The role of massive stars and clusters in the evolution of KH instabilities in molecular clouds

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Here, we investigate the influence of radiation pressure from massive stars and clusters on KH instabilities in the interface between HII region and molecular clouds. The stability of the interface between HII region and molecular cloud in the presence of radiation pressure has been studied using the linear perturbation analysis in a certain range of wavelengths in which the growth rate is high. A linear analysis shows that the radiation pressure has a destabilizing effect on the growing KH modes and decreases the e-fold time scale of instability, specially in small perturbations. Based on our results, the radiation pressure is a triggering factor in the development of KH instabilities and subsequently formation of turbulent-structures.

I. INTRODUCTION

The wave-like structures at the surface of the Orion cloud has been recently observed by Berné, Marcelino and Cernichora (2010), mainly seen near massive star-forming regions (Figure.1). They proposed that these ripples may be produced by some hydrodynamical instabilities taking place in the interface between the hot diffuse gas, which is ionized by massive young stars, and the cold dense molecular cloud, which was nursery of the star-forming pawns.The most likely hydrodynamical instability that may be able to describe the ripples appropriately, seems to be the Kelvin-Helmholtz (KH) instability. There are some significant evidences which confirm this claim that rippled structures has been created by KH instability: the molecular cloud is subject to an important velocity gradient that is due to champagne flow occurred by the exploding HII region, the passage of flow of diffuse HII gas and the acceleration of the molecular cloud by it makes a velocity sheer in the interface between two regions.The radiation pressure of massive stars and stellar clusters has been one of the issues that has been considered frequently in dynamics of clouds. For example, the radiation pressure is a physical process that can disrupt giant molecular clouds, and has been mentioned as an important feedback mechanism which can affects the efficiency of star formation (e.g., Murray, Quataert and Thompson 2010). Also, the exerted radiation pressure of ambient non-ionizing radiation on the cloud cores and filaments, can alter the structure of them and can promote the gravitational collapse (e.g., Seo and Youdin 2016).

Trapezium cluster is an illustrious source and responsible for much of the illumination of the surrounding Orion nebula. It is a tight group of OB stars in the center of the Orion nebula and includes several extremely bright young stars that the luminosity of each one of them is several thousand times of that of the sun (Simón-Díaz et al. 2006). In this way, we expect that the radiation pressure of Trapezium cluster, which are in the vicinity of Orion's ripples, may have significant effects on development of the KH instability and formation of rippled structure. For this purpose, we investigate the effect of radiation pressure from Trapezium cluster on development of KH instability in the different situations in Orion molecular cloud. We can roughly estimate the radiation pressure of this association at the place of the rippled structures. Cluster has total luminosity $L^T = L_n + L_i$ where L_n and L_i are the non-ionizing and ionizing luminosities of Trapezium cluster for $h\nu < 13.6eV$ and $h\nu > 13.6eV$ photons, respectively. For massive stars and clusters including massive stars, whose luminosity comes mostly from ionizing photons, $L^T = L_i$. The total average flux of radiation at the distance d is $F^T_{rad} = xL^T/4\pi d^2$ where x is transmission coefficint of photons to the layer. We assume that some fraction of photons are dispersed via the scattering. In this way, the radiation pressure on layer can be estimated by the flux of radiation as $P_r \approx x \times 0.1\frac{F^T_{rad}}{c}$, where c is the speed of light. If we express L^T in unit of solar luminosity ($L_\odot$) and d in the scale of parsec, we have

$$P_r \approx x \times 1.1 \times 10^{-15} \frac{L^T_{(L_\odot)}}{d^2_{(pc)}} \quad \frac{dyne}{cm^2}. \tag{1}$$

Considering the luminosity of OB stars $L_{\rm OB} = 0.8 \times 10^{39} erg/s \simeq 2{\times}10^5 L_\odot$ (Drain 2011) and analyzed stars of Trapezium as given by Simón-Díaz et al. (2006) and including about 10-100 stars in cluster, we predict that the total luminosity of this stellar association is 10^6 up to 10^7 times of that of Sun. For a typical distance $2pc$, according to scale of distance in the Figure 1 of Berné, Marcelino and Cernichora (2010) and for a minimum value for transmission factor; $x = 0.1$, the radiation pressure at

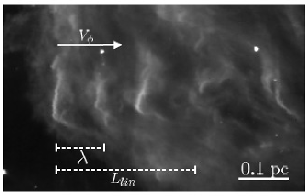

FIG. 1. Observation of the ripples in Orion at 8 μm, taken with the Spitzer Infrared Array Camera. λ denote the spatial wavelength of the structure, L_{lin} is the distance over which the instability is linear and and V_ϕ is the phase velocity of KH waves at the surface of cloud. Figure. 1 is from Berné & Matsumoto (2012)).

