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Parker instability in the nonadiabatic ISM

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Abstract

We study Parker instability under the influence of heating and cooling processes. We distinguish three models with respect to different heating functions. We find that the properties of the Parker instability in such a system are significantly different with respect to the adiabatic and isothermal cases.

1 Introduction

The Parker instability (PI) (Parker 1966) is considered as a mechanism contributing to the formation of molecular cloud complexes (Blitz & Shu 1980). This idea has been criticized by Kim et al. 1998, who conclude from their simulations, that: (i) the elongated shapes of gas condensations, resulting from the PI, do not correspond to the observed shapes of molecular clouds, and (ii) too small densities are achieved by interstellar gas in magnetic valleys. The suggestion of Parker & Jokipii 2000 is that the mentioned deficiencies of the PI should disappear, when thermal instability (Parker 1953, Field 1965) is taken into account along with effects of turbulent viscosity and stochastic topology of galactic magnetic fields. The thermal instability itself, resulting from the presence of nonadiabatic processes, may lead to formation of condensed cool gas clouds, however its relation to the effects on Parker instability is still unknown. In this paper we address the question of the role of nonadiabatic processes, for the Parker instability.

2 Problem description

We consider a disk equilibrium of ideal, ionized gas characterized by the profiles of pressure $P_0(z)$, density $\rho_0(z)$, temperature $T_0(z)$ and azimuthal magnetic field $B_0(z)$, stratified in vertical (uniform) gravitational field g_z. Assuming $P_{\mathrm{mag}} = \alpha P_0$, we construct a magnetohydrostatic and thermal equilibrium:

$$(1+\alpha)\frac{dP_0}{dz} = -\rho_0 g_z, \qquad n_0^2\Lambda(T_0) = \Gamma(n_0) \tag{1}$$

where $n_0 = \rho_0/m_H$ is a number density, $g_z = 2\times10^{-9}$ cm s^{-2} is the vertical disk gravity and $\alpha = 1$ is a constant. The cooling function $\Lambda(T) = L_C T^{\epsilon}$ is a modified power-law approximation of the one given by Dalgarno & McCray 1972, L_C and ϵ are constants fitted for temperature range 6000K < T < 14000K and Γ is a heating rate per unit volume (heating function). We consider models with three kinds of heating mechanisms contributing to the total heating rate:

I. Heating by UV-radiation from young massive stars. The properties of the heating function come from photoionization models: $\Gamma_{UV}(n) = n^2 G_0$, where G_0 is a constant characterizing the warm ionized gas.

II. Supplemental heat sources postulated by Reynolds et al. 1999), resulting from photoelectric heating by dust, dissipation of interstellar turbulence, Coulomb collisions with cosmic rays, which are proportional to n through $\Gamma_1 = nG_1$ or from magnetic reconnection through $\Gamma_2 = G_2$, where G_1 and G_2 are constant factors.

In order to examine consequences of the three types of heating processes, we consider three models of the Parker instability: **(A)** for $\Gamma = \Gamma_{UV}$, **(B)** for $\Gamma = \Gamma_{UV} + \Gamma_1$ and **(C)** for $\Gamma = \Gamma_{UV} + \Gamma_2$. The equilibrium temperatures and densities of the models depend on the coefficients G_0, G_1, G_2, which are adopted from Reynolds et al. 1999, and presented in Tab. 1. The other parameters are $\epsilon = 10.73$, $L_C = 7.4 \times 10^{66}$ erg cm^3 s^{-1} K$^{-10.73}$.

