

Generation of Alfvén Waves by Small-Scale Magnetic Reconnection in Solar Spicules

Zahra Fazel

Astrophysics Depart., Physics Faculty, University of Tabriz, Tabriz, Iran; email: z_fazel@tabrizu.ac.ir

Abstract. Alfvén waves dissipation is an extensively studied mechanism for the coronal heating problem. These waves can be generated by magnetic reconnection and propagated along the reconnected field lines. Here, we study the generation of Alfvén waves at the presence of both steady flow and sheared magnetic field in the longitudinally density stratified of solar spicules. The initial flow is assumed to be directed along the spicule axis, and the equilibrium magnetic field is taken 1-dimensional and divergence-free. We solve linearized MHD equations numerically and find that the perturbed velocity and magnetic field oscillate similarly which can be interpreted as generation and propagation of Alfvénic waves along spicule axis. The results of calculations give periods of around 25 and 70 s for these waves which are in good agreement with observations.

Keywords: ISM: solar spicules, ISM: Alfvén waves, ISM: magnetic reconnection

1 Introduction

The mechanism of coronal heating is one of the major problems in solar physics. The magnetic structure of the corona can play an important role on the problem of heating, so it should be necessary to study the converting of the magnetic energy to heat. A prime candidate for transferring energy up to coronal levels is a flux of Alfvén waves. Heyvaerts & Priest [1] proposed an idea for the behavior of Alfvén waves when the local Alfvén speed varies across the magnetic field lines. The propagation and damping of shear Alfvén waves in an inhomogeneous medium has been studied in more detail [2, 3, 4, 5, 6]. The damping of Alfvén waves is defined by various dissipative processes such as mode coupling [7], resonant absorption [8, 9, 10, 11], magnetohydrodynamic (MHD) turbulence [12], and phase mixing [1].

As an origin of Alfvén waves, Kudoh & Shibata [13] considered a photospheric random motion propagating along an open magnetic flux tube in the solar atmosphere, and performed MHD simulations for the solar spicule formation and the coronal heating. They have shown that Alfvén waves transport sufficient energy flux into the corona. Moriyasu et al. [7] performed 1.5D MHD simulations of the propagation of nonlinear Alfvén waves along a closed magnetic loop, including heat conduction and radiative cooling. They found that the corona is heated by fast- and slow-mode MHD shocks generated by nonlinear Alfvén waves via nonlinear mode-coupling.

He et al. [14] have shown the generation of kink waves due to chromospheric small-scale magnetic reconnection, by using Solar Optical Telescope (SOT) observations [15] in the Ca II H-line. The kink wave is identified by the upward propagation of a transverse-displacement oscillation along the spicule trace. This transverse oscillation appears to originate from the cusp position of an inverted Y-shaped magnetic structure, where a surge was taking place,

including the occurrence of magnetic reconnection according to [16]. Cranmer & Van Ballegoijen [17] studied the generation, propagation and reflection of Alfvén waves in solar atmosphere. They modeled waves as thin-tube kink modes by assuming that all of the kink-mode wave energy is transformed into volume filling Alfvén waves above the merging height (a critical flux tube height which waves are modeled).

Alfvén waves can be generated by magnetic reconnection process. Magnetic reconnection is a fundamental dynamical process in highly conductive plasmas. Sweet, Parker, Petschek and Soward & Priest [18, 19, 20, 21] introduced magnetic reconnection as the central process allowing for efficient magnetic to kinetic energy conversion in solar flares and for interaction between the magnetized interplanetary medium and the magnetosphere of Earth. [22] modeled X-ray and EUV jets and surges observed with $H\alpha$ in the chromosphere by performing a resistive 2D MHD simulation of the magnetic reconnection occurring in the current sheet between emerging magnetic flux and overlying pre-existing coronal magnetic fields. *Hinode* observation revealed that jets are ubiquitous in the chromosphere [23]. De Pontieu et al. [24], from *Hinode* data estimated the energy flux carried by transversal oscillations generated by spicules. They indicated that the calculated energy flux is enough to heat the quiet corona.