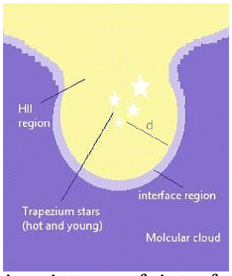

FIG. 2. Schematic picture of interface between HII region and molecular cloud in the presence of radiation field of Trapezium.

the interface layer is estimated as $2.7 \times 10^{-11}\ \frac{dyne}{cm^2} \lesssim P_{\rm r} \lesssim 2.7 \times 10^{-10}\ \frac{dyne}{cm^2}$. On the other hand, if we adopt the observational data for the density and temperature of HII region and molecular cloud which were used by Berné and Matsumoto (2012): $n_{II} = 20cm^{-3}$, $T_{II} = 10^4 K$, $n_{MC} = 10^4 cm^{-3}$, $T_{MC} = 20K$, the gas pressure at the interface is equal to $P_g = k_B n_{II} T_{II} = k_B n_{MC} T_{MC} = 2.7 \times 10^{-11} (\frac{dyne}{cm^2})$. Thus, by comparing the gas pressure with the estimated radiation pressure, it can be deduced that $1P_g \lesssim P_r \lesssim 10P_g$. For a distance $3pc$, we obtain this estimation as $0.3P_g \lesssim P_r \lesssim 3P_g$. The more amount of the radiation pressure is obtained , If we consider the more fraction of photons enter to the layer. Therefore, it is expected that the radiation pressure may have a significant dynamical impact on the formation of rippled structures of the Orion molecular cloud around HII region, especially on the instabilities which are constituted there. For this purpose, we investigate the influence of radiation pressure on the growth rates of the KH instability for real physical conditions in the Orion. We also can obtain the corresponding time-scales of these growth rates of instabilities, by the linear perturbation analysis method.

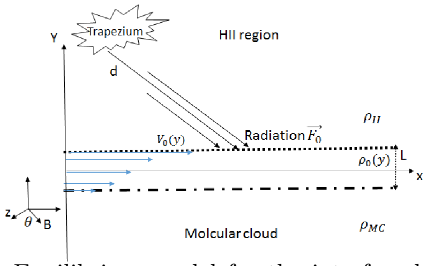

FIG. 3. Equilibrium model for the interface between HII region and molecular cloud in the presence of radiation field of Trapezium.

II. THE EQUILIBRIUM MODEL FOR RADIATED LAYER

Here, we investigate the equilibrium of the interface layer between HII region and molecular cloud in the presence of the radiation field. The geometry of setup used for the interface layer between HII region and molecular cloud is a two dimensional setup that is depicted in Fig (3). The upper part corresponds to the hot, low density HII region with density and temperature ρ_{II} and T_{II}, respectively, the lower part represents the cold, high density molecular cloud with density and temperature ρ_{MC} and T_{MC}, respectively, and both are separated by a thin middle layer with thickness L, which is estimated about 0.01pc by means of observations (Berne, Marcelino and Cernichora 2010). The radiation pressure acts on the matter of this interface layer.

The coordinates are chosen so that the interface layer is in the x-axis; the density and velocity gradients are along the y-axis.

$$\mathbf{V}_0(y) = \frac{V_0}{2}\left(1 + \tanh\frac{y}{L}\right)\mathbf{e}_x, \tag{2}$$

$$\rho_0(y) = \frac{\rho_{II}}{2}\left[(1-\alpha)\tanh\frac{y}{L} + (1+\alpha)\right] \tag{3}$$

where V_0 is the total variation of velocity across the transition layer, $\mathbf{e}_x$ is the unit vector along the x-axis, and $\alpha \equiv \rho_{MC}/\rho_{II}$. The magnetic field direction is in the xz plane and its orientation is defined by the angle θ between $\mathbf{B}$ and z. In general, we have $\mathbf{B}_0 = B_0(y)\sin\theta\mathbf{e}_x + B_0(y)\cos\theta\mathbf{e}_z$ so that the magnetic divergence equation, $\nabla\cdot\mathbf{B}_0 = 0$ is satisfied. We choose the density and temperature of HII region and molecular cloud so that the gas pressure, P_{0g}, be equal between the upper and lower mediums and is independent of y. In this way, the general equilibrium condition of the interface layer, in the y direction,

$$P_{0g} + P_{0r}(y) + \frac{B_{0z}^2(y)}{2\mu_0} = const., \tag{4}$$

implies that the magnetic field at HII region must be smaller than its value at the molecular cloud because the radiation pressure at HII region is greater than its value at the molecular cloud. This result is in consistent with the observations of Abel et al. (2004) and Brogan et al. (2005) who found that the magnetic field varies between $5nT$ at the Trapezium region to $25nT$ at the Veil region.

