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On the possible reason for the formation of impulsive coronal mass ejections

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Abstract

The stability of a thin magnetic tube located at different depths of the convective zone has been studied numerically and analytically. Three spectral regions are shown to be responsible for different processes related to solar activity. Numerical simulation shows that Parker instability in the high frequency domain (wave number $m > 20$) may accelerate magnetic fibrils to emerge into the solar atmosphere at supersonic speed. Such a physical process may be responsible for impulsive CME generation.
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1. Introduction

The resolution of modern tools allows one to state that the magnetic field of the Sun does not represent a smooth vector field frozen into the plasma, but rather consists of magnetic tubes located in almost field-free media (Knolker and Schussler, 1988). Such phenomenon is the result of the interaction of the turbulent plasma of the convective zone and surfaces of emerging large scale magnetic structures which experience many instabilities and splits up into thin magnetic tubes (Parker, 1979). The tubes then emerge into the photosphere (Gilman, 2000).

Now it is obvious that solar flares, eruptive prominences and coronal mass ejections (CME (Temmer et al., 2010)) are the result of powerful destabilization of the coronal magnetic field made by the emerging magnetic field which enters the solar atmosphere from sub-photospheric regions (Parker, 1979; Obridko, 1985; Eselevich and Eselevich, 2013). For some events, emerging magnetic fields are just triggers of the activity. The present paper addresses the possibility of CME to be a result of a magnetic tube escaping from the convective zone at supersonic speed (Eselevich and Eselevich, 2013). Since (MacQueen and Fisher, 1983), CME are separated on slow (gradual) CME, and impulsive CME, which have different generation mechanism. In the present paper we argue that impulsive CME may be driven by the emerging magnetic field. Different modes of emergence of a magnetic tube due to Parker instability (Parker, 1979) are studied numerically (Romanov and Romanov, 2008). Comparison of these results with observations allows one to isolate physical details of impulsive CME formation.

2. Problem setup

The linear and nonlinear stability of thin magnetic tube oscillations in the convective zone have been studied in different formulations (Moreno-Insertis and Schussler, 1992;

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Fan et al., 1999). Usually the magnetic field is initially located horizontally at the bottom of the convective zone (Fig. 1a). The full system of equations of this evolution is written in Lagrangian variables as follows:

$$\begin{cases} \frac{d\vec{r}}{dt} = \vec{v} & (1) \\ \frac{d\vec{v}}{dt} = \frac{(\vec{f},\vec{\ell})\cdot\vec{\ell}}{\rho_i} + \frac{\vec{f}-\vec{\ell}\cdot(\vec{f},\vec{\ell})}{\rho_i+k\cdot\rho_e} & (2) \\ \vec{f} = \frac{H}{4\pi}\cdot\frac{\partial\vec{H}}{\partial\ell} + (\rho_i-\rho_e)\cdot\vec{g} & (3) \\ H\cdot\sigma = const & (4) \\ \left(\frac{p_i}{\rho_i^{\gamma}}\right) = const & (5) \\ p_i + \frac{H^2}{8\pi} = p_e & (6) \\ \vec{\ell} = \sigma\rho_i\cdot\frac{\partial\vec{r}}{\partial s} & (7) \\ (\vec{\ell},\vec{\ell}) = 1 & (8) \end{cases} \qquad (1)$$

This system of equations allows one to study the stability of the magnetic field in the convective zone of the Sun addressing standing waves with different wavelengths. Initially the tube rests horizontally in mechanical equilibrium in the equatorial plane of the Sun (Fig. 1a).

Linear analysis of the system (1)–(8) shows that the magnetic tube features two types of linear waves: fast (Alfven) waves, and slow magnetosonic waves (Fig. 1b). In a gravitational field the slow waves are the most unstable (Alekseenko et al., 2000). In the course of instability development the regions of the tube with dense plasma sinks, while regions with low plasma density rise up due to buoyancy force. Such instability is well known as Parker instability (Alekseenko et al., 2000).

