THE KELVIN–HELMHOLTZ INSTABILITY IN ORION: A SOURCE OF TURBULENCE AND CHEMICAL MIXING

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ABSTRACT

Hydrodynamical instabilities are believed to power some of the small scale (0.1–10 pc) turbulence and chemical mixing in the interstellar medium. Identifying such instabilities has always been difficult, but recent observations of a wavelike structure (the Ripples) in the Orion nebula have been interpreted as a signature of the Kelvin–Helmholtz instability (KHI), occurring at the interface between the H II region and the molecular cloud. However, this has not been verified theoretically. In this Letter, we investigate theoretically the stability of this interface using observational constraints for the local physical conditions. A linear analysis shows that the H II/molecular cloud interface is indeed KH unstable for a certain range of magnetic field orientation. We find that the maximal growth rates correspond to typical timescales of a few 105 years and instability wavelengths of 0.06–0.6 pc. We predict that after 2 × 105 years the KHI saturates and forms a turbulent layer of about 0.5 pc. The KHI can remain in linear phase over a maximum distance of 0.75 pc. These spatial and timescales are compatible with the Ripples representing the linear phase of the KHI. These results suggest that the KHI may be crucial to generate turbulence and to bring heavy elements injected by the winds of massive stars in H II regions to colder regions where planetary systems around low-mass stars are being formed. This could apply to the transport of 26Al injected by a massive star in an H II region to the nascent solar system.

Key words: astrochemistry – instabilities – ISM: kinematics and dynamics – magnetohydrodynamics (MHD)

1. INTRODUCTION

Over 50 years ago, it was postulated by Spitzer (1954) and Frieman (1954) that hydrodynamical instabilities may form in interface regions between the hot diffuse gas ionized by massive stars and cold dense molecular clouds. In particular, these authors suggested that elephant trunk, or spike structures, which are widely observed in star-forming regions, may result from the Rayleigh–Taylor instability (RTI; see Chandrasekhar 1961). Another classical type of interface instability is the Kelvin–Helmholtz instability (see Chandrasekhar 1961) which occurs in the presence of a velocity shear across the interface and is characterized by a wavelike periodic structure. Both types of instabilities have been considered to play a dominant role in the interstellar medium (ISM), as a power source for small scale (0.1–10 pc) turbulence (Elmegreen & Scalo 2004) and in the mixing of chemical elements (Roy & Kunth 1991). Observationally, it has been hard to confirm the existence of these instabilities. Although the observed sizes of elephant trunks match first-order theoretical models of RTI (Frieman 1954), recent observations of the velocity field in the Pillars of Creation and the Horsehead nebula by Pound (1998) and Pound et al. (2003) tend to discard the RTI hypothesis for the formation of these structures (instead, the selective photodissociation model of Reipurth 1983 is invoked). More recently, Berné et al. (2010, hereafter BMC) observed a periodic wavelike structure (the Ripples hereafter), at the surface of the Orion cloud (Figure 1) which appears to be compatible with a KHI. However, this work was mostly qualitative and lacked a detailed model to assess if the development of the KHI is possible in conditions as those found in Orion. In addition, this former study did not consider the possible effect of magnetic fields—which are known to be strong in Orion (Abel et al. 2004)—on the KHI. Finally, even if there is evidence for the existence of the KHI in the ISM, it remains unclear over which timescale this instability may convert energy into turbulent motion of the gas and hence if it can actually play a role in mixing the hot and cold gas. On the theoretical side, extensive numerical magnetohydrodynamical (MHD) models for the KHI have been developed and successfully applied to explain observed phenomena in solar-system plasmas (e.g., Matsumoto & Hoshino 2004). In addition, Matsumoto & Seki (2010) have studied in great detail the saturation of the KHI and its evolution into turbulence and mixing of the gas. In this Letter, we perform a linear MHD analysis applied to the situation in Orion’s Ripples, using physical parameters determined observationally. We derive the key parameters that characterize the instability and use them to determine the timescales over which the gas becomes turbulent due to the saturation of the instability. We discuss these results in the context of chemical mixing in the ISM and transport of 26Al in the solar system.