III. BASIC EQUATIONS AND LINEAR PERTURBATION ANALYSIS

We consider a compressible fluid and neglect the self gravity, which is ineffective in our interesting place of the Orion's molecular cloud as outlined by Berné and Matsumoto (2012). Our basic equations are standard ideal MHD equations with assumption that the gas and the radiation are in perfect radiative equilibrium. Also, we have good isotropic thermal coupling to the matter so that the radiation pressure, P_r, and the radiation energy density, E_r, are related as $P_r = E_r/3$. In this situation, the radiation conduction approximation gives for the diffusive flux (e.g., Shu 1992)

$$\mathbf{F}_r = -\frac{c}{3\rho\kappa}\nabla E_r = -\frac{c}{\rho\kappa}\nabla P_r \tag{5}$$

where κ is the mean opacity of the gas at the interface layer. In this way, the MHD equations in the presence of radiation field are

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho\mathbf{v}) = \mathbf{0}, \tag{6}$$

$$\frac{\partial\mathbf{v}}{\partial t} + (\mathbf{v}.\nabla)\mathbf{v} = -\frac{1}{\rho}\nabla(P_g + P_r + \frac{B^2}{2\mu_0}) + \frac{1}{\rho\mu_0}(\mathbf{B}.\nabla)\mathbf{B}, \tag{7}$$

$$\frac{\partial P_g}{\partial t} = -(\mathbf{v}.\nabla)P_g - \gamma P_g(\nabla.\mathbf{v}), \tag{8}$$

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}), \tag{9}$$

$$\frac{\partial E_r}{\partial t} + \nabla.(\mathbf{F_r} + E_r\mathbf{v}) = -P_r\nabla.\mathbf{v} \tag{10}$$

where ρ is the fluid mass density, $\mathbf{v}$ is the velocity, P_g is the gas pressure, B is the magnetic field, and γ is the gas adiabatic index.

We perturb quantities linearly from an equilibrium state as

$$\begin{aligned} \rho &= \rho_0 + \delta\rho, \\ \mathbf{v} &= \mathbf{V}_0 + \delta\mathbf{v}, \\ P_g &= P_{0g} + \delta P_g, \\ P_r &= P_{0r} + \delta P_r, \\ \mathbf{B} &= \mathbf{B}_0 + \delta\mathbf{B}. \end{aligned}$$

We consider the perturbations in the form of $\delta f(y)\exp[i(k_x x - \omega t)]$, where k_x and ω are the wave number in the x-direction and the angular frequency, respectively, so that $\omega = \omega_r + i\omega_i$, where ω_r and ω_i are the real and imaginary parts of the angular frequency. In this way, the linearized form and normalized of the MHD equations (6)-(10) can then be written as follows Our analysis is done for transverse case of magnetic field ($B_{0x} = 0$), as these have the fastest growth rates according to the results of Berné and Matsumoto (2012).

$$\begin{aligned}
\omega\delta v_x &= k_x V_{0x}\delta v_x - i\frac{\delta V_{0x}}{\partial y}\delta v_y + \frac{k_x}{2\eta_0(y)}\delta P_g \\
&+ \frac{k_x}{2\eta_0(y)}\delta P_r + \frac{kB_{0z}\delta B_z}{\eta_0(y)}, \\
\omega\delta v_y &= k_x V_{0x}\delta v_y - \frac{i}{2\eta_0(y)}\frac{\partial\delta P_g}{\partial y} - \frac{i}{2\eta_0(y)}\frac{\partial\delta P_r}{\partial y} \\
&- \frac{i}{\eta_0(y)}B_{0z}\frac{\partial\delta B_z}{\partial y}, \\
\omega\delta P_g &= \gamma P_{0g}k_x\delta v_x - i\gamma P_{0g}\frac{\partial\delta v_y}{\delta y} + k_x V_{0x}\delta P_g, \\
\omega\delta P_r &= \frac{4}{3}P_{0r}k_x\delta v_x - i\frac{4}{3}P_{0r}\frac{\partial\delta v_y}{\delta y} + (k_x V_{0x} + \varepsilon\frac{ick_x^2}{V_0}\delta P_r \\
&+ \varepsilon\frac{ic}{3\rho_0(y)V_0}\frac{\partial\rho_0}{\partial y}\frac{\partial\delta P_r}{\partial y} - \varepsilon\frac{ic}{3V_0}\frac{\partial^2\delta P_r}{\partial y^2}, \\
\omega\delta B_z &= k_x B_{0z}\delta v_x - iB_{0z}\frac{\partial\delta v_y}{\partial y} \\
&- k_x B_{0x}\delta v_z + k_x V_{0x}\delta B_z.
\end{aligned} \tag{11}$$

We also have assumed that the interface layer is a opaque gas and all of the photons which are mostly ionizing photons will be absorbed in this area.

