NONLINEAR WAVES IN CHROMOSPHERIC JETS

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ABSTRACT

We present results of numerical simulation of nonlinear flows in the chromosphere and corona generated by strong magnetic perturbations in the lower solar atmosphere. The flows exhibit quasi-periodic fluctuations resulted from non-linear waves accompanying the flows. Ejections of the chromospheric plasma to high altitudes are likely to be driven by emerging magnetic dipoles, and may be recurrent. The theoretical models qualitatively agree with recent observations.

1. MODELS

1.1 Equations of plasma flows

The equations describing vertical motions in a magnetic flux tube in a 1.5D approximation are

$$\frac{dz}{dt} = v, \quad \frac{\partial v}{\partial t} = -A\frac{\partial p}{\partial s} - g, \quad \frac{\partial}{\partial t}\left(\frac{1}{A\rho}\right) = \frac{\partial v}{\partial s},$$

$$\frac{\partial \epsilon}{\partial t} = -p\frac{\partial}{\partial s}\left(\frac{1}{\rho}\right) - Q_{\rm rad}, \quad p + \frac{B^2}{8\pi} = p_{\rm ext},$$

$$BA = \Phi = {\rm const},$$

where s is the Lagrange mass variable ($ds = \rho A dz$), z is the height above the photosphere, $A(t,z)$ is the area of a circular cross-section of the magnetic tube, v is the velocity, p and B are the gas pressure and the magnetic field strength inside the tube, respectively, Φ is the magnetic flux, $p_{\rm ext}$ is the total gas and magnetic pressure outside of the tube, ρ is the density inside the tube, ϵ is the internal energy density, g is the gravitational acceleration, $Q_{\rm rad}$ is the radiative cooling rate. Plasma ionization, which increases dissipation of the wave energy in the upper chromosphere due to bulk viscosity resulting from the relaxation of the state of the gas, is considered according to Hartman and MacGregor (1980). The radiative cooling is taken in the optically thin approximation.

1.2 Initial conditions

For the initial flux-tube model we have chosen a model with linear increase of the flux-tube diameter with the height suggested by Ulmschneider *et al.* (1991). The temperatures inside and outside the tube are assumed to be equal at every given height. With the specification of the tube radius of 100 km and the magnetic field strength of 1500 G at $z = 0$, the structure parameters of the tube are determined uniquely from the hydrostatic equations.

1.3 Driving mechanisms

1.3.1 Compression of a magnetic flux tube in the lower atmosphere.

We have suggested that spicules are generated by an increase in the external pressure resulting from the interaction of the magnetic tube with nearby magnetic structures or as a result of strengthening of the external magnetic field (see Andreev & Kosovichev, 1994).

1.3.2 Emerging magnetic flux.

We have considered a simple model, in which bipolar magnetic structures emerging from the solar surface, are represented by a thin magnetic loop driven by increasing background magnetic field beneath it. Such a model was originally suggested by Pneuman (1980). It is in agreement with direct 3D MHD simulations (Shibata & Tajima, 1990).

We consider a magnetic flux tube bounded by field lines lying at distances r_1 and r_2 from the Sun's surface. If the magnetic field is frozen into the plasma and all parameters inside the tube vary smoothly and monotonically, then the equations of motion for the magnetic tube boundaries can be written as:

$$\rho\frac{dV_1}{dt} = \frac{2(P-P_1)}{D} + \frac{B^2 - B_1^2}{4\pi D} - \frac{B^2}{4\pi R_c} - g\rho,$$

$$\rho\frac{dV_2}{dt} = -\frac{2(P-P_2)}{D} - \frac{B^2 - B_2^2}{4\pi D} - \frac{B^2}{4\pi R_c} - g\rho,$$

where $D = (r_2 - r_1)$ is the diameter of the tube, $S = 0.5(r_1 + r_2)$ is its mean radius, R_c is the radius of curvature of the tube, B_1 and B_2 are the magnetic field strengths above and beneath the magnetic tube, $g = GM/(R_\odot + S)^2$. Inside the magnetic tube the density ρ is determined from the equation of conservation of mass; the magnetic field B is determined from the condition of conservation of magnetic flux; and the gas-dynamic pressure P is inferred from the adiabaticity equation. The pressure P_1 above the loop is determined from solution the gas-dynamic equations, governing the motion of the overlying plasma. Thus, the motion of the loop depends on the ambient reaction.

2. RESULTS

2.1 Compression of the magnetic flux tube

Some typical results of mass ejections driven by perturbations of the pressure have been presented by Andreev and Kosovichev (1994). The upward motion of the elements shows oscillatory behaviour resulted from the quasi-periodic slow MHD shocks generated in the tube with frequency of about the acoustic cut-off frequency of the chromosphere (Kosovichev & Popov, 1978). The upper boundary of spicules can be identified in our model with the sharp region of transition between relatively cool ($T \approx 10^4 K$) and dense plasma to high-temperature coronal plasma. The boundary reaches the maximum height of $\approx$ 6000 km. The material returns slowly because of continuing support by the quasi-periodic shocks in the wave wake for a long time after the initial impulse. In the case of a stronger perturbation of the external pressure the maximum height can be about 7000 km.