2. OBSERVATIONS

Figure 1 shows the Spitzer Space Telescope (Werner et al. 2004) mid-infrared (mid-IR) image of the Ripples in Orion, which have been attributed to a KHI by BMC. KHI occurs at the interface between two fluids flowing relative to each other. In the case of Orion, the two fluids are the H II gas and the neutral gas of the molecular cloud, and the velocity shear results from the champagne flow created by the H II region bursting through the parental molecular cloud. When growing, the KHI gives to the interface a wavelike structure which can be seen in Figure 1. An important parameter of the KHI is its spatial wavelength λ, which is connected to the physical conditions in which the instability occurs. Here, λ can be measured directly from the image and is found to be λ = 0.11 pc for a distance...
to the Orion nebula of 414 pc. This corresponds to a spatial wavenumber \(k = 2\pi/\lambda = 2 \times 10^{-15} \text{ m}^{-1}\).

3. LINEAR ANALYSIS OF THE KELVIN–HELMHOLTZ INSTABILITY IN ORION

3.1. Objectives and Method

Our goal here is to study from the theoretical point of view, and using realistic physical conditions, the stability of an H\(\text{II}\)/molecular cloud interface against the KHI. In particular, we want to determine whether magnetic fields can play a stabilizing role. It is also of great interest to derive some of the key parameters, for instance the growth rate \(\gamma\) and the range of acceptable wavelengths. In order to do this, we perform a linear stability study which includes magnetic field, compressibility, and an analytical velocity profile across the sheared layer (see below). This differs greatly from the preliminary study of BMC which relied on an ideal case (Chandrasekhar 1961) of incompressible fluids with a discontinuous velocity profile and no magnetic field. The present study is performed in a two-dimensional slab geometry, described in Figure 2 for the initial conditions. These initial conditions are maintained by the MHD equilibrium. The density gradient and velocity gradients are along the MHD equilibrium. The density gradient and velocity gradients are of hyperbolic-tangent form (Miura & Pritchett 1982). The velocity is oriented along the \(x\)-axis. The magnetic field direction is inside the plane defined by \(y\) and \(z\) and its orientation is defined by the angle \(\theta\) between \(\mathbf{B}\) and \(z\). For this first analysis, we have not considered the azimuthal dependence for the orientation of \(\mathbf{B}\) because this would imply heavy complications in the solving of the MHD equations. For the adopted configuration, the MHD equations are linearized and a perturbed quantity \(f\) can be expanded as a plane wave in the form of \(f(x, y) = \hat{f}(y) \exp[i(k_x x - \omega t)]\). The linearized equations can then be solved, with boundary conditions in the \(y\)-direction and a given wavenumber \(k_x\) for the corresponding eigenvalue (angular frequency and growth rate) as an eigenvalue problem. This is described in mathematical terms in the following section.

4. LINEAR MODEL

4.1. Basic Equations

The basic MHD equations are

\[
\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V} \cdot \nabla)\mathbf{V} - \frac{1}{\rho} \nabla \left( P + \frac{B^2}{8\pi} \right) + \frac{1}{4\pi} (\mathbf{B} \cdot \nabla)\mathbf{B},
\]

\[
\frac{\partial P}{\partial t} = -(\mathbf{V} \cdot \nabla)P - \Gamma P(\nabla \cdot \mathbf{V}),
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = -c \nabla \times \mathbf{E},
\]

with the frozen-in condition

\[
\mathbf{E} = -\frac{\mathbf{V}}{c} \times \mathbf{B},
\]

where \(\Gamma = 5/3\) is a polytropic constant. The mass density \(\rho\) and the magnetic field \(\mathbf{B}\) are normalized by characteristic values of \(\rho_0\) and \(B_0\), the velocity \(\mathbf{V}\) by the velocity jump across the boundary, \(V_0\), the pressure \(P\) by \(B_0^2/8\pi\), the spatial scale by the initial shear width \(L\), and the time by \(L/V_0\).