In these conditions we solve equations numerically using the difference-method and obtain the growth rates: imaginary part of ω versus wave number k. We place boundaries at $y = \pm b$ far away from layer and set the relevant boundary conditions thereon. For the initial parameters, we use the values of typical densities and temperatures of HII region and molecular clouds in ISM (Tielens 2005), observational constraints are utilized by Matsumoto and Berné (2012) and estimations from radiation pressure of Trapezium.

IV. RESULTS AND DISCUSSION

Figure 4 shows the normalized growth rate of instability $\omega_i L/V_0$ as a function of normalized wave number $k_x L$, for the sample of five selected values of the ratio of radiation pressure to gas pressure P_{0r}/P_{0g}, introduced by Π. Each curve demonstrates different value for Π, from bottom to top as 0, 10, 30, 50, 100.

Clearly for $\Pi = 0$ we can find solution presented by Matsumoto and Berné(2012). As the radiation pressure

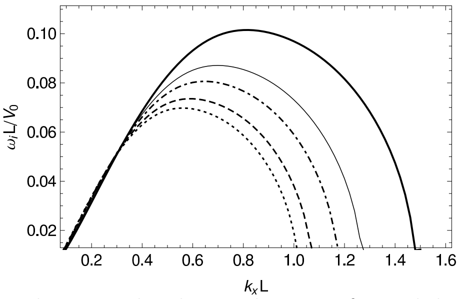

FIG. 4. The normalized growth rates of instability $\omega_i L/V_0$ as a function of normalized wave number $k_x L$. Each curve demonstrates different value for $\Pi = P_{0r}/P_{0g}$ from bottom to top as 0, 10, 30, 50, 100. The lowermost curve represents the case in which there is no radiation pressure. Magnetic field strength, variation of the velocity and density contrasts between two regions are considered $B = 20nT$, $10kms^{-1}$ and 500, respectively. Number densities and temperatures are taken to be $n_{II} = 20cm^{-3}, T_{II} = 10^4k$ and $T_{MC} = 20k, n_c = 10^4cm^{-3}$.

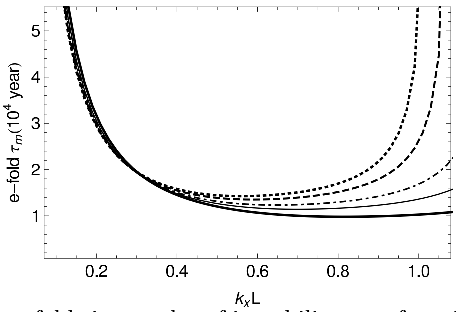

FIG. 5. e-fold time scales of instability as a function of the normalized wave number. Each curve indicates different value for $\Pi = P_{0r}/P_{0g}$ from top to bottom as 0, 10, 30, 50, 100.

increases, normalized growth rate of instability increases, while for $k_x L < 0.4(\lambda_{\rm KH} > 0.15pc)$, the growth rate is not sensitive to radiation pressure.

Figure 5 shows e-fold time scales of instability as a function of wave numbers $k_x L$ for different values of Π. Each curve demonstrates different values for Π, from top to bottom as 0, 10, 30, 50, 100. The e-fold time scale decreases by increasing the radiation pressure, for $k_x L > 0.4$, while e-fold time scale of the instability for $k_x L < 0.4$ does not depend to the radiation pressure. This figure also shows that in large wave numbers, reduction rate of e-fold time scales is more than other wave numbers.

In this work, we studied the dynamical effect of radiation pressure from Trapezium cluster on the growth rate of KH instabilities in Orion nebula. Orion nebula is representative of many star forming regions, therefore the obtained results are generalizable for other star formation regions which have the favorable conditions for forming rippled structures. We have shown that the radiation pressure has a destabilizing effect on the growing KH modes and decreases the e-fold time scale of instability. In addition the domain of instability is extended and includes more wavelengths special small wavelengths. Our results shows that for $\lambda_{\rm KH} > 0.15pc$, the growth rate of KH instability dose not depend to the radiation pressure. The results also indicate that e-fold time scale of instability decreases significantly, specially in small wavelengths. Mutsumoto and Berné (2012) studied the evolution of linear phase of KH instability toward saturation phase and claimed that the turbulent structures are formed during time $t_{\rm sat}$. Our results shows that the radiation pressure accelerates the development of KH instabilities in linear phase and subsequently, it is expected that the formation of turbulent structures precess. Since, e-fold time scales of instability are short comparing to the life time of OB associations $\sim 10Myr$, thus the radiation pressure can act effectively on surrounding during life time of OB stars. As well as, the radiation pressure is probably a significant factor to generate small scale ($< 0.15pc$) turbulences in molecular clouds near massive stars. These results suggest that radiation pressure is a triggering factor in ISM. On the other hand, it confirms the disruptive role of the radiation pressure in ISM certified by others.

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