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Magnetic Kelvin–Helmholtz instability in the solar atmosphere

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ABSTRACT

Main aim of this paper is to twofold: firstly, to investigate the formation mechanism and secondly to search the effects of fundamental parameters like magnetic field, shear velocity and wave number on the growth rate of the magnetic Kelvin–Helmholtz instability occured in the solar atmosphere. In this investigation, occurrence and unoccurrence of instability are determined for the different values of magnetic field, shear velocity and wave number in the solar atmosphere. We have obtained the critical values of shear velocity and magnetic field.

1. Introduction

Instability can be defined as an unstable response to a small perturbation. A system must have a free energy source for instability to occur (Chandrasekhar, 1961). It will grow in amplitude to non-equilibrium stages, once this small perturbation to the initial equilibrium is applied (Lobanov et al., 2003). The free energy of the Kelvin–Helmholtz instability (KHI) comes from the kinetic energies of the anti-parallel velocity components across a plane boundary of fluids. KHI in fluids results from a turbulence of two fluid layers which move at different speeds and directions. When the interface is slightly disturbed, growing of perturbations evolve. Therefore, KHI must be well understood for plasma, gas and fluid dynamical applications (Foullon et al., 2011; Ofman and Thompson, 2011).

There are many theoretical studies on the effect of shear flow. Early works concentrated on the effect of shear flow on the structure as it is stated in the work of Knoll and Brackbill (2002). Shear flow in unmagnetized plasma gives rise to the KHI. It can be stabilized by a magnetic field in the direction of the flow (Cassak, 2011). Shear type flows are typical of many atmospheric structures of the Sun and are subject to both resistive and fluid instabilities. Such instabilities may play a crucial role in the formation and acceleration of both the slow and fast components of the solar wind (Velli et al., 2003). In the work of Landi and Velli (2009) it was shown that, the effects of KHI type shear-flow instabilities may cause much of the observed events seen in the solar atmosphere such as wind, coronal plumes and pressure-balanced structures in the solar wind.

Flows and instabilities take a crucial position in the dynamics of MHD plasma of solar atmosphere as said in the work of Foullon et al. (2011) and Ofman and Thompson (2011). The studies denote the possibility of MHD wave propagation along magnetic structures in the solar atmosphere as it is noted in Rae (1993) and Frank et al. (1996). Observations indicate the presence of guided flows in which the surface and body waves become unstable under certain flow and plasma conditions. The study of KHI in the solar atmosphere is therefore important. According to theoretical studies KHI is important in dissipation of free energy in shear flows and jets, and in the transition to turbulence. In their observational study of KHI, Ofman and Thompson (2011) stated, this instability may also arise on small scales in solar corona in the existence of shear flows, leading to enhanced dissipation of waves and impulsive events (such as flares) in the solar corona, and can help the heating of the solar coronal plasma.

In the atmosphere of the Sun, a large flare occurs when a prominence becomes MHD unstable and it erupts from the solar surface. A magnetic field below the erupting prominence closes back down by magnetic reconnection and creates magnetic loops with temperatures up 10 million Kelvins (Priest, 1983). For a low-speed flow the KHI can drive magnetic reconnection which is defined as fast dynamic decoupling of plasma magnetic fields (Knoll and Brackbill, 2002). These types of flows are often observed in the magnetosphere and solar corona. However, a clear understanding of the role of KHI in reconnection requires a fully detailed study. There have also been many theoretical studies on the effect of shear flow.

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Early analytical studies addressed the effect of shear flow on the shock structure of reconnection as said in Cassak (2011). Therefore this instability plays an important role for the turbulence and heating in the plasma of solar atmosphere (Ofman and Thompson, 2011).

The KHI is studied since this instability is considered as a new possible mechanism for the formation of magnetic reconnection and heating in the solar atmosphere. The main purpose of this article is to describe the basic mechanism of magnetic KHI in the solar atmosphere. MHD equations defining the momentum, mass and energy conservations and magnetic induction for incompressible plasma should be solved in order to define this type of instability. The formalism used for this study is explained in more detail in the following section. The effects of magnetic field, shear velocity and wave number on the growth rate are searched. The boundary conditions and our results are given in Section 3 for the solar atmosphere. They are compared with other similar works in Section 4 together with a discussion and conclusion.

2. Physical and mathematical fundamentals

We consider the ideal MHD system of equations as formulated by many authors (e.g. Chandrasekhar, 1961; Priest, 2000). For an idealised case, without rotation, viscosity and turbulence, we assume electronic charge density equal to ionic charge density. Fundamental MHD equations can be written as follows in the application of this example to the investigation of KHI:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}) = 0 \tag{1}$$

$$\rho\frac{d\vec{v}}{dt} = -\nabla p + \rho\vec{g} + \frac{1}{\mu_0}(\vec{\nabla}\times\vec{B})\times\vec{B} \tag{2}$$

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\times(\vec{v}\times\vec{B}) \tag{3}$$

$$\vec{\nabla}\cdot\vec{v} = 0 \tag{4}$$

$$\vec{\nabla}\cdot\vec{B} = 0 \tag{5}$$

μ_0 is the usual magnetic permeability constant. Basic MHD equations to be solved consist of the equation of continuity (1), the momentum transfer equation (2). Magnetic induction, incompressibility and the absence of a magnetic monopole are represented by the Eqs. (3)–(5) respectively. Here ρ, $\vec{v}$, p and $\vec{B}$ denote the mean values of density, velocity, pressure and magnetic field respectively. Eqs. (1)–(5) as given in the above forms describe the behaviour of the mean flow as a function of time. However, these equations being originally highly nonlinear, analytical solutions are not so simple. Then, we shall proceed as follows.

