Investigation of the non-linear magnetic reconnection in solar chromosphere

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Abstract
In order to see the occurrence of magnetic reconnection in the solar chromosphere, we investigate the behavior of non-linear perturbations on the magneto hydrodynamic (MHD) equations. Numerical study of the resistive tearing instability in a current sheet is presented by considering the MHD framework. To do this, the four field model is applied. It is shown based on the simulation that the non-linear terms make the reconnection occur faster during the spicule life time in the chromosphere.

Keywords: solar spicules, magneto hydro dynamic

1. Introduction
When a new active region emerges into upper solar atmosphere, its magnetic field interacts with pre-existing large scale field. Zhang and Low [1] showed that such interaction may open up some closed bipolar fields or even affect the polarity reversal of global magnetic field. As new flux grows, local reconnection changes the topology of magnetic fields in vicinity of the emerging region. Magnetic reconnection occurs on timescales intermediate between slow resistive diffusion of the magnetic field and fast Alfvénic timescales [2, 3, 4]. The Sweet-Parker model describes time-independent magnetic reconnection in the resistive MHD framework when the reconnecting magnetic fields are antiparallel (oppositely directed) and the effects related to viscosity and compressibility is unimportant [5, 6].

Because magnetic reconnection is a universal physical process that can occur on any spatial or temporal scale [7], it could occur in the chromosphere and the photosphere [8], as well as the corona. The chromospheric reconnection can lead to coronal heating by Joule heating, by the generation and subsequent dissipation of high-frequency Alfvén and magnetoacoustic waves, or by the response of the coronal magnetic field to a sudden change in connectivity [9, 10]. Chromospheric reconnection could inject sufficient chromospheric gas into the corona to balance the known steady downward flow of coronal gas through the transition region.

Spicules act as long, thin, magnetically dominated chromospheric waveguides in which the internal plasma density is greater than the surrounding atmosphere [11-14]. Antolin and Shibata [4] modeled a magnetic flux tube being subject to Alfvén wave heating through the mode conversion mechanism. They showed that these waves constitute an attractive heating agent due to their ability to carryover the many different layers of the solar atmosphere sufficient energy to heat and maintain a corona. He et al. [15] found the signatures of small scale reconnection in spicules based on Hinode/SOT observations. They concluded that magnetic reconnection can exit kink waves along spicules. Takeuchi and Shibata [16] have investigated photospheric magnetic reconnection induced by convective intensification of solar surface magnetic fields. They concluded that the upward propagating slow waves or Alfvén waves are usually assumed as initial perturbations in models of solar spicules.

The formation of magnetic reconnection has been already studied in solar spicules. The linear terms led to the magnetic reconnection with increasing reconnection rate. As a consequence, the energies grew linearly without any saturation. Since spicules are short-lived structures, so the necessity of fast reconnection is needed. In the present work, the non-linear terms are added to the MHD equations. It should be noted that steady flows, magnetic twists and the compressibility are neglected for the sake of simplicity. We expect that at the presence of such a non-linear regime, the reconnection rates grow more rapidly than the linear one.
Moreover, under these circumstances the energies may be saturated during the time. To do this, the four field model is used in solar spicules.

Numerical simulation of non-linear magnetic reconnection is presented due to the tearing mode instability. Section 2 gives the basic equations and assumptions. In section 3, numerical results are presented and discussed, and a brief summary is followed in section 4.

