Rayleigh-Taylor instability in an ionized medium

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Abstract We study linear theory of the magnetized Rayleigh-Taylor instability in a system consisting of ions and neutrals. Both components are affected by a uniform vertical gravitational field. We consider ions and neutrals as two separate fluid systems where they can exchange momentum through collisions. However, ions have direct interaction with the magnetic field lines but neutrals are not affected by the field directly. The equations of our two-fluid model are linearized and by applying a set of proper boundary conditions, a general dispersion relation is derived for our two superposed fluids separated by a horizontal boundary. We found two unstable modes for a range of the wavenumbers. It seems that one of the unstable modes corresponds to the ions and the other one is for the neutrals. Both modes are reduced with increasing the collision rate of the particles and the ionization fraction. We show that if the two-fluid nature is considered, RT instability would not be suppressed and also show that the growth time of the perturbations increases. As an example, we apply our analysis to the Local clouds which seems to have arisen because of the RT instability. Assuming that the clouds are partially ionized, we find that the growth rate of these clouds increases in comparison to a fully ionized case.

Keywords Instabilities - Rayleigh-Taylor instability - Magnetohydrodynamics

1 introduction

Rayleigh-Taylor (RT) instability occurs when a heavy fluid is supported by a lighter fluid in a gravitational field, or, equivalently, when a heavy fluid is accelerated by a lighter fluid. RT instability and the related processes have found applications in various astronomical systems, such as the expansion of supernova remnants (e.g., Ribeyre et al. 2004) (where inertial acceleration plays the role of the gravitational field), the interiors of red giants (e.g., Chairborne and Lagard 2010), the radio bubbles in galaxy clusters (Pizzolato and Soker 2006). The evolution of the RT instability is influenced by many different factors. For example, viscosity tends to reduce the growth rate and to stabilize the system (e.g., Chandrasekhar 1961). Growth rate of the short-wavelength unstable perturbations decreases because of the compressibility (e.g., Shivamoggi 2008). A dynamically important radiation field affects RT instability as well (Jacquet and Krumholz 2011). However, the most important effects in the astrophysical context are probably those due to the presence of the magnetic fields. One can decompose the magnetic field lines into a component perpendicular to the interface and a component parallel to it. We will deal only with the effect of a tangential magnetic field.

Incompressible RT instability in a plane parallel to a uniform tangential magnetic field in both fluids has been studied analytically by Chandrasekhar (1961). The linear stability theory shows that a tangential magnetic field slows down the growth rate of the RT instability. The growth rate $\omega$ for the modes with wavenumber $k_x$ parallel to the magnetic field lines is given by

$$\omega^2 = \frac{\rho_{02} - \rho_{01}}{\rho_{02} + \rho_{01}} g k_x - \frac{2B^2}{4\pi} \frac{k_x^2}{\rho_{02} + \rho_{01}}.$$  \hspace{1cm} (1)

Here, we use Cartesian coordinates and denote the quantities of the plasma below the discontinuity ($z \leq 0$)
with a subscript 1 and those in above the discontinuity \((z \geq 0)\) with a subscript 2. The magnetic field permeating the plasma is uniform and tangent to the discontinuity, so \(\mathbf{B} = B\mathbf{e}_z\), while gravity is perpendicular to it, so \(\mathbf{g} = -g\mathbf{e}_z\). If we set \(B = 0\), the classical dispersion relation for RT instability is obtained, i.e.
\[
\omega^2 = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} g k_x. \tag{2}
\]

