Heating of the Solar Atmosphere by Spicules

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Abstract. We simulate a solar spicule numerically with a single quasi- impulsive wave, which is generated in the photosphere and propagates upward along a flux tube. In the calculations radiation, ionization, conduction and mechanical heating are taken into account. From the rise and fall of the spicular material it is shown that the observed downflow at the temperature of $10^5 K$ in the chromosphere-corona transition region is a direct result of the spicular upflow, and that the spicules can play a significant role in the energy balance and the heating of the upper solar atmosphere.

1. Introduction

Solar spicules have a jet-like structure and are believed to be relatively cool gas masses protruding from the upper chromosphere into the hot corona. Spicules are observed to have a temperature of $T \approx 1.5 \cdot 10^4 K$ and a density of $\rho \approx 1 \cdot 10^{-13} g/cm^3$. They may rise to maximum heights between $6000 \sim 10000 km$ with average velocities of $v \approx 20 km/s$. The lifetime of spicules is about 25 minutes (Beckers, 1972). The estimated average mass flux of the spicules exceeds that which emerges as solar wind by about two orders of magnitude (Athay and Holzer, 1982). Therefore, most of the spicular mass must return to the solar surface.

Systematic downflows with velocities of $v \approx 4 \sim 17 km/s$ are observed in the CIV line at $T \approx 1 \cdot 10^5 K$ in the transition region (TR). Athay and Holzer (1982) found that the mass flux of the downflows agrees well with that of the spicular upflows. Thus, it is possible that the material observed in the downflow has its origin in the upward moving spicule material.

In this work we investigate the occurence of a downflow at $T = 10^5 K$ and the role of spicules in heating of the solar atmosphere using a numerical simulation of a spicule.

2. Method

We assume a flux tube with constant cross sectional area along the height x measured from the base where $\tau_{5000} \approx 1$. The simulation is performed by solving the time- dependent equations of mass-, momentum- and energy conservation numerically with the *implicit upwind code* developed by Korevaar (1989). Effects of optically thin radiation, ionization of hydrogen, heat conduction and mechanical heating are included in the calculations. The initial model is a stationary solar atmosphere with transmitting left- and right boundaries.

The initial wave pulse is generated at the left boundary by a single half-cycle sine-wave with velocity amplitude $v_w = 2.24 km/s$ and period $P_w = 180 s$. Due to the strong nonlinearity, the wavefront evolves into a shock with an oscillative wake behind it which generates so-called rebound shocks. The shock resulting from the wavefront interacts with the TR and lifts it up. The ascending material flux following the TR can be regarded as a spicule since it has the major properties of the observed spicules (Hollweg, 1982; Sterling et. al., 1988). Because of the radiative losses, the gravitation and the effects of the rebound shocks, the transition region oscillates about

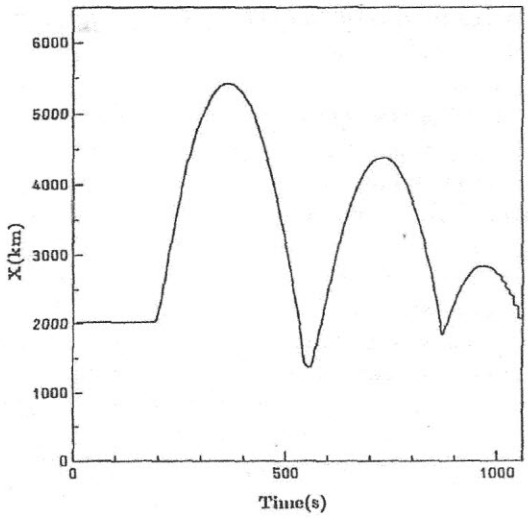

Fig. 1: Time variation of the top of the spicule (TS) height.

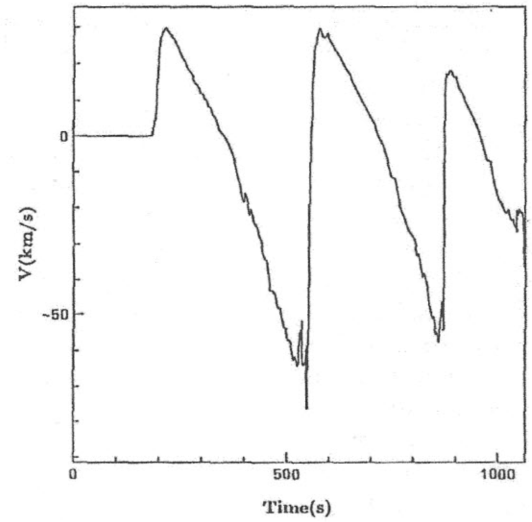

Fig. 2: Time variation of the velocity (km/s) at the level $T = 10^5 K$.