4.2. Linearization and Solution

We consider perturbed quantities from an equilibrium state as

\[
\mathbf{V} = \mathbf{V}_0 + \delta\mathbf{v},
\]

\[
P = P_0 + \delta p,
\]

\[
\mathbf{B} = B_0 + \mathbf{b}.
\]

The perturbed quantities are expressed as a plane wave in the form, \(\delta A = \Delta(y) \exp[i(k_x x - \omega t)]\), where \(\Delta\), \(k_x\), and \(\omega = \omega_r + i\omega_i\) denote a physical parameter, the wavenumber in the \(x\)-direction, and the angular frequency, respectively.

Linearizing the above MHD Equations (1–4), one obtains

\[
\omega \delta v_x = k_x V_x \delta v_y - i \frac{k_x}{2 n_0} \delta v_y + k_x \frac{B_{0y}}{n_0} b_y + \frac{i}{n_0} \frac{\partial B_{0x}}{\partial y} b_y,
\]

\[
\omega \delta v_y = k_x V_x \delta v_y - \frac{i}{2 n_0} \frac{\partial}{\partial y}(\delta p + 2 B_0 \cdot \mathbf{b}) - k_x \frac{B_{0x}}{n_0} b_y,
\]

\[
\omega \delta v_z = k_x V_x \delta v_z - k_x \frac{B_{0x}}{n_0} b_x + \frac{i}{n_0} \frac{\partial B_{0x}}{\partial y} b_y.
\]
Table 1

| Parameter                          | Symbol | Reference |
|-----------------------------------|--------|-----------|
| Heliocentric distance             | $d$    | 414 pc    | (1)       |
| Neutral gas density               | $n_I$  | $10^4$ cm$^{-3}$ | (2)   |
| Ionized gas density               | $n_H$  | 20 cm$^{-3}$ | (2)   |
| Neutral gas temperature           | $T_I$  | 20 K      | (3)       |
| Ionized gas temperature           | $T_H$  | 10$^4$ K  | (4)       |
| Velocity sheer adopted here       | $V_0$  | 10 km s$^{-1}$ | (5) |
| Gravitational field               | $g$    | $3.5 \times 10^{-11}$ m s$^{-2}$ | (2) |
| Magnetic field strength           | $B$    | 20 nT     | (6)       |
| Magnetic field orientations       | $\theta$ | 0°–90°  |           |
| Instability wavelength            | $\lambda$ | 0.11 pc | (2) |
| Width of the sheered layer        | $L$    | 0.01 pc   | (2)       |
| Linear regime length              | $L_{lin}$ | 0.3 pc | Figure 1  |

Derived values (for maximal growth rate)

| Instability growth rate           | $\gamma$ | $2.3 \times 10^{-13}$ s$^{-1}$ |
| Instability phase velocity        | $V_p$    | 3.6 km s$^{-1}$ |
| Instability saturation timescale  | $t_{sat}$ | $2 \times 10^5$ yr |
| Size of mixing layer after $t_{sat}$ | $L_{mix}$ | 0.5 pc |
| Distance traveled before saturation | $L_{sat}$ | 0.74 pc |

References. (1) From Menten et al. (2007); (2) from BMC; (3) typical for molecular clouds (Tielens 2005); (4) typical for H$\text{ii}$ regions (Tielens 2005); (5) from Roy & Kunth (1991); (6) based on Abel et al. (2004).