There are a number of astrophysical systems in which the magnetic RT instability is expected to be important, among them are the accretion onto the magnetized compact objects (Wang and Nepveu 1983), buoyant bubbles generated by the radio jets in clusters of galaxies (Robinson et al. 2005), and the thin shell of ejecta swept up by a pulsar wind (Bucciantini et al. 2004). But one should note magnetic RT growth rate (i.e., Equation (1)) is based on the ideal MHD approximation, in which the multifluid nature is neglected for simplicity. However, a partially ionized plasma represents a state which often exists. Thus, we are interested to know how the growth rate of RT instability is modified in a partially ionized medium, in particular when the coupling between the ionized and the neutral components is not complete. There are a few studies related to this issue. For example, Chhajlani (1998) studied magnetic RT instability considering the surface tension and Finite Larmor Radius correction (FLR) in the absence of gravity and the pressure gradient for the neutral particles. It was found that an increase in the collision frequency causes a decrease in the growth rate of the system. Just recently, Diaz, Soler & Ballester (2012) (hereafter DSB) studied RT instability in a partially ionized compressible (and also incompressible) plasma. Their purpose was to study the stability thresholds and the linear growth rate of the RT unstable modes in a two-fluid plasma consisting of ions and neutrals. They also studied the effects of compressibility and the collision between the particles. They calculated the growth rate as a function of the wavelength of the perturbations for different values of the gravity and concluded that collisions are not able to fully suppress the instability. But in the highly collisional regime the growth rate is significantly lowered by an order of magnitude in comparison to the classical result, specially for low values of gravity. Also, the linear growth rate is significantly lowered by compressibility and ion-neutral collisions compared to the incompressible collisionless case. Then, as an astrophysical implication, DSB applied their results to the solar prominences.

In this article, although we follow a similar problem to DSB, not only our presentation of the results are different from that study, but also we apply the results to another astronomical object which is subject to RT instability. More specifically, we study RT instability in a two-fluid magnetized medium consisting of the ions and the neutrals and obtain the growth rate of the unstable modes for different wavenumbers (not different gravity like DSB) and compare them with the fully ionized or neutral cases. We also determine the most unstable mode and its relation to the wavenumber. Then, possible effects of ionization and the collisions on the growth rates are analyzed. More important, we apply our results to an astronomical object different from DSB system, i.e. the interaction zone between Loop 1 and Local Bubble, which seems to be subject to RT instability and the maximum growth rate and the corresponding wavenumber are obtained. Breitschwerdt, Freyberg and Egger (2000) showed the local clouds surrounding the solar system have been formed as a result of the growing magnetic RT instability in the interaction zone between the Loop 1 and Local Bubble. We now know that these clouds are partially ionized (Slavin 2008, welsh 2009). Thus, we can apply our results to the interaction region between the Loop I and the Local Bubble. In the second section, we will present the basic equations and the assumptions of the model. In the third section, we will analyze the growth rate of the unstable perturbations and finally in forth section we perform an application to interaction region between the Loop I and the Local Bubble.

2 General Formulation

We follow the analysis of Chandrasekhar (1961), but including neutrals and ions which are coupled via collisions. Our basic equations are similar to the other related two-fluid studies (e.g., Shadmehri and Downes 2007), but here there is a gravitational acceleration in the equations of motion for both the ions and the neutrals. In order to proceed analytically, it is assumed that the system is incompressible and the non-ideal dissipative process related to the evolution of the magnetic field are neglected. So, the convective term in the induction equation dominates the resistive one. We suppose the neutral and ion components have not velocity in the unperturbed state. The magnetic field is assumed to be parallel to the interface, i.e. \(\mathbf{B} = B_x\mathbf{e}_z\). Finally, all the unperturbed physics quantities are assumed to be spatially uniform in each medium. The basic equations are
\[
\nabla \cdot \mathbf{u}_{n,i} = 0, \tag{3}
\]
\[
\rho_n \frac{D\mathbf{u}_n}{Dt} = -\nabla p_n - \gamma_{i,n}\rho_n\rho_i(\mathbf{u}_n - \mathbf{u}_i) - \rho_n g\mathbf{e}_z, \tag{4}
\]
where \( \gamma_{n,i} \) is the collision rate coefficients per unit mass so that \( \nu = \gamma_{n,i} \rho_i \) is the neutral-ion collision frequency. The collision frequency determines the coupling between each component and the magnetic field. Here, \( \mathbf{g} = -g \mathbf{e}_z \) is a uniform vertical gravitational acceleration. Now, we perturb the physical variables as \( \chi(z, x, t) = \chi(z) \exp(\omega t + ik_z x) \). Thus, linearized equations for the neutrals become