Spicules, the grass-like, thin and elongated structures are one of the most pronounced features of the chromosphere. They are seen in spectral lines at the solar limb at speeds of about $20 - 25 \text{ km s}^{-1}$ propagating from the photosphere into the magnetized low atmosphere of the sun [25]. Their diameter and length varies from spicule to spicule having the values from 400 km to 1500 km and from 5000 km to 9000 km, respectively. Their typical lifetime is 5 – 15 min. The typical electron density at heights where the spicules are observed is approximately $3.5 \times 10^{16} - 2 \times 10^{17} \text{ m}^{-3}$, and their temperatures are estimated as 5000–8000 K [26, 27]. Oscillations in spicules have been observed for a long time. [28] and [29] observed their transverse oscillations with the estimated period of 20 – 55 and 75 – 110 s by analyzing the height series of $H\alpha$ spectra in solar limb spicules.

Recently, Ebadi et al. [30] based on *Hinode*/SOT observations estimated the oscillation period of spicule axis around 180 s. They concluded that the energy flux stored in spicule axis oscillations is of order of coronal energy loss in quiet Sun.

In this paper, we are interested to study the generation of Alfvén waves in solar spicules by magnetic reconnection process. Section 2 gives the basic equations and theoretical model. In section 3, numerical results are presented and discussed, and a brief summary is followed in section 4.

2 Theoretical modeling

We consider effects of the stratification due to gravity in 2D, $x - z$ plane in the presence of steady flow and shear magnetic field. The generation of Alfvén waves is studied in a region with nonuniform Alfvén velocity both along and across the spicule axis due to mass density and magnetic field inhomogeneities. The non-ideal MHD equations in the plasma dynamics are as follows:

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + \rho \mathbf{g} + \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B}, \quad (1)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \quad (2)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (3)$$

$$p = \frac{\rho RT}{\mu}. \quad (4)$$

where η is constant resistivity coefficient, which its typical value in the solar chromosphere is $8 \times 10^8 T^{-3/2} \text{ m}^2 \text{ s}^{-1}$ [31]. μ_0 is the vacuum permeability, μ is the mean molecular weight. We assume that spicules are highly dynamic with speeds that are significant fractions of the Alfvén speed. Perturbations are assumed to be independent of y , i.e.:

$$\begin{aligned}\mathbf{v} &= v_0 \hat{k} + v_y(x, z, t) \hat{j}, \\ \mathbf{B} &= B_{0z}(x) \hat{k} + b_y(x, z, t) \hat{j},\end{aligned}\tag{5}$$

and the equilibrium sheared magnetic field is one-dimensional and divergence-free as:

$$B_{0z}(x) = B_0 \tanh\left(\frac{x - z_t}{z_w}\right).\tag{6}$$

where z_w is the thickness of the initial current sheet and z_t is the position of the middle of a spicule. The equilibrium magnetic field is assumed force-free and pressure is balanced by gravity force. The longitudinally stratified pressure and density are given by [32, 33]:

$$p_0(z) = p_0 \exp(z/H),\tag{7}$$

where H is the pressure scale height. The linearized dimensionless MHD equations with these assumptions are:

$$\frac{\partial v_y}{\partial t} + v_0 \frac{\partial v_y}{\partial z} = \frac{1}{\rho_0(z)} \left[B_{0z}(x) \frac{\partial b_y}{\partial z} \right],\tag{8}$$

$$\frac{\partial b_y}{\partial t} + v_0 \frac{\partial b_y}{\partial z} = B_{0z}(x) \frac{\partial v_y}{\partial z} + \eta \nabla^2 b_y.\tag{9}$$

where density, velocity, magnetic field, time and space coordinates are normalized to ρ_0 (the plasma density at dimensionless $z = 6$), V_{A0} , B_0 , τ , and a (spicule radius), respectively. Also the gravity acceleration is normalized to a^2/τ . The second terms in the left hand side of Eqs. (8) and (9) present the effect of steady flows. Eqs. (8) and (9) should be solved under following initial and boundary conditions:

$$\begin{aligned}v_y(x, z, t = 0) &= 0, \\ b_y(x, z, t = 0) &= 0.\end{aligned}\tag{10}$$

and

$$\begin{aligned}v_y(x = 0, z, t) &= v_y(x = 4, z, t) = 0, \\ b_y(x = 0, z, t) &= b_y(x = 4, z, t) = 0, \\ v_y(x, z = 0, t) &= v_y(x, z = 16, t) = 0, \\ b_y(x, z = 0, t) &= b_y(x, z = 16, t) = 0.\end{aligned}\tag{11}$$

3 Results

We use the finite difference and the Fourth-Order Runge-Kutta methods to take the space and time derivatives in the coupled Eqs. (8) and (9). The implemented numerical scheme is used by the forward finite difference method to take the first spatial derivatives with the truncation error of (Δx) , which is the spatial resolution in the x direction. The order of

approximation for the second spatial derivative in the finite difference method is $O((\Delta x)^2)$. On the other hand, the Fourth-order Runge-Kutta method takes the time derivatives in the questions. The computational output data are given in 17 decimal digits of accuracy. We set the number of mesh-grid points as 256×256 . In addition, the time step is chosen as 0.0005, and the system length in the x and z dimensions (simulation box sizes) are set to be (0,4) and (0,16).