The results of the linear analysis concern the linear growth of the instability. They are presented in Figures 3 and 4. Figure 3 shows the influence of the value of $\theta$, the inclination of the magnetic field, on the normalized growth rate $\gamma L/V_0$ and on the normalized wavenumber $k_L$. The growth rate decreases with increasing angle but for $-25^\circ \lesssim \theta \lesssim 25^\circ$ the growth rate is non-zero, implying that the interface is KH unstable. In this range of values for $\theta$, the wavenumber $k_L$ is almost constant, showing that it does not depend on magnetic field orientation. Figure 4 shows the evolution of the normalized growth rate $\gamma L/V_0$ as a function of the normalized wavenumber $k_L$ for $\theta = 0^\circ$. The most unstable mode corresponds to $k_L = 0.56$, and typically, for $0.1 < k_L < 1$, the growth rate is high and corresponds to an $e$-fold timescale of less than $10^5$ years, short compared to the lifetime of an OB association ($\sim 10$ Myr). Therefore, it is expected that instabilities with $0.1 < k_L < 1$ appear in star-forming regions. Using $L = 0.01$ pc imposes that the wavelength of the instability $\lambda_{KH}$ will range between 0.06 and 0.6 pc. This number also places limits on the detectability of their results, we adopt $n_I = 10^4$ cm$^{-3}$ and $T_I = 20$ K. For the H$\text{ii}$ region, we consider a typical temperature $T_H = 10^4$ K, and $n_H = 20$ cm$^{-3}$. The velocity sheer is taken to be $V_0 = 10$ km s$^{-1}$ following Roy & Kunth (1991), also typical for such environments. Magnetic field strength has been measured in the Orion nebula by Brogan et al. (2005) and Abel et al. (2004) and found to vary between 5 nT for the Trapezium region and 25 nT in the Veil region. The Ripples are likely situated between the Trapezium and the Veil, so we adopt a conservative value of $B = 20$ nT. The value of $\theta$ cannot be determined independently, so we have considered various values between 0° and 90° (with symmetrical results in the $-90^\circ$–$0^\circ$ range). Finally, BMC derived a gravitational field at the cloud surface $g = 3.5 \times 10^{-11}$ m s$^{-2}$. We can compare the potential to kinetic energy using the Richardson number $R_i = gL/(V_0)^2$ (Chandrasekhar 1961). The value of $L$ can be estimated to be the thickness of the photodissociation region measured by BMC, which is essentially the region where the gas is converted from fully neutral to fully ionized and where the temperature changes from a few 10 K to a few 1000 K (Tielens & Hollenbach 1985). $L$ is typically 0.01 pc (BMC), hence $R_i \sim 10^{-3}$, which implies that gravity is ineffective and it is no further included in the calculations.

5. RESULTS

5.1. Linear Phase of the KHI

The results of the linear analysis concern the linear growth of the instability. They are presented in Figures 3 and 4. Figure 3 shows the influence of the value of $\theta$, the inclination of the magnetic field, on the normalized growth rate $\gamma L/V_0$ and on the normalized wavenumber $k_L$. The growth rate decreases with increasing angle but for $-25^\circ \lesssim \theta \lesssim 25^\circ$ the growth rate is non-zero, implying that the interface is KH unstable. In this range of values for $\theta$, the wavenumber $k_L$ is almost constant, showing that it does not depend on magnetic field orientation. Figure 4 shows the evolution of the normalized growth rate $\gamma L/V_0$ as a function of the normalized wavenumber $k_L$ for $\theta = 0^\circ$. The most unstable mode corresponds to $k_L = 0.56$, and typically, for $0.1 < k_L < 1$, the growth rate is high and corresponds to an $e$-fold timescale of less than $10^5$ years, short compared to the lifetime of an OB association ($\sim 10$ Myr). Therefore, it is expected that instabilities with $0.1 < k_L < 1$ appear in star-forming regions. Using $L = 0.01$ pc imposes that the wavelength of the instability $\lambda_{KH}$ will range between 0.06 and 0.6 pc. This number also places limits on the detectability of...
KHIs: at a distance of 1 kpc this is an angular size of $4^\circ$–$40^\circ$, and at 10 kpc this is $0.4^\circ$–$4^\circ$. Hence, KHI structures are expected to be of small angular size and can only be observed with high angular resolution telescope and/or in nearby regions of massive star formation like Orion.

