ALFVÉN WAVE MODEL OF SPICULES

T. Kudoh, K. Shibata
National Astronomical Observatory of Japan, Mitaka, Tokyo 181, Japan

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 torsional 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 propagates upward 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 lifts up the transition region and produces a spicule. The remaining Alfvén wave propagates upward to the corona and will contribute to heating of the corona. Our simulation shows the following results. If the root mean square of the random motion is greater than \( \sim 1 \text{ km/s} \) in the photosphere, 1) the transition region is lifted up to more than \( \sim 5000 \text{ km} \) (i.e., the spicule is produced), 2) the energy flux enough for heating the quiet corona (\( \sim 3.0 \times 10^{8} \text{ erg/s/cm}^{2} \)) is transported into the corona, and 3) non-thermal broadening of emission lines in the corona is expected to be \( \sim 20 \text{ km/s} \).

Key words: spicules; coronal heating; MHD.

1. INTRODUCTION

Spicules are one of the dynamic phenomena in the quiet regions of the solar atmosphere (Beckers 1972, Foukal 1987, Matsuno & Hirayama 1988, Nishikawa 1988, Suematsu, Wang, & Zirin 1985). 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 & Suematsu 1982, Hollweg 1982, Suematsu 1985, Sterling & Mariska 1990, Cheng 1992a;1992b, Sterling, Shibata & Mariska 1993, and Andreev & Kosovichev 1994) considered gasdynamic shocks which propagate along a magnetic flux tube (i.e., slow mode MHD shocks) and lift up the transition region. They suggested that the elevated, upward-moving chromospheric material is observed as spicules. Hollweg, Jackson, & Galloway (1982), Mariska & Hollweg (1985), Hollweg (1992), and Cargill, Spicer & Zalesak (1997) studied the dynamical effects of axisymmetric torsional motions propagating in an axisymmetric vertical magnetic flux tube. Their numerical simulations show 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 (see also, e.g., Ofman & Davila 1995: 1997a; 1997b; Boynton & Torkelsson 1996). Recently, Haerendel (1992) and de Pontieu (1997) showed the another model in which the dissipation of the Alfvén wave caused by the neutral elements is important for the production of spicules.

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.

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 torsional 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 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 torsional Alfvén waves, and fall down by the gravity. The maximum height is about 5000 km in this case. Fig. 3 and Fig. 4 show


© European Space Agency • Provided by the NASA Astrophysics Data System
Figure 1. The shape of the flux tube we assumed. The initial plasma beta is $\beta = 1$ in the photosphere, and $\beta = 0.04$ in the corona.

Figure 2. The time variation of density distribution. The plots at various time are stacked with time increasing upward in uniform increments of 7.2 second.

Figure 3. The time variation of velocity along the magnetic field line.

Figure 4. The time variation of $B_\phi/B_s$.

the time variation of the velocity along the field line and the toroidal magnetic field ($B_\phi$) normalized by the poloidal field ($B_s$), respectively. We can see that the slow mode MHD wave is generated by the torsional Alfvén wave propagating in the chromosphere. Fig. 5 shows the density (upper) and temperature
3.2. Coronal Heating

Fig. 6 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. 7 shows time variation of velocities along the flux tube in the photosphere (upper) and in the corona (lower). The nonlinear effect of the torsional Alfvén wave produces a longitudinal wave (slow wave) 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.

Fig. 8 and Fig. 9 show power spectra of velocities. Since we input the random torque in the photosphere, the spectra in the photosphere nearly show the flat spectra (cf. Tarbell et al. 1990). We can see the mode of high frequency is dumped in the corona. The spectra in the corona show 'Power $\propto$ Frequency$^{-2}$' in the rough.

The Alfvén wave which propagates up to the corona will contribute to heating of the corona. Fig. 10 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 $\sim 3.0 \times 10^{5}$ erg s$^{-1}$ 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. 11 shows that the root mean square of velocities as a function of temperature. The velocities increase with temperature until $\sim 10^{6.5}$ K, and they are nearly constant when the temperature is greater than $\sim 10^{4.5}$ 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
3.4. Coronal Heating and Spicules

We performed the simulation of several cases by changing the strength of the torque in the photosphere. Fig. 12 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 (∼ 3.0 × 10^3 erg/s/cm^2) is transported if the root mean square of the random motion is greater than ∼ 1 km/s in the photosphere, and (2) the transition region is lifted up to more than ∼ 5000 km when the enough energy flux for coronal heating is transported to the corona.

The lower panel shows that the rotational velocity is greater than 20 km/s when the enough energy flux is transported to the corona.

4. DISCUSSIONS

The speed of the turbulent convection in the photosphere is observed to be > 1 km/s, and this could buffer the flux tube randomly. The magnetic reconnection between the network field (flux tube) and the mixed polarity (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 (∼ 20 km/s) is consistent with the observations when the enough energy...
Figure 12. The mean value of the flux at the corona as a function of the root mean square of the rotational velocity at the photosphere (upper), and the root mean square of the rotational velocity at the corona as a function of the root mean square of the rotational velocity at the photosphere (lower).

...flux for coronal heating is transported to the corona. Moreover, it is interesting that the transition region is lifted up to more than \( \sim 5000 \text{ km} \) when the energy flux in the corona is greater than \( \sim 3.0 \times 10^{3} \text{ erg s}^{-1} \text{ cm}^{-2} \). 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 reconnection in the photosphere, and propagate along the magnetic flux tube in the solar atmosphere.

Numerical computations were carried out on VX/4R at the Astronomical Data Analysis Center of the National Astronomical Observatory, Japan.

REFERENCES

Andreev, A.S., Kosovichev, A.G. 1994, Space Science Reviews, 70, 53

De Pontieu, B., 1997, Doctor Thesis
Shibata, K. 1982, Solar Phys., 81, 9
Shibata, K., Nishikawa, T., Kitai, R., & Suematsu, Y. 1982, Solar Phys., 77, 121
Shibata, K., & Suematsu, Y. 1982, Solar Phys., 78, 333