Table 1: heating rate coefficients

model	$G_0(\times 10^{-24}$erg cm^3 s$^{-1})$	$G_1(\times 10^{-25}$erg s$^{-1})$	$G_2(\times 10^{-27}$erg cm^{-3} s$^{-1})$
A	1.34	0	0
B	0.30	1.60	0
C	0.95	0	7.60

2.1 Linear stability analysis

We use the standard MHD equations, i.e. equations of continuity, energy, equation of motion (with uniform vertical gravity) and the induction equation. In case of nonadiabatic ideal plasma we write the energy equation as:

$$\frac{\rho^\gamma}{\gamma - 1}\left[\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right]\left(\frac{P}{\rho^\gamma}\right) = \Gamma - n^2\Lambda(T), \qquad (2)$$

where $P = nk_BT$, γ is the adiabatic index and other symbols have their usual meaning. We perform linear stability analysis by substituting $P = P_0 + \delta P$, $\rho = \rho_0 + \delta\rho$, $T = T_0 + \delta T$, $\mathbf{v} = (v_x, v_y, v_z)$, $\mathbf{B} = (b_x, B_0 + b_y, b_z)$. By imposing perturbations of the form $\delta f = f_1(z)\exp\left(\omega t - i(k_x x + k_y y)\right)$, we obtain a system of eight first-order partial differential equations, which can be reduced to a single second-order ordinary differential equation for one unknown function, vertical velocity component v_z:

$$A_1 v_z'' + A_2 v_z' + A_3 v_z = 0. \qquad (3)$$

Coefficients A_1, A_2 and A_3 depend on z, ω, k_x, k_y and other parameters. This ordinary differential equation is solved together with an appropriate set of boundary conditions.

We decompose the spatial domain into two regions: the disk in which solutions to the Eqn. (3) are constructed with the aid of numerical integration, surrounded by semi-infinite upper and lower hot-halo atmospheres (for $|z| \geq z_b$), for which analytical solutions are available (see eg. Hanawa et al. 1992). We limit the domain to the upper half-space and consider only symmetric perturbations with respect to the disk midplane. The applied boundary conditions, corresponding to the hot halo and symmetric perturbations, are: $v_z = v_z^h$, $P_{total} = P_{total}^h = const$ at the interface of disk and halo, where $v_z^h(z) \propto \exp\left(-\sqrt{k_x^2 + k_y^2}\, z\right)$ represents the velocity perturbations in halo and $v_z(0) = 0$ is the condition for symmetric perturbations.

3 Numerical procedure and results

Our aim is to find the eigenstates of the system, i.e. such solutions of Eqn. (3) that fulfill the specified boundary conditions. We construct numerical solutions with the aid of the shooting method and obtain the growth rate $\omega_R = \mathrm{Re}(\omega)$ for the instability. In the subsequent considerations we examine the whole range of unstable azimuthal wavenumbers $0 \leq k_y \leq 6$ kpc^{-1} and fix the radial wavenumber to the plausible finite value $k_x = 10$ kpc^{-1}. The disk-halo interface is placed at $z = z_b = 1$ kpc.

The nonadiabatic effects are parameterized by the value of λ. By setting $\lambda = 0$ we can switch off the heating and cooling effects for each model while $\lambda = 1$ represents the realistic values. The choice of different values of γ makes it possible to investigate separately the adiabatic ($\gamma = 5/3$) and isothermal ($\gamma = 1$) cases, when the nonadiabatic terms are switched off. In Fig. 1 (first three panels) we present the dependence of the growth rate on k_y and the magnitude of nonadiabatic effects parametrized by λ for models A, B, C. The major effects apparent in the plots can be described as follows. (1) In model A (UV-heating) the nonadiabatic effects of realistic magnitude ($\lambda = 1$) lead to the same growth rate as in the isothermal case, while in models B and C the nonadiabatic effects enlarge the growth rate above the isothermal limit and widen the range of unstable wavenumbers of the Parker instability.