The parameters in spicule environment are as follows: $a = 250$ km (spicule radius), $L = 6000$ km (Spicule length), $v_0 = 25$ km s $^{-1}$, $n_e = 11.5 \times 10^{16}$ m $^{-3}$, $B_0 = 1.2 \times 10^{-3}$ Tesla, $T_0 = 14\,000$ K, $g = 272$ m s $^{-2}$, $R = 8300$ m 2 s $^{-1}$ k $^{-1}$ (universal gas constant), $V_{A0} = 75$ km/s, $\mu = 0.6$, $\tau = 3.5$ s, $\rho_0 = 1.9 \times 10^{-10}$ kg m $^{-3}$, $p_0 = 3.7 \times 10^{-2}$ N m $^{-2}$, $\mu_0 = 4\pi \times 10^{-7}$ Tesla m A $^{-1}$, $z_w = 0.1$ and $z_t = 2$ (in our dimensionless units), $H = 750$ km, $\eta = 10^3$ m 2 s $^{-1}$, and $k = \pi/8$ (dimensionless wavenumber normalized to a).

Fig. 1 shows perturbed velocity variations with respect to time in $x = 250$ km, $z = 875$ km and $x = 250$ km, $z = 2500$ km, respectively. In Fig. 2, perturbed magnetic field variations are presented for $x = 250$ km, $z = 875$ km and $x = 250$ km, $z = 2500$ km, respectively.

At the first height ($z = 875$ km), total amplitude of both velocity and magnetic field oscillations have values near to the initial ones. As height increases, these amplitudes does increase. This means that with an increase in height, amplitude of velocity oscillations is expanded due to significant decrease in density, which acts as inertia against oscillations. Similar results are observed by time-distance analysis of solar spicule oscillations [30]. It is worth to note that the density stratification effect on the magnetic field is weak, which is in agreement with Solar Optical Telescope observations of solar spicules [34].

Behavior of both perturbed velocity and magnetic field with time is similar in Figs. 1 and 2. In these figures, we can see two types of periodic oscillations: one is related to the generated Alfvén waves at the first height; and the other one which occurs at higher heights shows a periodic standing oscillations. Figs. 3 and 4 illustrate the 3D plots of the perturbed velocity and magnetic field with respect to x , z for $t = 5\tau$ s, $t = 50\tau$ s, and $t = 80\tau$ s.

4 Discussion

The generation of Alfvén waves is investigated in a medium with steady flow and sheared magnetic field along spicule axis. I take into account the density stratification and an initial antiparallel magnetic field. This component of the magnetic field indicates a simple magnetic reconnection at the base of a spicule in solar chromosphere. The initially generated Alfvén waves are propagated in the medium and led to packets in higher heights. The period of transverse oscillations that are included in the medium due to the propagation of Alfvén waves are in agreement with those observed in spicules. Two types of periods are seen at the perturbed velocity and magnetic field variations. At the first height, Alfvén waves oscillate with the period of $\simeq 25$ s which may correspond to the transverse oscillations observed in spicules. Moreover, at the higher heights, Alfvén wave packets are formed with the period of $\simeq 70$ s [29]. These periods depend on the plasma density and the initial magnetic field in the medium. The perturbed velocity and magnetic field oscillate with the same periods and amplitudes which may be interpreted as generation and propagation of Alfvén waves along spicule axis.