5.2. Saturation of the KHI

Matsumoto & Seki (2010) studied in details the two-dimensional evolution of the KHI for conditions similar to those presented here and found that the growth of the instability leads to saturation. This results in the formation of a turbulent layer where the two fluids are mixed, over a timescale of the order of $t_{\text{sat}} \sim 200L/V_0$. Hence, using the observed value for $L$ (Table 1), this results in a saturation timescale $t_{\text{sat}} \sim 2 \times 10^5$ years. It is important to realize that even if $t_{\text{sat}}$ is short there is always a part of the instability that remains linear. According to the results of our linear analysis, we find that the KHI mode travels along the boundary layer with a speed of $V_\phi = 0.36 \times V_0$, that is, $\sim 3.6 \text{ km s}^{-1}$. Hence, we can define $L_{\text{sat}}$, the spatial scale before the instability has saturated by $s_{\text{sat}} = V_\phi t_{\text{sat}}$ and find $L_{\text{sat}} \sim 0.74 \text{ pc}$. These theoretical results have several implications. First, the timescale for saturation is short compared to the lifetime of an OB association, so KHIs will saturate and will be a source of turbulence. Second, the scale size over which it is possible to see the linear regime is at maximum $0.74 \text{ pc}$.

6. THE Ripples AS A KHI

Based on the theoretical results described above, we investigate in more details if the Ripples can be interpreted as an occurrence of the linear phase of the KHI. The observed value of $\lambda$ for the Ripples is $0.1 \text{ pc}$, which falls in the range defined from the theoretical investigation ($0.06 < \lambda_{\text{KH}} < 0.6 \text{ pc}$).

The Ripples seem to preserve a very periodic structure, suggesting linear regime, over a distance $L_{\text{lin}} = 3\lambda = 0.3 \text{ pc}$ (Figure 1). The following two billows, instead, start showing some chaotic structure suggesting the beginning of the saturation of the instability. After about $5\lambda$, the periodic structure has disappeared. Hence, the traveled distance in linear regime $L_{\text{lin}}$ for the Ripples is, consistent with the KHI model, smaller than the maximal theoretical value of $L_{\text{sat}} = 0.74 \text{ pc}$ discussed in Section 5. Therefore, we argue that the observed evolution of the Ripples structure results from the motion of the KH wave toward saturation, from left to right in Figure 1. Our last remark concerns the importance of the magnetic field. As mentioned above, the Ripples can only result from a KHI if they are in a region of small $\theta$. Orientations of the magnetic field lines in Orion have been measured by, e.g., Houde et al. (2004) and Poidevin et al. (2010) using polarimetry. Unfortunately, this does not cover the Ripples region and, in addition, performing such measurements at the arcsecond scale remains challenging. We can only stress the importance—often neglected—that magnetic fields have in shaping the ISM, in this case because they can stabilize interfaces between H$\text{n}$ regions and molecular clouds.

Altogether, we conclude that the study presented in this Letter brings additional evidence that the Ripples result from a KHI. This raises one question, however: why do we only see one occurrence of the KHI in Orion? This is perhaps because only in this region are the conditions (e.g., magnetic field, velocity flow) favorable at the moment we observe Orion. Over the lifetime of the region, however, this may occur a high number of times. Ripples have indeed been observed recently in another star-forming region (Cygnus OB2) by Sahai et al. (2012), suggesting that the structure in Orion is not unique. It is also possible that more of these structures exist in Orion, but given their small angular size or unfavorable orientation on the plane of the sky, they remain undetectable (see Section 5).

