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Kelvin-Helmholtz instability in solar spicules

H Ebadi[1,2]

1.Astrophysics Department, Physics Faculty, University of Tabriz, Tabriz, Iran
2.Research Institute for Astronomy and Astrophysics of Maragha, Maragha, Iran

E-mail: hosseinebadi@tabrizu.ac.ir

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Abstract

Magneto hydrodynamic waves, propagating along spicules, may become unstable and the expected instability is of Kelvin-Helmholtz type. Such instability can trigger the onset of wave turbulence leading to an effective plasma heating and particle acceleration. In present study, two-dimensional magneto hydrodynamic simulations performed on a Cartesian grid is presented in spicules with different densities, moving at various speeds depending on their environment. Simulations being applied in this study show the onset of Kelvin-Helmholtz type instability and transition to turbulent flow in spicules. Development of Kelvin-Helmholtz instability leads to momentum and energy transport, dissipation, and mixing of fluids. When magnetic fields are involved, field amplification is also possible to take place.

Keywords: sun, spicules, Astrophysical Magneto Hydrodynamics (MHD) waves, Kelvin-Helmholtz instability

1. Introduction

Coronal heating mechanism is one of the major unsolved problems in solar physics [1]. Since the energy flux carried by acoustic waves is too small, the possibility of heating by MHD waves can play an important role [2, 3, 4]. Among the proposed theories for coronal heating is the one that considers the role of spicules in that process [5].

Spicules are one of the most fundamental components of solar chromosphere. They are seen in chromospheric spectral lines in solar limb at speeds of about 20-25 km/s, propagating from chromosphere into solar corona [6]. Their diameter and length varies from spicule to spicule having the values between 400-1500 km and 5000-9000 km, respectively. Their typical lifetime is 5-15 min. The typical electron density, at heights where the spicules are observed, is approximately 3.5×10^{16}-$2\times10^{17}m^{-3}$, and their temperatures are estimated as 5000-8000 K [7, 8]. Spicules are almost 100 times denser than surrounding coronal plasma [7]; therefore, they can be considered as cool magnetic tubes embedded in hot coronal plasma. Kukhianidze et al. [9] and Zaqarashvili et al. [10] observed their transverse oscillations with estimated period of 20-55 and 75-110 s by analyzing height series of Hα spectra in solar limb spicules [11,10]. More recently, Ebadi et al. [11], Ebadi [12] and Fazel and Ebadi [13] estimated the oscillation period of spicule axis around 90 and 180 s, based on Hinode/SOT observations. Estimates of energy flux, carried by MHD (kink or Alfven) waves in spicules, and comparisons with advanced radiative magneto hydrodynamic simulations indicate that such waves are energetic enough to accelerate the solar wind and possibly to heat the quiet corona [11,14]. Some other studies carried out two-dimensional simulations of the nonlinear evolution of unstable sheared magneto hydrodynamic flows [15, 16]. Two equal density compressible fluids were separated by a shear layer with a parabolic tangent velocity profile. Magnetic topologies lead to reconnection and dynamical alignment of magnetic and velocity fields. Their fluctuations are closely aligned which represents Alfven wave propagation along flux tubes. Their simulations show Kelvin-Helmholtz instability in density, magnetic and velocity fields. MHD waves propagating along spicules may become unstable and the expected instability can be of Kelvin-Helmholtz (KH) type, which can trigger the onset of wave turbulence leading to an effective plasma heating and particle acceleration. Zhelyazkov [17] studied the conditions under which MHD waves, propagating along spicules, become unstable because of Kelvin-Helmholtz instability. They concluded that very high jet speeds are required to ensure that Kelvin-Helmholtz instability occurs for kink waves propagating in type II spicules. Zhelyazkov and Zaqarashvili [18] studied the same phenomena but in the uniformly twisted flux tubes. They found that in weekly twisted magnetic flux tubes, the critical Alfven-Mach numbers are lower than untwisted ones. Moreover, a weak external magnetic field increases this critical value. They showed that the typical tube speeds, required for the onset of Kelvin-Helmholtz instability, are of the same order detected in photosphere tubes.

In present work, two-dimensional simulations of MHD equations are performed to show that Kelvin-Helmholtz type instability may take place in spicule conditions.