\[
i k_z u'_n + \frac{\partial u'_n}{\partial z} = 0, \quad \rho_n \omega u'_n = -ik_z p'_n - \gamma_{i,n} \rho_n (u'_n - u'_i), \quad \rho_n \omega w'_n = -\frac{\partial p'_n}{\partial z} - \gamma_{i,n} \rho_n (w'_n - w'_i), \tag{8}
\]

where \( u'_n \) and \( w'_n \) are the \( x \) and the \( z \) components of the perturbed velocity of the neutrals, respectively. Also, the linearized equations for the ions are

\[
i k_z u'_i + \frac{\partial u'_i}{\partial z} = 0, \quad \rho_i \omega u'_i = -ik_z p'_i - \gamma_{i,n} \rho_i (u'_i - u'_n), \tag{11}
\]

\[
\rho_i \omega w'_i = -\frac{\partial p'_i}{\partial z} - \gamma_{i,n} \rho_i (w'_i - w'_n) + \frac{B^2}{4\pi \omega} \frac{\partial^2 w'_i}{\partial z^2} - k_z^2 w'_i, \tag{13}
\]

where \( u'_i \) and \( w'_i \) are the \( x \) and the \( z \) components of the perturbed velocity of the ions, respectively. After some mathematical manipulations, we can reduce the above differential equations to a set of two differential equations for \( w'_n \) and \( w'_i \), i.e.

\[
(\rho_i \omega + \frac{B^2 k_z^2}{4\pi \omega}) Dw'_i = \gamma_{i,n} \rho_i D (w'_i - w'_n), \tag{14}
\]

\[
\rho_i \omega Dw'_n = \gamma_{i,n} \rho_n D (w'_n - w'_i), \tag{15}
\]

where \( D = d^2/d^2 z - k_z^2 \). Up to this point, our basic linearized equations are similar to Shadmehri and Downes (2007) who studied two-fluid Kelvin-Helmholtz instability. However, the boundary conditions for RT instability are different from Kelvin-Helmholtz instability. Having solutions of the above equations and by imposing appropriate boundary conditions, we can obtain a dispersion relation for RT instability.

Behavior of the flow at the upper and the lower layers is determined by the general solutions of the linear differential equations \((14)\) and \((15)\). One can easily show that the general solution of the equations is a linear superposition of two independent solutions \( \exp(+k_z z) \) and \( \exp(-k_z z) \). Now, we must apply the following proper boundary conditions to obtain a physical solution: (1) The perturbations tend to zero as \( z \) goes to the infinity; (2) The \( z \)-component of the velocity is continuous at the interface; (3) The total pressure is also continuous at the interface. Thus, the general solutions become

\[
w'_i = \begin{cases} Ae^{+k_z z} & \text{for } z < 0 \\ A'e^{-k_z z} & \text{for } z > 0, \end{cases} \tag{16}
\]

\[
w'_n = \begin{cases} Ce^{+k_z z} & \text{for } z < 0 \\ C'e^{-k_z z} & \text{for } z > 0, \end{cases} \tag{17}
\]

where \( C, C', A \) and \( A' \) are constants to be determined from the above boundary conditions. Continuity of the vertical displacement at \( z = 0 \) (the second boundary condition) gives the following relations

\[
C = C', \quad A = A'. \tag{18}
\]