7. THE KHI AND CHEMICAL MIXING IN STAR-FORMING REGIONS

7.1. Saturation of the Instability: Turbulence and Chemical Mixing

We have discussed in Section 5 the saturation of the KHI toward a turbulent regime. This may have an important role in chemical mixing in star-forming regions. Roy & Kunth (1991) were the first to recognize the importance of the KHI in chemical mixing of the ISM. They studied the influence of KHIs by defining the $\epsilon$-fold timescale assuming a spatial wavelength of 100 pc (the size of a large H$\text{n}$ region), and from this derived a timescale of $1.5 \times 10^5$ years, which is smaller than the lifetime of an OB association. However, their model was based on an ideal hydrodynamical case with no magnetic field, for which the wavelength of maximal growth rate cannot be determined. This is partly due to the fact that no observational evidence of KHIs existed at the time. The results presented in this Letter using a more detailed model and guided by direct observations are clearly incompatible with a maximal growth rate corresponding to $\lambda = 100 \text{ pc}$. In addition, Roy & Kunth (1991) used the $\epsilon$-fold timescale as a measure of mixing timescale, which is not appropriate. Instead, we can use the results found here and those of Matsumoto & Seki (2010) to obtain some general appreciation of the efficiency of the KHI mixing in star-forming regions. First, as mentioned above, full mixing of the fluids occurs after $t_{\text{sat}}$, which we have found to be of the order of a few $10^5$ years. Again, this is short compared to the lifetime of an OB association, so the process will be efficient. After this time, the size of the mixed layer is $L_{\text{mix}} = 50 \times L$ (Matsumoto & Seki 2010, Figure 9), that is, 0.5 pc. All in all, in agreement with Roy & Kunth (1991; although making different hypotheses), we conclude that the KHI can be an efficient mechanism to mix chemical elements in the ISM.

7.2. Further Implications: $^{26}\text{Al}$ in the Solar System

It is believed that low-mass star formation is triggered in the overdense shell of molecular cloud that lies around H$\text{n}$

![Graph showing normalized growth rate $\gamma L/V_0$ versus normalized spatial wavenumber $kL$ for the KH instability.](https://example.com/graph.png)
regions (see, e.g., Deharveng et al. 2010). In a recent paper, Gounelle & Meynet (2012) argue that the solar system may have formed in such an environment, based on the abundances of short-lived radionuclides found in meteorites. In particular, they propose that $^{26}$Al was brought to the forming solar system by the winds of a massive star (see also Montmerle et al. 2007) rather than by supernovae. This requires that a nearby massive star ($M_\star > 32 M_\odot$) injected $^{26}$Al during a few million years, and that this element was then well mixed with the H ii gas, and eventually that the H ii gas was mixed with the surrounding molecular shell efficiently. In Orion at least, the gas from the wind seems to be well mixed with the H ii region as shown by Gudel et al. (2008). The efficiency of H ii mixing with the molecular shell was not evaluated by Gounelle & Meynet (2012). However, they derive the time $t_\star$, during which the molecular shell has to be enriched before the solar system starts to form. This value ranges between 0.65 and 6.2 Myr. The mixing timescale we have derived here ($t_{\text{mix}} = 2 \times 10^5$ yr) is smaller than $t_\star$, so that indeed mixing by the KHI is efficient to enrich the molecular shell with $^{26}$Al. Hence, the KHI (and possibly other instabilities) could have played an important role in the transport of $^{26}$Al to the forming solar system.

8. CONCLUSION

We have shown that the KHI develops rapidly at the H ii molecular cloud interface in conditions like Orion (which are representative of many massive star-forming regions). After traveling at the surface of the cloud during a time of a few $10^5$ years and over a maximum distance of $\sim 0.74$ pc, the instability reaches saturation. Hence, as suspected, the KHI is probably a significant mechanism to generate small scale ($<1$ pc) turbulence in molecular clouds near massive stars. In addition, since the H ii region is contaminated by the chemical elements injected by massive stars winds, the KHI may be a relevant process to bring these elements inside the molecular cloud, in regions where planetary systems around young stars are formed. This could have been at play to transport $^{26}$Al to the nascent solar system. Periodic structures corresponding to the linear phase of the KHI (like the Ripples) should be relatively widespread in star-forming regions, for instance on the surface of molecular globules as reported recently (Sahai et al. 2012). However, these structures are expected to be small (few arcseconds) and hence require high angular resolution observations to be identified.

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