2. Theoretical modeling

The equations of compressible, adiabatic, in viscid, ideal magneto hydrodynamics (MHD) are as follows [19]:

$$\frac{\partial \rho}{\partial t} = \nabla.(\rho \mathbf{v}), \tag{1}$$

$$\frac{\partial(\rho \boldsymbol{v})}{\partial t} + \nabla.\left(\rho \mathbf{vv} - \mathbf{BB} + P^*\right) = 0, \tag{2}$$

$$\nabla.\mathbf{B} = 0, \tag{3}$$

$$\frac{\partial \mathbf{B}}{\partial \mathrm{t}} = \nabla \times \left(\mathbf{v} \times \mathbf{B}\right), \tag{4}$$

$$P^* = P + \frac{\mathbf{B.B}}{2}, \tag{5}$$

$$\frac{\partial E}{\partial t} + \nabla.\left[\left(E + P^*\right)\mathbf{v} - \mathbf{B}\left(\mathbf{B.v}\right)\right], \tag{6}$$

$$E = \frac{P}{\gamma - 1} + \frac{\rho(\mathbf{v.v})}{2} + \frac{\mathbf{B.B}}{2}, \tag{7}$$

where ρ is the mass density, **v** is the velocity, **E** is the total energy density, **B** is magnetic field, P is the gas pressure, and γ is the adiabatic index (ratio of specific heats). These equations are written using units in which the magnetic permeability equals 1 (μ=1). It should be noted that there is no microscopic dissipation of any kind (viscosity, resistivity, or conduction) in this configuration. These equations are dimensionless and densities, velocities, magnetic field, time and space coordinates are normalized to ρ_0, $V_{A0} \equiv B_0/\sqrt{\mu\rho_0}$, $B_0/\sqrt{4\pi}$, τ (the time scale of transit Alfven time defined as $\tau = a/V_{A0}$), and a (spicule radios), respectively.

Perturbations are assumed to be independent of y and are two-dimensional (x-z plane), i.e:

$$\mathbf{v} = v_0\left(x\right)\hat{k} + v_x\left(x,z,t\right)\hat{i} + v_z\left(x,z,t\right)\hat{k} \tag{8}$$

$$\boldsymbol{B} = B_0\left(x\right)\hat{k} + b_x\left(x,z,t\right)\hat{i} + b_z\left(x,z,t\right)\hat{k} \tag{9}$$

where:

$$v_0\left(x\right) = 25\frac{\mathrm{km}}{\mathrm{s}} \quad \mathit{if} \quad |x| < 0.5 \tag{10}$$

$$v_0\left(x\right) = 0 \quad \mathit{if} \quad 0.5 < |x| < 1$$

The equilibrium density profile is assumed to be:

$$\rho_0\left(x\right) = \rho_0 \quad \mathit{if} \quad |x| < 0.5 \tag{11}$$

$$\rho_0\left(x\right) = \rho_e \quad \mathit{if} \quad 0.5 < |x| < 1$$

here ρ_0 and ρ_e denote plasma density inside and outside of spicule, respectively.

Initial conditions for velocity perturbations are set as:

$$v_z\left(x,z,t=0\right) = \delta v \, e^{-(\frac{z}{4\omega})^2} \sin(kx), \tag{12}$$

where the initial velocity perturbation amplitude is set to be $\delta v = 0.01\ \mathrm{V_{A0}}$, and ω = a is the width of initial wave packet.

3. Numerical results and discussion

Here two-dimensional magneto hydrodynamic simulations performed on a Cartesian grid with Athena3d code has been presented [19]. Athena is a grid-based code for MHD. It was developed primarily for studies of interstellar medium, star formation, and accretion flows. Athena has been made freely available to the community in the hope that others may find it useful. An f90/95 compiler is really all you need for the serial version. The parallel version will require a parallel system and MPI libraries. A Make file is supplied to ease the process of compiling. It is assumed that you are reasonably familiar with simple make files. User choices in code configuration are made prior to compiling. This includes choosing whether to compile the serial version or the parallel version. A Perl script, build Athena is also supplied to further simplify the build operation, if one is so inclined.

There are four "flavors" of physics available to use: hydrodynamics or magneto hydrodynamics, and adiabatic or isothermal equation of state. There is a routine for each dimensionality. The main integration routine is integrate 3-D one step; there is a routine for each dimensionality. This routine evolves the fluid variables over one time step. Schematically, the routine computes a left and right value at every interface, uses those values to compute a flux, then updates the conservation equation using those fluxes. Inside this routine, one can choose the order of interpolation and the type of EMF integration.