Therefore, we have concluded that the MHD model with compression of a vertical magnetic flux tube by enhanced external pressure in the lower chromosphere can reproduce some basic features of spicules, such as impulsive quasiperiodic behaviour of the plasma ejection, and fast fluctuations of the velocity which is changing its sign (Papushev, 1981; Papushev & Salakhutdinov, 1994). The model predicts the highly inhomogeneous structure of the spicular material (Livshits, 1966) and its slow return to the solar surface. However, the compression mechanism seems to be unable to provide ejections of the chromospheric material to higher than 7000 km.

2.2 Emerging magnetic flux

Ejections of the chromospheric plasma are likely to be driven by magnetic forces. We have considered the dynamics of a magnetic loop with the following initial parameters: height S_0 = 300 km, diameter D_0 = 100 km, density $\rho_0 = 10^{-9}$ g/cm^3, internal magnetic field B_0 = 200 G, external background magnetic field B_2 = 200 G. Three different regimes depending on the evolution of the background magnetic flux have been found.

2.2.1 Oscillating low-lying magnetic loop.

If the flux of the background magnetic field is conserved (the strength of the magnetic field decreases with height as z^{-2}) then the loop is oscillating in the chromosphere with the period of about 3 min, producing quasi-periodic ejections of the

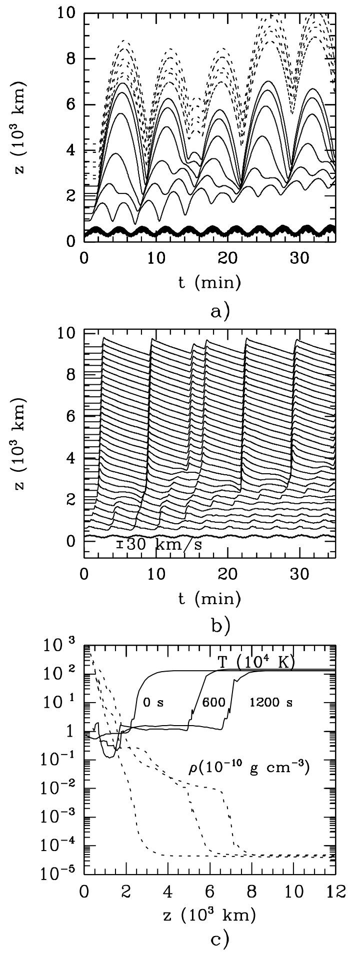

Figure 1: Oscillating low-lying magnetic loop: the flux of the driving magnetic field beneath the loop is conserved (a model of recurrent events). a) Lagrangian motions of the loop (black ribbon at the bottom) and of the 9 mass elements which initially were at the heights of 300, 900, 1200, 1800, 2200, 2400, 2700, 2900, 3200, 3500, 3900 and 4200 km (solid curves - chromospheric elements; dashed curves - coronal elements); b) The velocity as a function of time, of the loop (thick curve at the bottom) and of the plasma at the different heights in the solar atmosphere, which are separated by 300 km; c) The temperature (continuous curves) and the density (dashed curves) as functions of the height in the tube at the initial moment ($t = 0$), at $t = 600$ s and at $t = 1200$ s.

chromospheric plasma to the maximum height of about 7000 km (Fig. 1).

2.2.2 Expanding high-density magnetic loop.

If magnetic flux beneath a plasma loop of the initial density 10^{-9} g cm^{-1} is growing so that the strength of the magnetic field decreases with height as z^{-1}, the loop expands to $z = 30000$ km (Fig. 2). Then, it falls back under the gravity and magnetic tension forces producing a picture of "ballistic" motion with the characteristics close to the values recently observed in macrospicules by Karovska & Habbal (1994).

3. CONCLUSION

We have demonstrated that macrospicules and coronal mass ejections are likely to be driven by emerging magnetic flux. The general feature of the mass ejections is a series of quasi-periodic slow-MHD nonlinear waves which lift the chromospheric plasma above the expanding structures. Our model is in agreement with the recent observations by Wang (1996) who found strong correlation between chromospheric jets and magnetic dipoles.

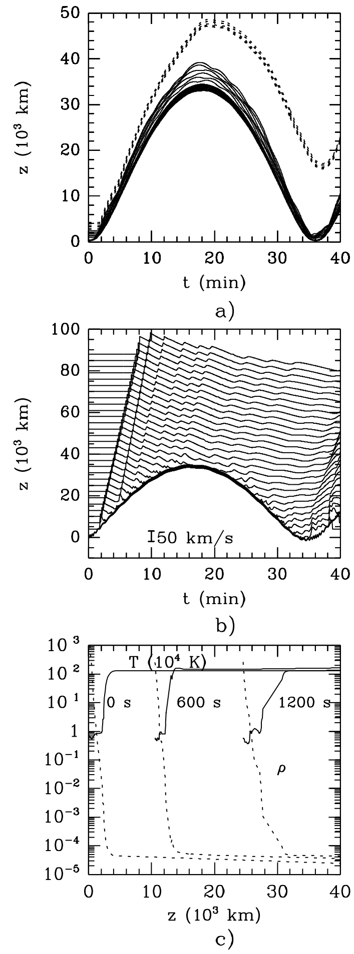

Figure 2: The same as in Fig.1 but for expanding magnetic loop: the flux of the driving magnetic field B_2 beneath the loop is increased due to emerging magnetic flux (a model of macrospicules). The heights in diagram b) are separated by 3000 km.

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