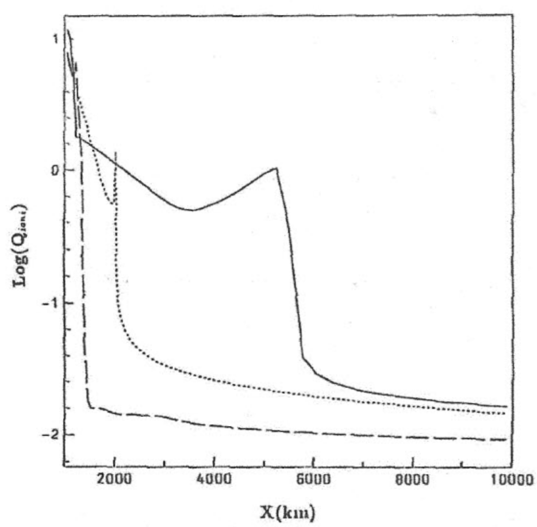

Fig. 3: Distribution of the ionization energy $E_{ioni}(erg/cm^3)$ at $t = 0s$ (dotted), $t = 361s$ (solid) and $t = 557s$ (dashed).

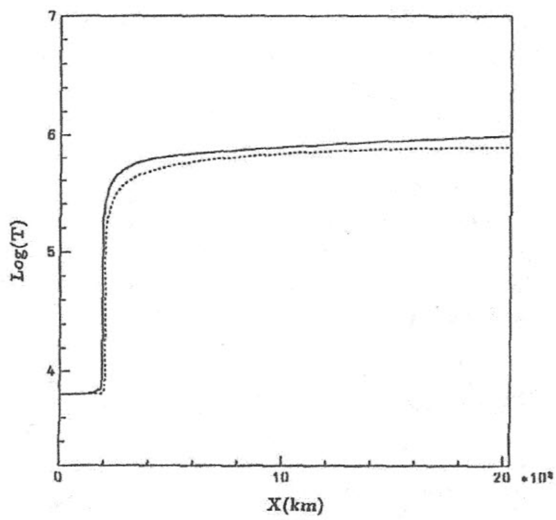

Fig. 4: Distribution of the temperature $T(K)$. Dotted: $t = 0s$; solid: $t = 1070s$. Solar atmosphere has been heated by the spicule.

its equilibrium position and the spicule disappears gradually. Finally the transition region comes back to the initial stationary state.

3. Results

Fig. 1 shows the time variation of the top of the spicule height (TS) with TS the height where the density $\rho = 1 \cdot 10^{-13} g/cm^3$. At time $361s$ the TS reaches the maximum height $5420km$. The average ascending velocity is about $20km/s$ and the ascending time is $172s$, which are the typical values obtained from observations of spicules. The spicule falls with about the same velocity and the same time as it ascends. It declines gradually and shows recurrent behavior.

Fig. 2 shows the velocity at the height where $T = 1 \cdot 10^5 K$. The amplitude of the negative velocity is much larger than that of the positive velocity, and the negative velocity occurs also for a longer time during one cycle. Averaging the velocity over the first oscillation period we find a mean value $\bar{v}$ of about $-12.2km/s$. From $190s$ to $2230s$ the average velocity is $-6.6km/s$. This indicates an average downflow in the CIV emitting region where $T = 10^5 K$. A detailed calculation shows that the downflow velocity $\bar{v}$ at the level of $T = 10^5 K$ has a maximum value, and is considerably smaller above and below this level. This result gives a natural explanation of the observations (Athay, 1987). Thus, the conclusion can be drawn here that a systematic downflow at the temperature $10^5 K$ level might be a consequence of the decline of spicules.

Considering the exchange of energies, we have found that, when the material of the spicule rises, the kinetic energy turns into potential and thermal energy, while during the return of the material the potential and thermal energies decrease and partly change into kinetic energy again. The ionization of hydrogen plays a significant role in the exchange of energies. Fig. 3 shows distributions of the ionization energy $E_{ioni}(erg/cm^3)$, with dotted line at time $t = 0s$, solid line at $t = 361s$ where TS has the maximum height and dashed line at $t = 557s$ where TS has the minimum height (see also Fig. 1).

Fig. 4 presents the distributions of the temperature at $t = 0s$ (dotted) and at $t = 1070s$ (solid). It can be seen that the upper solar atmosphere is heated by the spicule.

4. Conclusion

Using a time-dependent numerical simulation of a solar spicule, we have investigated the observed downflow at the temperature near $10^5 K$ where the CIV lines are emitted, and found that the downflow might well be a direct consequence of the spicular upflow and that spicules can play a role in the heating of the upper solar atmosphere.

Our calculation has provided a reasonable explanation of the lifetime of spicules and of the persistent downflow velocities near $T = 10^5 K$. Although there are upward- and downward motions of the material at the position where the temperature $T = 10^5 K$, a temporal average of the velocity shows that the negative velocity is significantly larger and thus a downflow emerges naturally.

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