The number of mesh grid points is set as 200×800. In addition, the time step is chosen as 10-5, and the system length in x and z dimensions (simulation box sizes) are set to be (-1, 1) and (0, 8). The parameters in spicule environment are as follows [18, 20]: a=500 km (spicule radius), L=8000 km (spicule length), $v_0 = 25$ km/s (steady flow), $B_0 = 10$ G, $\rho_0 = 1.9 \times 10^{-10}$ $\mathrm{kgm^{-3}}$ (spicule density), $\rho_e = 1.9 \times 10^{-12}\ \mathrm{kg\,m^{-3}} = 1.9 \times 10^{-12}\,\mathrm{kgm^{-3}}$ (spicule environment density), $\rho_0 = 3.7 \times 10^{-2}$ N m^{-2}, $\gamma = 1.4$, $\mathrm{V_{A0}} = 50$ km/s, $\tau = 10\ s$, $k = \pi/2$ (dimensionless wave number). In figures 1 and 2 density variation at different times has been depicted. Initial density profile is plotted in the top left panel of figure 1 and it has been shown that spicule environment density is lower than spicule density by two orders of magnitude. The top right panel of figure 1 shows the onset of instability and transition to turbulent

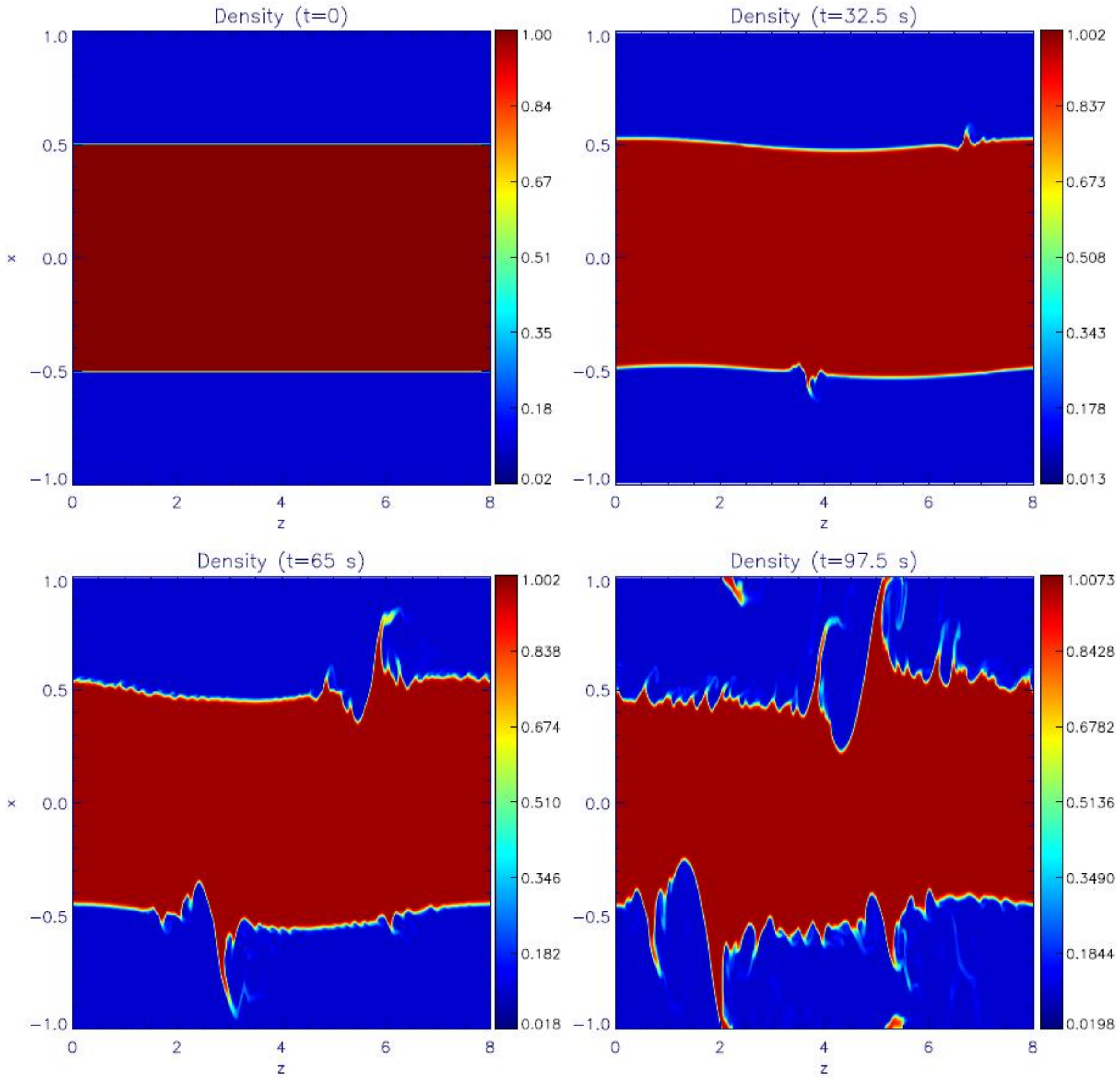

Figure 1. Density profiles for t=0, t=32.5 s, t=65 s, and t=97.5s.