2. Basic equations and Assumptions

The formal description of reconnection requires the choice of a dynamical model. We confine the discussion to magneto hydro dynamics for a finite resistivity (resistive MHD). The corresponding basic equations for the non-ideal MHD in the plasma dynamics are:

\[
\rho \frac{\partial \vec{V}}{\partial t} + \rho (\vec{V} \cdot \nabla) \vec{V} = -\nabla p + \rho \frac{1}{\mu_0} \left( \nabla \times \vec{B} \right) \times \vec{B}
\]

\[
\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{V} \times \vec{B}) + \eta \nabla^2 \vec{B}, \nabla \cdot \vec{B} = 0
\]

\[
P = \frac{\rho RT}{\mu}
\]

where \(\rho\) is mass density, \(\vec{V}\) is flow velocity, \(\vec{B}\) is the magnetic field, \(P\) is the gas pressure, \(R\) is the universal gas constant, \(\eta\) is constant resistivity coefficient, \(\mu\) is the vacuum permeability, and \(\mu_0\) is the mean molecular weight. We assume that spicules are highly dynamic and that the Alfvén speed \((\vec{V}_A = B_0/\sqrt{\mu_0 \rho_0})\).

A planar slab of uniform plasma is embedded in a sheared magnetic field and surrounded by two perfectly conducting boundaries at \(x = 0\) and \(x = L_x\), where \(L_x\) is the box size in the \(x\) direction:

\[
\vec{B}_0 = B_{0x}(x) \hat{x} + B_{0z}(x) \hat{k}
\]

(4)

with

\[
B_{0x} = 0
\]

(5)

\[
B_{0z} = \tanh(\frac{x-z_0}{\Delta z})
\]

(6)

where \(z_0 = L_z/2\) is the position of the middle of a spicule and \(\Delta z\) is the thickness of the initial current sheet (the shear length of magnetic field configuration). The \(\hat{x}\) and \(\hat{k}\) in eq. (4) correspond to unit vectors in \(y\) and \(z\) directions, respectively. The pressure is balanced by the gravity and Lorentz’s forces.

2.1 Non-Linear Perturbation

The governing equations defining temporal evolution of perturbations is a set of normalized MHD equations [17]:

\[
\frac{\partial \psi}{\partial t} = \left[ \psi, \psi \right] + \eta \nabla^2 \psi
\]

(10)

\[
\frac{\partial \phi}{\partial t} = \left[ \nabla \psi, \psi \right]
\]

(11)

where \(\psi\), the magnetic flux and \(\phi\), the stream function are the perturbed variables and they are defined as follows:

\[
\vec{B}(x, z, t) = \nabla \psi(x, z, t) \hat{x} + b_x(x, z, t) \hat{x}
\]

(12)

\[
\vec{V}(x, z, t) = \nabla \phi(x, z, t) \hat{x} + v_x(x, z, t) \hat{x}
\]

(13)

where \(b_x\) and \(v_x\) are the initial perturbed magnetic field and velocity, respectively:

\[
b_x(x, z, t = 0) = A_h \sin(\pi x) \sin(\pi z)
\]

\[
v_x(x, z, t = 0) = A_k \sin(\pi x) \sin(\pi z)
\]

(14)

\(A_h\) and \(A_k\) are small amplitudes of the perturbed magnetic field and velocity. The Poisson bracket notation \([A, B] = (\nabla A \times \nabla B) \hat{j}\) is adopted in eqs. (10) and (11).

The non-linear dimensionless MHD equations in terms of \(\psi\) and \(\phi\) are given by

\[
\frac{\partial \psi}{\partial t} + \frac{\partial \phi}{\partial z} + \frac{\partial \psi}{\partial x} + \frac{\partial \psi}{\partial z} + \eta \nabla^2 \psi = 0
\]

(15)

The second and third terms in the right-hand side of eq. (14), and two last terms in the right-hand side of eq. (15) are the non-linear terms of the perturbations. In these equations, the partial differences are obtained from eqs. (12) and (13) as follows:

\[
\frac{\partial \psi}{\partial x} = B_{0x}, \frac{\partial \psi}{\partial z} = -v_x, \frac{\partial \phi}{\partial z} = B_{0z}, \frac{\partial \phi}{\partial x} = \nabla \psi_0
\]

(17)

Here, velocity, magnetic field, magnetic flux, stream function, time and space coordinates are normalized to \(V_{A0}, B_0, a_0, \Delta \tau_{A0}, \tau_{A0}\) and \(a\) (spicule radius), respectively.