References

- [1] Heyvaerts, J., Priest, E.R., 1986, AAP 117, 220

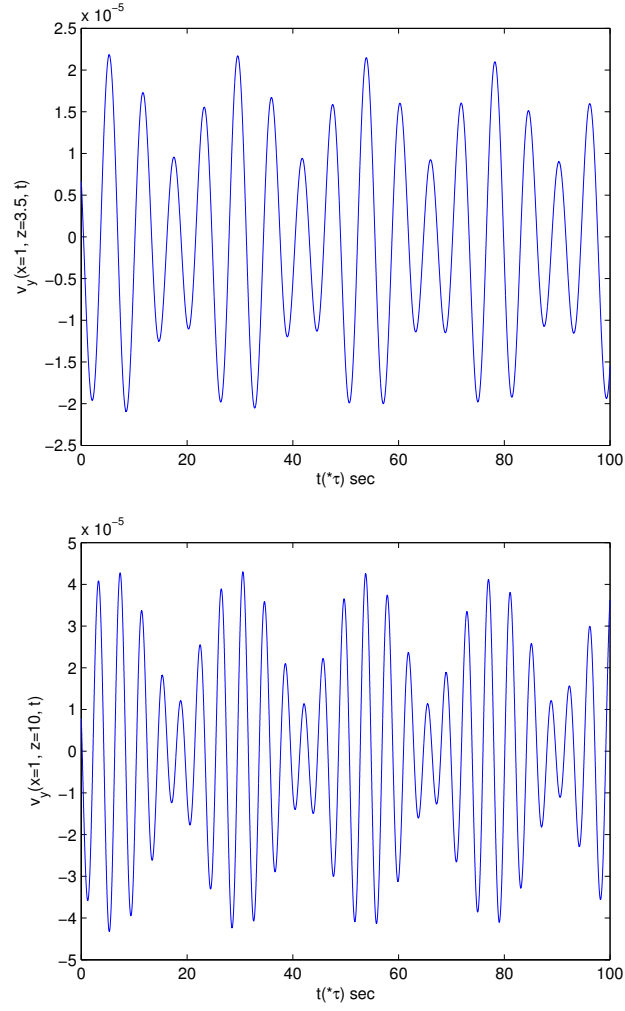


Figure 1: The perturbed velocity variations are shown with respect to time and $x = 250$ km for two values of $z = 875$ km and $z = 2500$ km from top to bottom. The perturbed velocity is normalized to V_{A0} .

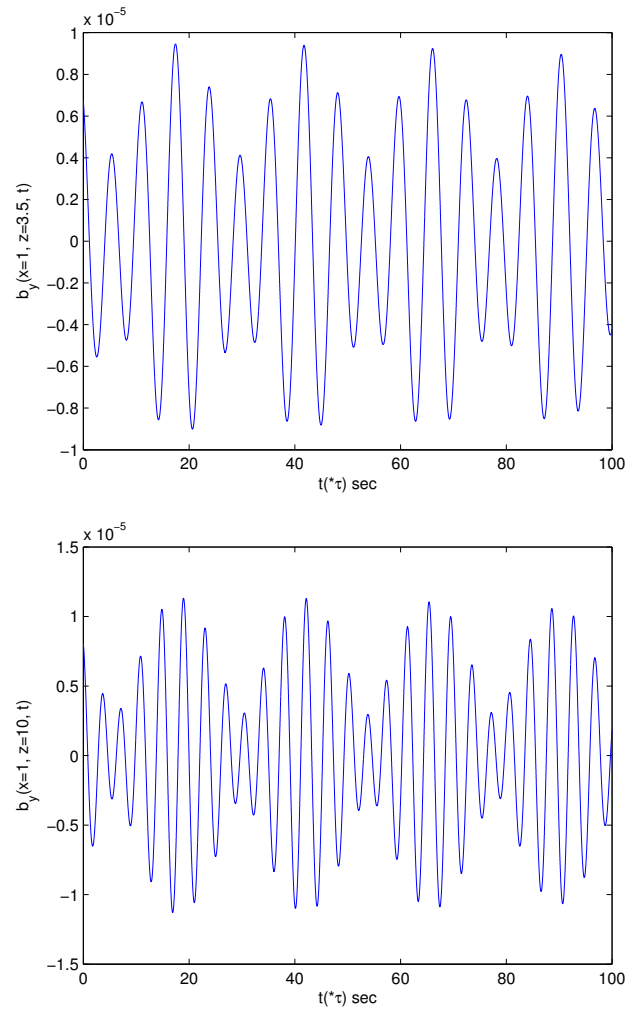


Figure 2: The perturbed magnetic field variations are shown with the same coordinates as inferred in figure 1. The perturbed magnetic field is normalized to B_0 .

