On a Mechanism of Spicule Formation by Shock Waves in Magnetic Tubes

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Abstract – A mechanism is considered that supports the existence of spicules owing to a sequence of magnetohydrodynamic shock waves propagating inside an expanding magnetic flux tube. Shock waves arise as a consequence of tube compression by external pressure, which increases in the lower chromosphere. The maximum velocities and height of ascent of the spicule material, as well as the process of its subsequent descent, significantly depend upon the radiative loss of power and other dissipative processes.

INTRODUCTION

Spicules are known to be one of the most widespread small-scale phenomena in the solar atmosphere. It is likely that their contribution to the transfer of heat and mass to the corona is quite significant. Our models are based on the idea of spicule origin and existence owing to the propagation of a shock wave sequence, which lifts the plasma in a vertically oriented flux tube [1]. The source of the shock waves is perturbations of a relatively strong magnetic field in the lower chromosphere regions. As a result of the nonlinear non-equilibrium wave effect [2], these perturbations lead to the emergence of quasiperiodic sequences of slow MHD shock waves, supporting the existence of spicules. Such a mechanism can take place not only in spicules but also in macropicules and various types of ejections, from microejections to strong coronal ejections. The lower end of the magnetic flux tube under discussion is situated in subphotospheric layers; the upper one goes into the corona. The model is described by a system of non-stationary MHD equations in a 1.5-dimensional approximation.

The preceding calculations [3 - 5] showed that, though some of the observed phenomena can be described by similar gasodynamical models, the discrepancies between theory and observation remain. This is particularly true of the maximum height and ascent speed of spicules. The spicules in the above-mentioned models arise as a result of piston action or pressure perturbation in the lower atmosphere. However, the initial perturbations leading to the spicule formation are likely to arise as a result of the complex interaction between plasma flows and the magnetic field; hence, they can be of a nonlocal character. To better understand the spicule mechanism, Andreev [6, 7] considered the following types of the initial perturbations: (1) the piston rising along the tube at a constant speed; (2) a modified Somov–Syrovatskii model [8], based on the idea of spicule material compression by the magnetic field [9]; (3) local heating and compression of the plasma in the regions of relatively strong vertical magnetic field in the lower chromosphere, mainly at the boundaries of the chromospheric network cells; and (4) the rising magnetic loop acting as a piston. The results of these computations have led to the preliminary conclusion that mechanism (2) of the magnetic compression in the chromosphere is most adequate for the spicule modeling. In this work, we present some new results on the investigation of the magnetic compression mechanism.

MODEL

Vertical motions in the magnetic flux tube are described by the following equations:

\[
\begin{align*}
\frac{dz}{dt} &= \nu, \\
\frac{d\nu}{dt} &= -A\frac{\partial p}{\partial s} - g, \\
\frac{\partial}{\partial t} \left( \frac{1}{A\rho} \right) &= \frac{\partial \nu}{\partial s}, \\
\frac{\partial E}{\partial t} &= -p\frac{\partial}{\partial s} \left( \frac{1}{\rho} \right) - Q_{\text{rad}}, \\
p + \frac{B^2}{8\pi} &= p_{\text{ext}}, \quad BA = \Phi = \text{const},
\end{align*}
\]

(1)

where \( s \) is the mass Lagrangian coordinate (\( ds = \rho Adz \)); \( z \) is the height above the photosphere; \( A(t, z) \) is the magnetic tube cross-section; \( \nu \) is velocity; \( p \) and \( B \) are, respectively, the gas pressure and the magnetic field intensity inside the tube; \( \Phi \) is the magnetic flux; \( p_{\text{ext}} \) is the sum of the gas and magnetic pressures outside the tube; \( p \) is the density inside the tube; \( E \) is the internal energy density; \( g \) is the gravity acceleration; and \( Q_{\text{rad}} \) is the cooling rate due to radiation. In accordance with [10], we consider the plasma ionization, which increases the wave energy dissipation in the upper chromosphere. The cooling due to radiation is considered in the optically thin layer approximation, in the form suggested in [11, 12].
For a numerical solution of equations (1) and (2), we employed a fully-conservative finite-difference scheme of the second-order approximation, in which the discrete analogs of mass, momentum, and energy conservation laws are strictly valid, together with additional expressions determining the balance between the internal energy on the one hand, and the sum of the kinetic and gravitational energy on the other hand [13].