flow in fluids of different densities, moving at various speeds. It should be noted that there is no observational evidence about Kelvin-Helmholtz instability in solar spicules to our knowledge until now. It is assumed that if such instability can take place in spicules, it needs to be observed with high resolutions. Another point that should be emphasized here is that simulations of this study show some different schemas for Kelvin-Helmholtz instability which may be related to the selected equilibrium flow (it is assumed to be zero in spicule environment). For more quantitative comparisons between schemes, time evolution of the total magnetic energy and total energy has been plotted in figures 3 and 4. Development of Kelvin-Helmholtz instability leads to momentum and energy transport, dissipation, and mixing of fluids. When magnetic fields are involved, the possibility of field amplification can take place. The linear stage of Kelvin-Helmholtz instability, like other macro-instabilities in MHD framework, is characterized byexponential growth of time: $e^{i\gamma t}$, where the negative imaginary part of γ satisfies this growth. The corresponding analytical growth rate, for example, is given by Cavus and Kazkapan [21]. As it is expected, magnetic and plasma velocity increase exponentially which leads to exponential growth of magnetic, kinetic and so the total energy (As seen in energy graphs). However, as the nonlinear terms turn out to be significant when instability develops, saturation of energies takes place which is an inherent property of nonlinear effects. Then, the exponential growth is gradually replaced by linear growth and eventually becomes saturated with almost a constant value (see energy graphs).

4. Conclusion

Much little progress has been made concerning Kelvin-Helmholtz instability in solar spicules both