Also, based on the continuity of the ions and neutrals pressures at the interface \( z = 0 \) (the third boundary condition), we have

\[
(p'_i + p'_{im} - \rho_i g \zeta_i)|_{z=0} = (p'_i + p'_{im} - \rho_i g \zeta_i)|_{z=0}, \tag{19}
\]

\[
(p'_n - \rho_n g \zeta_n)|_{z=0} = (p'_n - \rho_n g \zeta_n)|_{z=0}, \tag{20}
\]

where \( p'_{im} \) is the perturbed magnetic pressure. Having solutions \((16)\) and \((17)\), we can simply obtain perturbed pressures and substitute them into the above equations. Therefore, we obtain

\[
\omega A(\rho_{i2} + \rho_{i1}) + \gamma(A - C)(\rho_{i2} \rho_{n2} + \rho_{i1} \rho_{n1}) + \frac{2AB^2 k_z^2}{4\pi \omega} - \frac{gA}{\omega} (\rho_{i2} - \rho_{i1}) k_z = 0, \tag{21}
\]

\[
\omega C(\rho_{n2} + \rho_{n1}) + \gamma(C - A)(\rho_{i2} \rho_{n2} + \rho_{i1} \rho_{n1}) - \frac{gC}{\omega} (\rho_{n2} - \rho_{n1}) k_z = 0, \tag{22}
\]
and after lengthy (but straightforward) mathematical manipulations, we then obtain

\[
(\alpha_i + 1)(\alpha_n + 1)x^3 + (\alpha_n \alpha_i + 1)(\alpha_i + 1 + m\alpha_n + m)\lambda x^3
- \left[2y(\alpha_i \alpha_n - 1) - 2y^2(\alpha_n + 1)\right]x^2 + \left[2y^2\lambda(\alpha_i \alpha_n + 1) - y(\alpha_i \alpha_n + 1)\lambda(m\alpha_n - m + \alpha_i - 1)x - 2y^3(\alpha_n - 1) +
+ (\alpha_n - 1)(\alpha_i - 1)y^2 = 0,
\]

(23)

where

\[
\alpha_i = \frac{\rho_2}{\rho_1}, \alpha_n = \frac{\rho_n}{\rho_1}, m = \frac{\rho_n}{\rho_1}, x = \frac{\omega}{g} v_A, y = \frac{k_x}{g} v_A^2
\]

\[
\lambda = \frac{\nu}{g} v_A \quad \text{and} \quad (\nu = \gamma \rho_1),
\]

(24)

where \(v_A\) is Alfvén velocity for \(z \leq 0\). Dispersion relation (23) is the main equation of our stability analysis. Obviously, if we neglect collision between ions and neutrals (i.e., \(\lambda = 0\)), equation (23) simply reduces to a dispersion relation for the ions which are tied to the magnetic field lines and another dispersion relation for the neutral component, i.e.

\[
\left(x^2(\alpha_i + 1) + 2y^2 - (\alpha_i - 1)y\right)\left(x^2(\alpha_n + 1) - (\alpha_n - 1)y\right) = 0.
\]

(25)

If we set the first parenthesis equal to zero, magnetic criterion for RT instability is obtained. Also, the second parenthesis gives the classical condition of non-magnetic RT instability.

### 3 Analysis

Although dispersion relation for RT instability within one fluid approximation gives analytical solutions, it is very unlikely to obtain roots of equation (23) analytically. So, we follow the problem numerically by assuming some numerical values for the input parameters. We assume \(\alpha_i = \alpha_n = 6\) and the dispersion relation (23) is numerically solved for different values for the parameters \(\lambda, m\) and \(y\). Obviously, we would have an unstable mode if \(x\) has a positive real part.

Figure 1 shows non-dimensional growth rate \(x = \frac{\omega}{g} v_A\) of the unstable modes versus the non-dimensional wavenumber \(y = \frac{k_x}{g} v_A^2\). Parameter \(m\) denotes the ratio of densities of the neutrals and ions in layer 1. In Figure 1, we assume \(m = 1\) and each curve is labeled by the corresponding non-dimensional collision rate \(\lambda\).