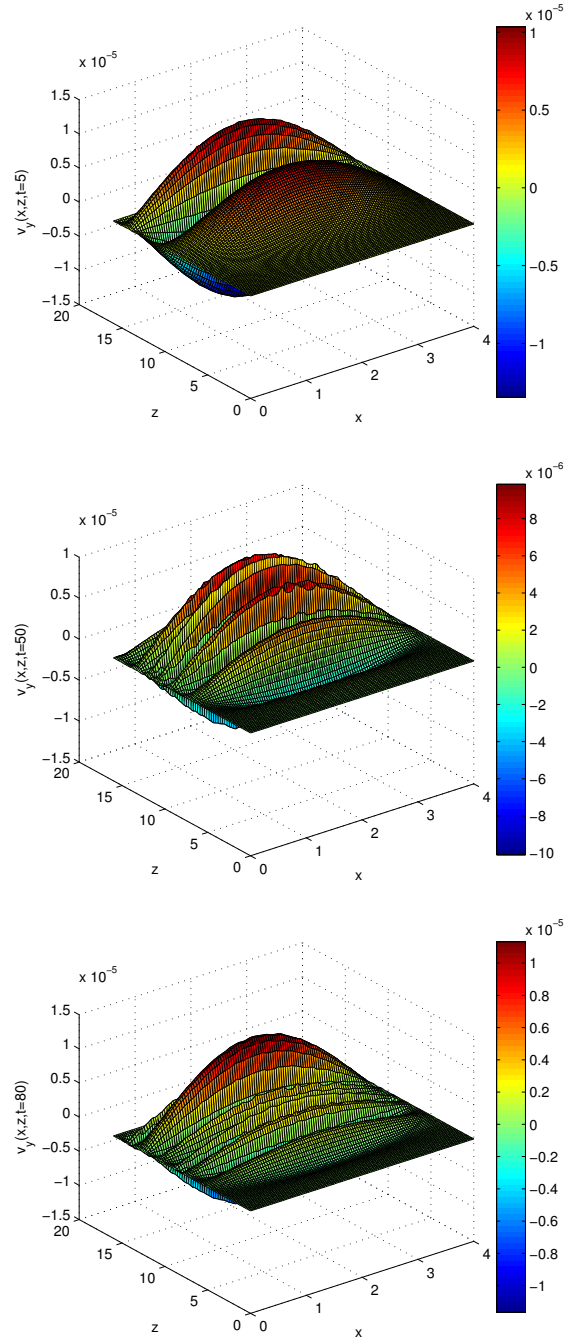


Figure 3: The 3D plots of the transversal component of the perturbed velocity with respect to x, z in $t = 5\tau$ s, $t = 50\tau$ s, and $t = 80\tau$ s.