In order to find a reason for the additional destabilization of models B and C, above the isothermal limit, we find magnetic field lines by integration of the normalized magnetic vector field. We find that the enhanced growth of Parker instability in the nonadiabatic cases results from a modification of pressure gradients along magnetic field lines associated with a drop of temperature in dense regions. This effect is pronounced in models B and C with supplemental heat sources and is absent in model A relying only on the UV heating. In Fig. 1 (bottom-right panel) we plot gas temperature in the nonadiabatic and isothermal cases vs. coordinate z spanned by the selected magnetic line for model C. The lowered temperature in magnetic valleys in the nonadiabatic cases may have important consequences for the subsequent evolution of the ISM. This is because large portions of gas may be shifted below the critical temperature around $T_{\mathrm{crit}} \simeq 6000$K where gas becomes thermally unstable (Kosinski and Hanasz 2005). Therefore the development of modes of Parker instability may trigger the thermal instability as soon as the negative temperature perturbations reach a sufficiently large amplitude.

4 Conclusions

The effect of nonadiabatic processes on the Parker instability can be summarized as follows. In presence of nonadiabatic effects (1) the range of unstable wavenumbers becomes wider, (2) the instability grows faster in comparison to the isothermal cases, (3) we note a possible triggering of the thermal instability and further growth of density is plausible in thermally unstable regions. The presented results support the idea, that Parker instability can trigger the formation of molecular cloud complexes.

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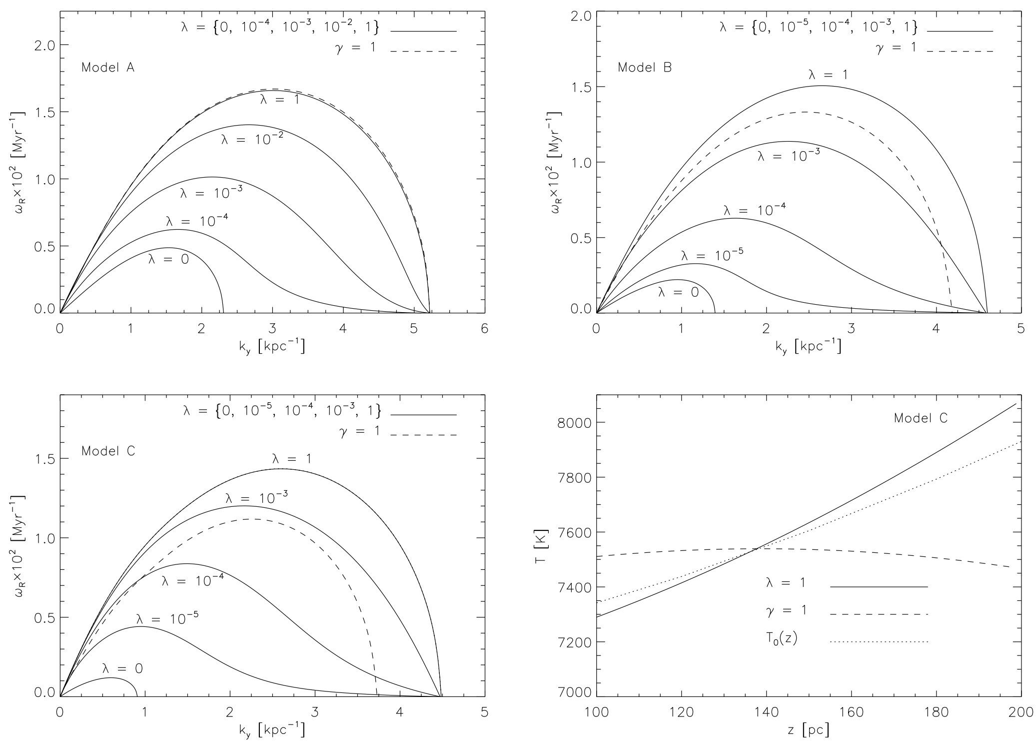

Figure 1: First 3 panels: growth rate of Parker instability for models A, B, C. Bottom-right panel: gas temperature along a selected magnetic field line as a function of z-coordinate, for model C in case of nonadiabatic evolution (full line), isothermal evolution (dashed line). The dotted line represents the temperature profile of the unperturbed equilibrium.

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