Figure 2 shows growth rate of the perturbations versus the wavenumber but for \(m = 100\). In this case, the ions are stable and the neutrals determine growth rate of the perturbations. Also, Figure 3 and 4 show the growth rate of the neutrals and the ions for \(m = 0.01\), respectively. Again, we can see the stabilizing role of the collision between the ions and the neutrals. Note that when there is no collision between the ions and neutrals (i.e., \(\lambda = 0\)), each component of our two-fluid system behaves independently. But when collision between ions and neutrals is considered, we found two unstable modes up to a certain wavenumber that are related on the neutral and ion fluids separately, with the neutral ones having a tendency with much larger growth rate. Curves with the same color are corresponding to the same value of \(\lambda\). Since magnetic field has a stabilizing role, we can see that unstable mode corresponding to the ions has a smaller growth rate in comparison to the neutrals unstable mode because of the coupling to the magnetic field lines. DSB obtained plots of dispersion relation of the unstable modes versus the non-dimensional gravity but we plot unstable modes versus wavenumber. Therefore, we can conclude:

(1) The neutral mode is unstable for all wavenumbers but for ions we can find a critical wavenumber for which the instability becomes ineffective. This result is valid irrespective of the ionization fraction and the collision rate.

(2) Growth rate of the unstable perturbations for the ions tends to become zero as the collision rate increases and thereby, behavior of the system is determined by the growth rate of the neutrals. Moreover, in this case, the profile of the growth rate for the neutrals is similar to the ions without collision.

(3) However, as the collision frequency increases, not only growth rate of ions reduces but the unstable perturbations for the neutrals are significantly reduced in particular at short wavelengths.

In the next section we apply our results to an astronomical object.

### 4 Astrophysical Implication: interaction zone between Loop1 and Local Bubble

Our solar system is embedded in an ionized cloud named Local Cloud. In vicinity of Local Clouds there are also other cloudlets of comparable size. Winds and supernovae events that are associated with clusters of massive early-type stars have a profound effect on the
surrounding interstellar medium (ISM), including the creation of large cavities. These cavities, which are often referred to as “interstellar bubbles”, are typically \( \sim 100 \text{pc} \) in diameter and have low neutral gas densities of \( n(H) \sim 0.01 \text{cm}^{-3} \) (Weaver et al. 1977). The local Clouds are inside a local X-ray emitting cavity which called the local bubble. Breitschwerdt et. al (2000) presented observational evidences based ROSAT PSPC data that manifest existence of an interaction shell between our local interstellar bubble and the adjacent Loop I superbubble. They showed that due to the overpressure in Loop I, a Rayleigh-Taylor instability would operate, even in the presence of tangential magnetic field. Their calculations showed that the most unstable mode has a growth time about \( 5 \times 10^5 \) years (Breitschwerdt et al. 2000) presented observational evidences based ROSAT PSPC data that manifest existence of an interaction shell between our local interstellar bubble and the adjacent Loop I superbubble. They showed that due to the overpressure in Loop I, a Rayleigh-Taylor instability would operate, even in the presence of tangential magnetic field. Their calculations showed that the most unstable mode has a growth time about \( 5 \times 10^5 \) years (Breitschwerdt et al. 2000 and 2006), we conclude the interaction zone between Loop I and Local Bubble has also a vital role. Ionized particles are coupled to the magnetic field lines, but their coupling to the neutral particles is determined via collisions (i.e., \( \lambda \)). Now, we found shorter growth time in comparison to the classical magnetic RT instability (around \( 5 \times 10^5 \) yrs). The wavenumber of the fastest growing mode is

\[
y_\ast = 5 = \frac{k_\ast B^2}{g4\pi \rho_{i2}}.
\]