Numerical modeling of the emergence of a magnetic tube is based on the high accuracy symplectic scheme (Romanov and Romanov, 2008) which allows one to preserve many system invariants with numerical accuracy.

3. Results of numerical modeling

At the nonlinear stage of a slow wave instability development, the shape of the tube is no longer sinusoidal but represents a wide arc with bases sinking down to the bottom of the convective zone (Fig. 2). Plasma flows down from the apex to the bases of the arc due to gravity, the apex of each ark nonlinearly accelerates to the surface while plasma leaves the apex and flows down. The development of Parker instability results solely from the interplay between plasma pressure, gravitational force, and tension of the magnetic field.

The role of the gravitational field is suppressed for tubes with stronger magnetic fields, and/or shorter wavelengths. Fig. 3 shows how critical values of MHD parameters of the tube depend on depth within the convective zone and wavenumber m. These distributions are computed using linear analysis of Parker instability (Alekseenko et al., 2000) using the model of the inner Sun (Christensen-Dalsgaard et al., 1996). Magnetic field strength varies from 0 to $2\cdot10^6$ G.

The distributions form a basis to study the nonlinear stage of Parker instability development, and allows one to draw some physical conclusions. For low frequency waves ($0 < m < 4$) the Parker instability destabilizes any magnetic field and forces it to leave the radiation transport zone regardless of magnetic field strength. The pressure difference between a tube located at the bottom of the convective zone and the same tube when it enters the atmosphere is about ten orders of magnitude (Christensen-Dalsgaard et al., 1996). Thus, such a field represents a weak background field (Obridko, 1985). For $m = 4$ wavelength $\lambda = 1.1\cdot10^6$ km.

When the wavelength becomes smaller, the spatial boundary of the unstable region shifts to the photosphere. For $m = 8$ ($\lambda = 5\cdot10^5$ km) the destruction of slowly emerging magnetic fields begins at a depth equal to 10^5 km (center of convective zone), and for $m > 18$ it starts in the vicinity of the photosphere (Parker instability develops only at a depth of about $5\cdot10^4$ km). The spectral region $10 < m < 20$ ($2\cdot10^5 < \lambda < 4\cdot10^5$ km) plays a very important role in the physics of the active Sun. In that range of wavelengths, Parker instability is able to deliver strong magnetic fields ($H \approx 10^3$ G) to the photosphere.

The second most important spectral region is short wavelengths, $m > 20$. In this region conditions for Parker instability development are very favorable. At the nonlinear stage, the size of apex of the magnetic arc is about $\lambda/6$ ($<3\cdot10^4$ km) and accelerates upward. Plasma flows down the sides of the arc which do not move significantly. The size of the apex becomes smaller than the original depth of the tube for $m > 20$ ($\leqslant 5\cdot10^4$ km down from

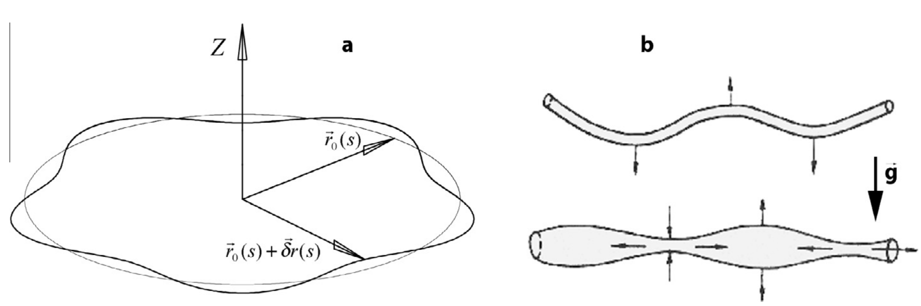

Fig. 1. Shape of a thin magnetic tube hosting an oscillation with wave number $m = 5$ (a); plasma flow structure for Alfven and slow magnetosonic waves (b).

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