time variation of rotational velocities of a flux tube in the photosphere (upper) and in the corona (lower). The random torque imposed in the photosphere causes the rotation of the flux tube. It propagates along the tube as an Alfvén wave. The rotational velocities in the corona is larger than that in the photosphere because the density of the corona is smaller than that of the photosphere.

Fig. 5 shows time variation of velocities along the flux tube in the photosphere (upper) and in the corona (lower). The nonlinear effect of the toroidal Alfvén wave produces a longitudinal wave (slow mode) in the flux tube. The velocity along a tube is very small in the photosphere, while in the corona, it becomes the same order of magnitude as rotational velocity.

The Alfvén wave which propagates up to the corona will contribute to heating of the corona. Fig. 6 shows the time variation of energy flux propagating in the corona (15000 km), and its integral by time. The enough energy flux which is needed for heating the quiet corona is about \( 3.0 \times 10^5 \text{ erg s}^{-1} \text{ cm}^{-2} \). The
mean value of the flux is greater than $3 \times 10^5$ erg cm$^{-2}$/s in this case.

3.3. Nonthermal Broadening of Emission Lines

Fig. 7 shows that the root mean square of rotational velocity as a function of temperature. The rotational velocity increases with temperature until $10^5$ K, and it is nearly constant when the temperature is greater than $10^5$ K. The rotational velocity of the flux tube would be observed as the nonthermal broadening of emission lines in the transition region and corona. Nonthermal broadening of optically-thin emission lines is summarized by Mariska (1992). The overall feature of Fig. 7 is consistent with the observations (Fig. 5.2 Mariska 1992).

3.4. Coronal Heating and Spicules

We performed the simulation of several cases by changing the strength of the torque in the photosphere. Fig. 8 shows the mean value of the flux in the corona as a function of the root mean square of the rotational velocity in the photosphere (upper), and the root mean square of the rotational velocity in the corona as a function of the root mean square of the rotational velocity in the photosphere (lower). The filled circles means that the maximum height of the transition region is greater than 5000 km, and the open circles is the case that it is smaller than 5000 km. The upper panel shows that (1) the enough energy flux for heating of the quiet corona ($\sim 3.0 \times 10^5$ erg/s/cm$^2$) is transported if the root mean square of the random motion is greater than $\sim 1$ km/s in the photosphere, and (2) the transition region is lifted up to more than $\sim 5000$ km when the enough energy flux for coronal heating is transported to the corona. The lower panel shows that the rotational velocity is
4. DISCUSSIONS

The speed of the turbulent convection in the photosphere is observed to be > 1 km/s, and this could buffet the flux tube randomly. The magnetic reconnection between the network field (flux tube) and the mixed polarized (small bipolar) in the photosphere could also be the efficient source of high frequency Alfvén waves. Our simulation shows that the enough energy for the coronal heating of the quiet sun can be transported into corona as Alfvén waves. The rotational velocity of the flux tube would be observed as the nonthermal broadening of lines in the transition region and corona. Its value (~ 30 km/s) is consistent with the observations when the enough energy flux for coronal heating is transported to the corona. Moreover, it is interesting that the transition region is lifted up to more than ~ 5000 km when the energy flux in the corona is greater than ~ 3.0 x 10^5 erg s^{-1} cm^{-2}. The result of our simulation suggests that the quiet hot corona, nonthermal broadening of lines, and spicules are all explained by the nonlinear Alfvén waves which are generated by the convections and/or the reconnection in the photosphere and propagate along the magnetic flux tube in the solar atmosphere.