Thus, the size of structures formed by RT instability reduces in comparison to the classical magnetic RT instability that is \( 2.2 \text{pc} \). When the nondimensional collision frequency lambda is large, the ionization fraction has also a vital role. Ionized particles are coupled to the magnetic field lines, but their coupling to the neutral particles is determined via collisions (i.e., \( \lambda \)). Now, we found shorter growth time in comparison to the classical magnetic RT instability (around \( 5 \times 10^5 \) yrs). The wavenumber of the fastest growing mode is

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we can consider two identical systems with the same input parameters except their ionization fractions. If both systems have a large collision rate, the system with a larger ionization fraction is more affected by the magnetic field lines in comparison to the system with a smaller ionization fraction. In other words, although the ionized and the neutral particles are coupled to the same level, but when the ionization fraction is larger the system is more under influence of the magnetic field lines. Figure 5 clearly shows this effect. Each curve is labeled by its ionization fraction. Here, the non-dimensional collision frequency is $\lambda = 2923$. We can see that as the ionization fraction increases, the growth rate of the unstable mode decreases simply because more particles are affected by the magnetic field lines. It is because of the two-fluid nature of the system. The effect is more significant when the collision frequency decreases and the coupling between the ionized and the neutral particles is not complete. Thus, it seems that one-fluid approach is not adequate even when the collision frequency is large but the ionization fraction is not large enough. However, it is difficult to determine a critical value for lambda so that beyond which the system tends to MHD case. Because such a transition depends on the ionization fraction among the other input parameters. Moreover, when two-fluid approach is adopted the maximum growth rate is modified. But compressibility does not lead to such an effect. In fact, compressibility becomes less effective when the density contrast of the layers increases. So, the compressibility correction in a two-fluid system subject to RT instability depends on the density contrast of the layers.

**5 Conclusions**

In this study, we investigated the magnetic RT instability in a two-fluid medium consisting of the neutrals and the ions. A general dispersion relation is obtained. By analyzing the unstable roots of the dispersion equation, two unstable modes are found that are related to those of the neutral and ion fluids separately, with the neutral ones having a much higher growing rate. For each ionization fraction and collision rate, the stability of the system only depends on the behavior of the neutrals. For lower values of collision rate the curves are similar to the collisionless case. We found that the growth rate of the unstable perturbations decreases when the collision rate increases. Also, the instability of the system strongly depends on the ionization fraction. When the ionization fraction increases, for a given collision rate, the growth rate of the perturbations decreases. Finally, we apply our results for interaction zone between the
Loop I and the Local Bubble that is caused form local clouds. We obtained a shorter value for the growth time and size of the clouds. Although classical magnetic RT instability has been applied to this system for explaining some of the observed structures, our analysis shows that RT instability may operate less effectively if the two-fluid nature of the system is considered. But we note that our results are valid within linear regime and non-linear numerical simulations are needed to confirm the linear results.

We note that magnetic effects only suppress the linear growth rate for perturbations aligned with the magnetic field. Those perpendicular to it are unaffected. Indeed, as shown by Stone & Gardiner (2007), in 3D the net effect of magnetic fields is actually to enhance the non-linear growth rate by suppressing secondary KH instabilities. Thus in the real world, it seems like magnetic RT instability never occur. The hydrodynamic modes perpendicular to the field always end up taking over.

We also think that the Hall effect is an interesting problem, but it is beyond the scope of the present study. Our analysis is restricted to a two-fluid case, i.e. a system consisting of ion and neutral particles. We could also start from the one fluid MHD equations, but considering modified induction equation with resistivity, Hall and ambipolar terms. In that framework we could study possible effects of non-ideal terms (including Hall term). But we think it deserves a separate analysis independent of the present study.

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Fig. 4 The same as Figure 3, but it shows growth rate for the ions.

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Fig. 5 Growth rate of two-fluid RT instability in the interaction zone between Loop I and Local bubble, as a function of the wavenumber of the perturbation corresponding to $\lambda = 2923$ and different ionization fractions.