In order to investigate the KHI arising at a velocity shear as shown in Fig. 1, here we attempt some special solutions of the Eqs. (1)–(5) highly conducting MHD plasma similar to Chandrasekhar (1961) and Priest (2000). Our basic approach is modal analysis. That is first linearize, assuming small perturbations around $z = 0$, so that we can drop terms which are second and higher order in these perturbations.

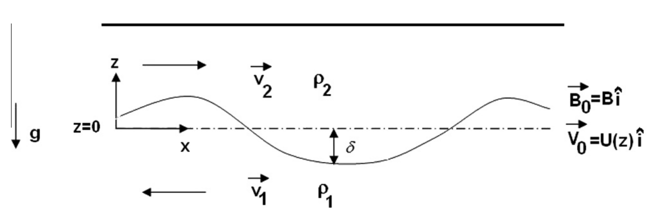

Fig. 1. The origin of KHI: Shear at an interface between two fluid layers in relative motion leads to instability and eventual mixing of the two fluids.

In order to proceed with the modal analysis, we take $\vec{v} = \vec{v}_0 + \delta\vec{v}$ where $\vec{v}_0 = U(z)\hat{i}$ and $\delta\vec{v} = u\hat{i} + v\hat{j} + w\hat{k}$ are the expressions of equilibrium and perturbation for velocity respectively. The pressure can also be decomposed as a summation of equilibrium $p_0 = p(z)$ and perturbation δp, $p = p_0 + \delta p$. Similar to pressure, the density is decomposed as $\rho = \rho_0 + \delta\rho$. Finally, the magnetic field has its equilibrium and perturbation part $\vec{B} = \vec{B}_0 + \delta\vec{B}$ similar to velocity where $\vec{B}_0 = B\hat{i}$ and $\delta\vec{B} = b_x\hat{i} + b_y\hat{j} + b_z\hat{k}$.

Each perturbed quantity is assumed to have the form

$$\delta f(x, y, z, t) = \delta f(z)e^{i(k_x x + k_y y + \omega t)}. \tag{6}$$

It is treated that the wave number $\vec{k}$ as given with a value $k^2 = k_x^2 + k_y^2$ and tried to find the behaviour of ω. Using these, by following the similar procedure in Chandrasekhar (1961), Priest (2000), Knoll and Brackbill (2002) and Ofman and Thompson (2011) the general characteristic equation for frequency is obtained for magnetised case (for detail see appendix),

$$\omega = -\frac{k_x}{\rho_1 + \rho_2}(\rho_1 U_1 + \rho_2 U_2) \pm \left[\frac{gk(\rho_1 - \rho_2)}{\rho_1 + \rho_2} - \left(\frac{k_x \Delta U}{\rho_1 + \rho_2}\right)^2 \rho_1\rho_2 + k_x^2 V_A^2\right]^{1/2}. \tag{7}$$

In the last equation V_A denotes the Alfven speed of plasma having density $(\rho_1 + \rho_2)/2$. U_1 and U_2 are the values of shear velocity in the region of fluid-1 and fluid-2 respectively and finally $\Delta U = U_1 - U_2$ shows their difference. The value of k_x is equal to $k\cos\theta$, where θ is the angle between x-axis and propagation direction of perturbation.

The frequency ω can be decomposed as $\omega = \omega_{real} + \omega_{imaginer}$. In particular if ω is real, Eq. (6) simply represents the oscillatory waves so that the system is stable. However if ω has imaginary part it represents a perturbation with grows exponentially with time that is the system is unstable as summarised in the following Table 1.

In the remaining part of this paper, the analysis of KHI mechanism will be done by $\omega^2_{imaginer}$ obtained from Eq. (7) for solar atmosphere by means of two and three dimensional plots.

3. Investigations

3.1. Values of some physical parameters in solar atmosphere

We search some solutions to Eq. (7) for solar atmosphere using the method given in previous section with MAPLE 9.5 mathematical package program (produced by division of Maplesoft in Waterloo Maple Inc. Company). We have chosen the values of physical parameters from old studies concerning solar atmosphere as tabulated in Table 2.

3.2. Results

Using the values of physical parameters given in Table 2, we attempt to solve Eq. (7) for $\omega^2_{imaginer}$ in order to analyse the instability in the solar atmosphere. In Figs. 2–7, the variations of $\omega^2_{imaginer}$ are given with respect to θ, k, B and ΔU.

3.2.1. Some three dimensional results

In Fig. 2, the three dimensional graph of $\omega^2_{imaginer}$ is given with respect to ΔU and k for the values of angle $\theta = 45°$ and the magnetic field $B = 8$ G. The system is unstable for the increasing values of shear velocity $\Delta U > 780$ km/s as shown in figure. The plot of