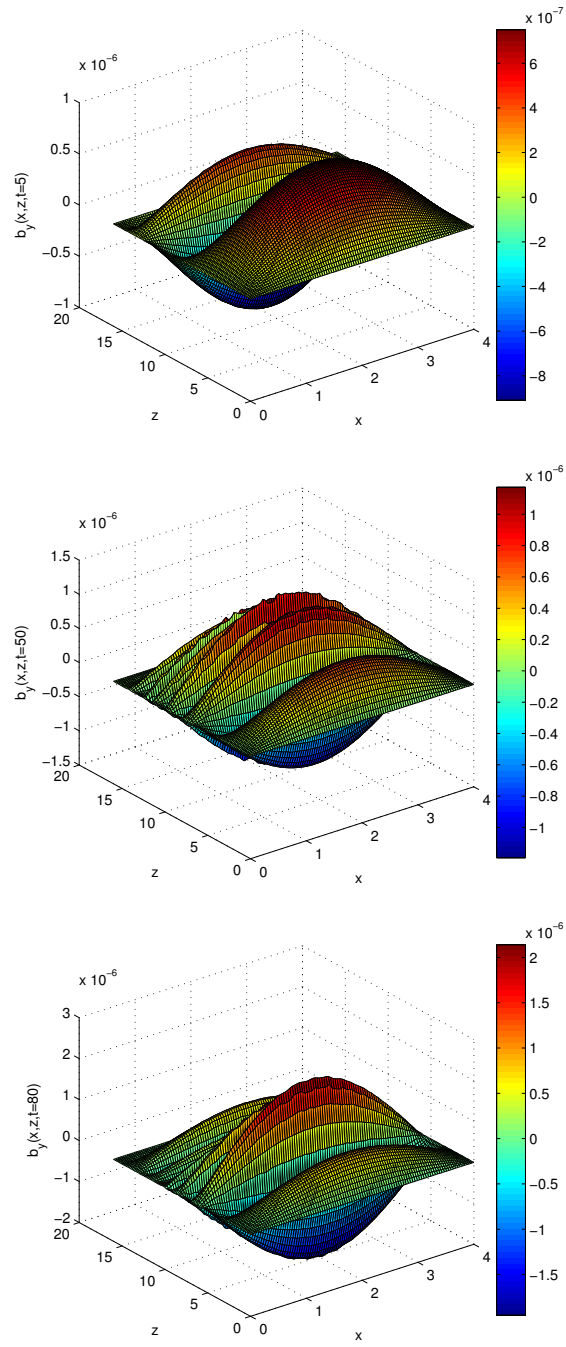


Figure 4: The same as in Fig. 3 for the perturbed magnetic field.

- [2] Ireland, J., Priest, E.R., 1997, SolPhys 173, 31
- [3] Browning, P.K., Priest, E.R., 1984, AAP 131, 283
- [4] Hollweg, J.V., 1986, J. Geophys. Res. 91, 4111
- [5] McKenzie, J.F., Banaszkiewicz, M., Axford, W.I., 1995, AAP 303, 45
- [6] Karami, K., Ebrahimi, Z., 2009, Publ. Astron. Soc. Aust. 26, 448
- [7] Moriyasu, S., Kudoh, T., Yokoyama, T., Shibata, K., 2004, APJ 601, 107
- [8] Ionson, J.A., 1978, APJ 226, 650
- [9] Ruderman, M.S., Berghmans, D., Goossens, M., Poedts, S., 1997, AAP 320, 305
- [10] Andries, J., Goossens, M., Hollweg, J.V., Arregui, I., Van Doorselaere, T., 2005, A & A 430, 1109A
- [11] Safari, H., Nasiri, S., Karami, K., Sobouti, Y., 2006, A & A 448, 375S
- [12] Matthaeus, W.H., Zank, G.P., Oughton, S., Mullan, D.J., Dmitruk, P., 1999, APJL 523, 93
- [13] Kudoh, T., Shibata, K., 1999, APJ 514, 493
- [14] He, J., Marsch, E., Tu, Ch., Tian, H., 2009, APJ 705, L217
- [15] Tsuneta, S. et al., 1008, SolPhys 249, 167
- [16] Shibata, K., et al., 2007, Science 318, 1591
- [17] Cranmer, S.R., Van Ballegooijen, A.A., 2005, Astrophysical J. Supplementary Series 156, 265
- [18] Sweet, P.A., 1958, in IAU Symp. 6, Electromagnetic Phenomena in Cosmical Phys., ed. Lehnert, B. (Cambridge Uni. Press) 123
- [19] Parker, E.N., 1963, APJS 8, 177
- [20] Petschek, H.E., 1964, in Proc. AAS-NASA Symp. on Physics of Solar Flares, ed. W.N. Hess (NASA SP-50), 425
- [21] Soward, A.M., Priest, E.R., 1982, J. Plasma Phys. 28, 335
- [22] Yokoyama, T., Shibata, K., 1995, Nature 375, 42
- [23] Kosugi, T. et al., 2007, SolPhys 243, 3
- [24] De Pontieu, B., McIntosh, S.W., Carlsson, M., et al., 2007, Science 318, 1574
- [25] Zaqarashvili, T.V., Erdélyi, R., 2009, SSR 149, 335
- [26] Beckers, J.M., 1968, SolPhys 3, 367
- [27] Sterling, A.C., 2000, SolPhys 196, 79
- [28] Kukhianidze, V., Zaqarashvili, T. V., Khutsishvili, E., 2006, AAP 449, 35

- [29] Zaqarashvili, T. V., Khutsishvili, E., Kukhianidze, V., Ramishvili, G., 2007, AAP 474, 627
- [30] Ebadi, H., Zaqarashvili, T.V., Zhelyazkov, I., 2012, ApSS 337, 33
- [31] Priest, E.R., 1982, Solar magnetohydrodynamics. p. 79, Reidel, Dordrecht.
- [32] Safari, H., Nasiri, S., Sobouti, Y., 2007, A & A 470, 1111S
- [33] Fathalian, N., Safari, H., 2010, APJ 724, 411F
- [34] Verth, G., Goossens, M., He, J.S., 2011, APJL 733, 15