3. Numerical results and discussion

The finite difference and the Fourth-Order Runge-Kutta methods are used to take the space and time derivatives in coupled eqs. (14) and (15). We set the number of mesh-grid points as 256x256. In addition, the time step is chosen as 0.001, and the system length in the \(x\) and \(z\) dimensions (simulation box sizes) are set to be \(0, n\) and \(0, 2n\), respectively.

Some important parameters in solar spicules' environment are as follows [18]:

\(a = 200\) km (spicule radius), \(L = 6000\) km (Spicule length), \(v_0 = 25\) km/s, \(n_0 = 11.5 \times 10^{10} \text{m}^{-3}\), \(B_0 = 1.2 \times 10^{-6}\) Tesla, \(T_0 = 14000K, g = 272\) m/s², \(R = 8300\text{m}^2/\text{K}(\text{universal gas constant})\), \(V_{A0} = 77\) km/s, \(a_0 = 0.6, \tau_{x0} = 2.5, \rho_0 = 1.9 \times 10^{-10}\) kg/m³, \(\rho = 3.7 \times 10^{-10} \text{N/m}^2, \gamma = 4\pi \times 10^{-10}\) Tesla m/A, \(z = 500\) km (reference height), \(z_0 = 0.5, \tau = 1.57\) (in dimensionless units), \(H = 400\) km, \(\eta = 10^3\) m²/s, \(k = 2\pi L_x = 1\) (dimensionless wave number normalized to a).

Figure 1 shows the contour plots of the perturbed flux function at different times, \(t = 0\) s and \(t = 400\) s. Magnetic islands continuously develop as a result of ongoing magnetic field line reconnection in the considered lifetime of a solar spicule. The growth rate of tearing

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mode instability can be numerically obtained by calculating the slope of energy-time graph. The non-linear terms in MHD equations lead to the fast magnetic reconnection. Since the observational evidences of magnetic reconnection have been presented in solar spicules [15], the necessity of reconnection simulation is needed to take place in spicule life time. It should be noted that the reconnection in linear phase occurs in longer times in comparison to the life time of spicules [19].

Figure 2 shows time variations of the magnetic reconnection rate. The reconnection rate is obtained by certifying the magnetic reconnection site at each time step, which is found from the value of the magnetic flux at the point (128, 163) (the dimensionless reconnection site in the simulation box). In this figure, the reconnection rate increases with time and reaches a maximum in which the magnetic islands are formed. In this maximum, there is an increase in the resistivity due to a rapid decrease in the gas density at the neutral point. This density decrease is because of gravitational downflow and of plasma rarefaction due to outflows accelerated by the magnetic tension of the reconnecting field lines when island is formed [20]. Our non-Linear simulation shows that the reconnection can occur during a spicule life time. This is demonstrated by He et al. [15] observationally in a typical limb spicule.

The logarithmic energy-time graph which has been shown in Figure 3 displays the time variation of dimensionless magnetic energy, \( E_m = \int (B_x^2 + B_y^2) dv \) and kinetic energy, \( E_k = \int (v_x^2 + v_y^2) dv \). In the linear phase, the logarithmic magnetic and kinetic energies grow linearly (or exponentially in the non-logarithmic case) with time, and then, enter into the non-linear phase, where an algebraic growth is expected.

4. Conclusion
The magnetic reconnection is studied in a non-linear regime in solar spicule environment of chromosphere. In order to study the tearing instability, a set of incompressible magneto hydro dynamic equation is considered. The spicule plasma is assumed homogeneous, which is embedded in the magnetic field of chromosphere. It is found that with the non-linear terms in MHD equations, magnetic reconnection takes
place faster than the linear case. The time duration for this phenomenon is in agreement with spicule life times. The reconnection rate grows exponentially and reaches a maximum at the reconnection point, then decreases due to the non-linear effects. In the linear phase, the logarithmic energies grow linearly with time, and then, enter into the non-linear phase, where an algebraic growth is expected.

References