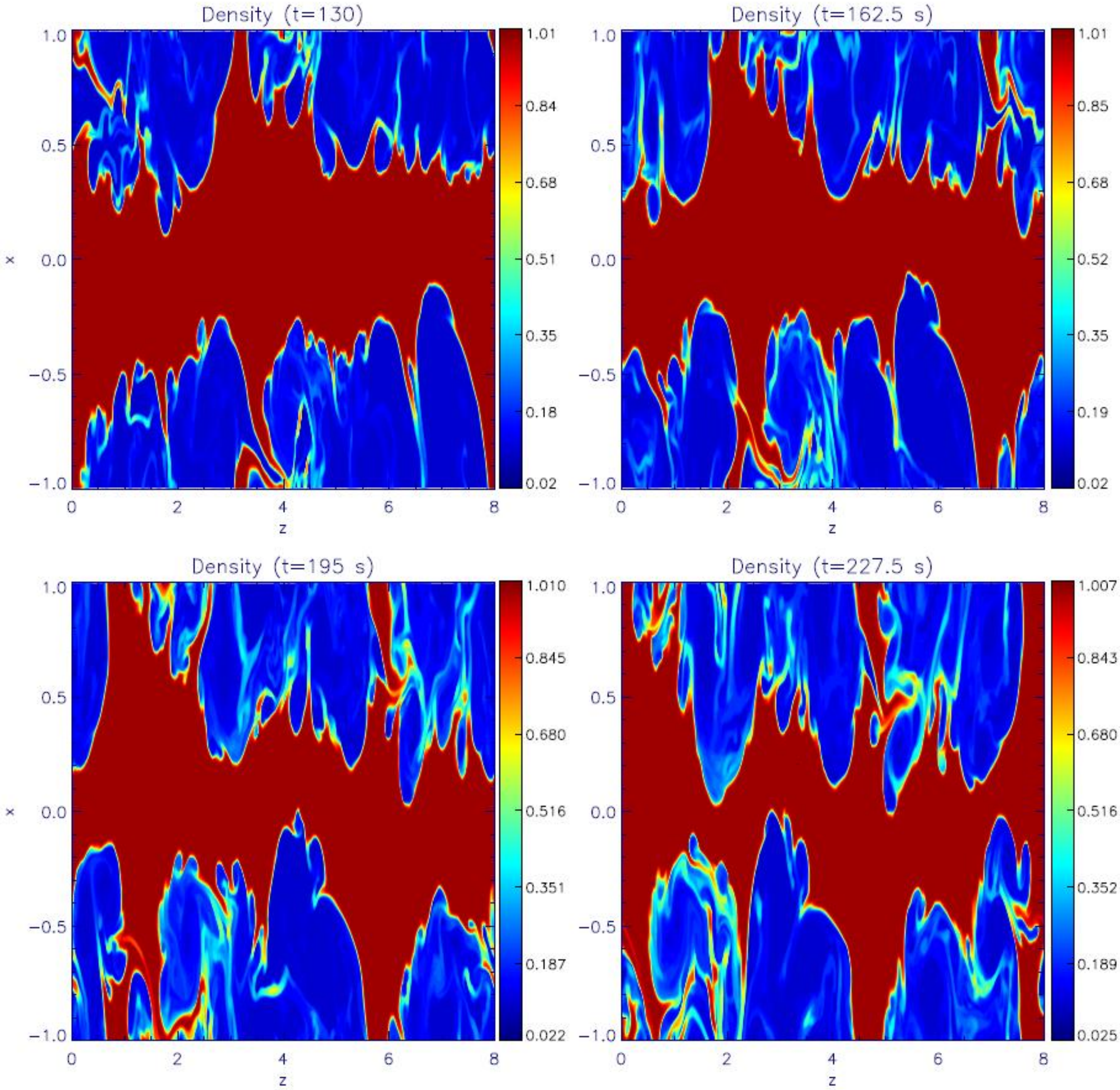

Figure 2. Density profiles for t=130 s, t=162.5 s, t=195 s and t=227.5 s.

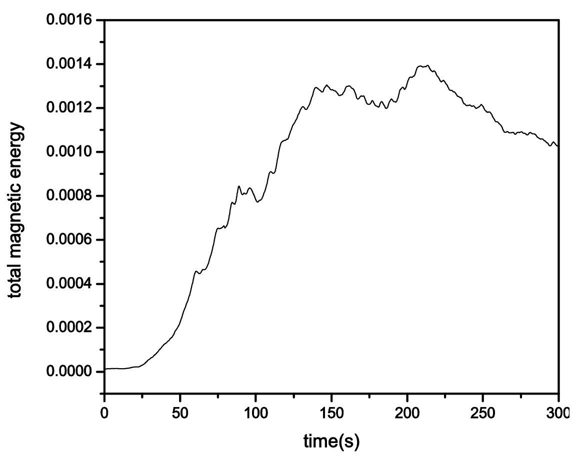

Figure 3. Total magnetic energy.

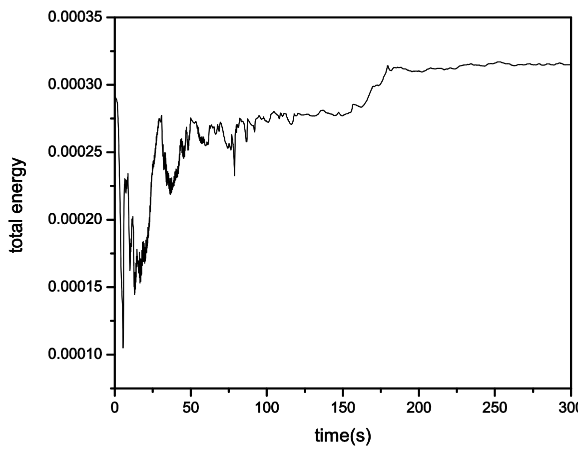

Figure 4. Total energy.

observationally and theoretically. It can be due to lack of high resolution observations and complexity of nonlinear evolution of Kelvin-Helmholtz instability. Since the heating of solar corona is one of the major unsolved problems in solar physics, damping and dissipations of waves propagating in solar spicules is important. MHD waves propagating along spicules may become unstable and expected instability is of Kelvin-Helmholtz type. Such instability can trigger the onset of wave turbulence leading to an effective plasma heating and particle acceleration. Consequently, two-dimensional magneto hydrodynamic simulations are performed on a Cartesian grid in spicules with different densities moving at various speeds based on their environment. simulations applied here show the onset of Kelvin-Helmholtz type instability and transition to turbulent flow in spicules. It should be emphasized that these simulations show some different schemas for Kelvin-Helmholtz instability which may be due to the selected equilibrium flow.

Acknowledgments
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