We used model [14], with a linear expansion of the magnetic lines of force with height, as the initial flux tube model. The temperature inside and outside the tube is thought to be equal at any given height. Taking the tube radius 100 km and the magnetic field 1500 G at the photospheric level (height \( z = 0 \)), the parameters of the tube are unambiguously determined from the equations of hydrostatics.

We suppose that the spicules form as a consequence of the external pressure \( p_{\text{ext}} \) increase, resulting either from the magnetic tube interaction with adjacent magnetic structures or from the external magnetic field amplification. This perturbation is described in our model by the following expression:

\[
p_{\text{ext}}(t, z) = p_{\text{ext}}(0, z) \times \left\{ 1 + \Delta \exp \left[ -\frac{(z-z_0)^2}{2\Delta z^2} \right] \sin \left( \frac{\pi t}{\Delta t} \right) \right\},
\]

for \( t \leq \Delta t \).

Here, \( \Delta a \), \( z_0 \), \( \Delta z \), and \( \Delta t \) are the perturbation relative amplitude, characteristic height, length, and duration, respectively. The computations were performed for \( \Delta a = 0 \text{ - } 5 \), \( z_0 = 0 \text{ - } 500 \text{ km} \), \( \Delta z = 500 \text{ - } 1000 \text{ km} \), and \( \Delta t = 100 \text{ - } 600 \text{ s} \).

RESULTS

Figure 1 shows the change in the plasma velocity with time at different levels of the solar atmosphere. As a result of a single pulse compression of the tube, a series of shock waves are formed, which are generated inside the tube with a frequency close to the acoustic cut-off frequency in the chromosphere. A typical velocity of the matter motion behind the shock wave fronts is \( \approx 20 \text{ km s}^{-1} \). Shock waves propagate with an average velocity of \( \approx 25 \text{ km s}^{-1} \) in the chromosphere and \( \approx 40 \text{ km s}^{-1} \) in the corona. The strongest waves, generated initially, lift the matter from the upper chromosphere several thousand kilometers upward (see Fig. 2). The rise occurs in a stepwise manner, very much like the process observed by Papuskev [1]. Upper boundaries of the spicules are restricted in our model by a thin transition region between a relatively cold \( (T \approx 10^4 \text{ K}) \) and dense chromospheric plasma and the high-temperature coronal plasma \( (T \approx 10^6 \text{ K}) \) (see Fig. 3). This boundary reaches a height of around 6000 km at \( t = 10 \text{ min} \), approximately 7 min after the instant of maximum tube compression. The density and temperature of the rising plasma column roughly correspond to the observed parameters of spicules. What follows is a slow descent of the matter, which is restrained by relatively weak secondary shock waves and also has a pulsating character. The average descent velocity is \( \approx 1 \text{ km s}^{-1} \).
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Fig. 2. Change with time in height of separate gas elements, initially situated at heights of 200, 700, 1200, 1700, 2200, 2700, 2900, 3600, and 4000 km. The parameters of the initial perturbation are the same as in Fig. 1.

Fig. 3. Dependencies of the density and temperature inside the magnetic tube upon the height, at the initial moment (t = 0), near the maximal ascent (600 s), and at the descent stage (1200 s). The parameters of the initial perturbation are the same as in Fig. 1.

It is worth noting that the maximum height of the chromospheric material ascent significantly depends upon the power of the radiation loss. In particular, the maximum height increases by more than 2000 km [15] (without allowing for loss increases), other conditions being equal. Moreover, the descending motions in spicules cannot be obtained under adiabatic conditions, as well as in the piston model [5]. It is interesting that the maximal spicule height is less sensitive to the initial perturbation amplitude. For instance, the
maximum height increases only by 1000 km (Fig. 4) for a much stronger perturbation of the external pressure $\Delta a = 3$.

CONCLUSION

The MHD model, with the compression of a magnetic flux tube from the excessive external pressure in the lower chromosphere, can reproduce some basic qualitative and quantitative properties of spicules. These properties include a quasiperiodic pulsed character of the plasma ejection and fast fluctuations of the velocity, involving a change in sign [1, 16]. The model predicts a highly nonuniform structure of the spicule matter [17] and its slow return to the solar surface. The radiative losses are shown to play an important part in spicule dynamics. Other nonadiabatic effects (for example, energy exchange with the surrounding plasma, turbulent viscosity, and thermal conductance) should be also taken into account in further modeling of spicules.

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REFERENCES


