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Three-Dimensional Simulations of the Jeans-Parker Instability

Sang Min Lee, Seung Soo Hong
Astronomy Program, SEES, Seoul National University, Seoul, KOREA

and Jongsoo Kim
Korea Astronomy Observatory, Daejeon, KOREA
Department of Physics, University of Notre Dame, Notre Dame, Indiana, USA
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ABSTRACT

We have studied the nonlinear evolution of a magnetized disk of isothermal gas, which is sustained by its self-gravity. Our objective is to investigate how the Jeans, Parker, and convective instabilities compete with each other in structuring/de-structuring large scale condensations in such disk. The Poisson equation for the self-gravity has been solved with a fourth-order accurate Fourier method along with the Green function, and the MHD part has been handled by an isothermal TVD code. When large wavelength perturbations are applied, the combined action of the Jeans and Parker instabilities suppresses the development of the convection and forms a dense core of prolate shape in the mid-plane. Peripheral structures around it are filamentary. The low density filaments connect the dense core to the diffuse upper region. On the other hand, when small wavelength perturbations are applied, the disk develops into an equilibrium state which is reminiscent of the Mouschovias's 2-D non-linear equilibrium of the classical Parker instability under an externally given gravity.

Key Words : Jeans-Parker instability – instability – ISM: GMCs – ISM: magnetic fields – MHD:

I. INTRODUCTION

The Parker instability is one of the most important processes through which large-scale structures have been generated in the Galactic ISM disk. According to numerous 2-D linear stability analyses, the Parker instability can account for the mean separation and lifetime of giant molecular cloud (GMC) complexes. Thus, it was once thought an important formation mechanism of the GMCs in the Galaxy (Parker 1966; Mouschovias et al. 1974; Blitz & Shu 1980; Shibata & Matumoto 1991).

When the stability analysis is generalized from 2-D to 3-D, however, the convection comes into the scene (Parker 1967). The perturbation propagating horizontally in the disk but perpendicularly to the magnetic fields triggers the interchange mode and drives the system convectively unstable. Since the convection grows faster for smaller wavelength perturbations, the whole system develops sheet-like structures before the undular mode has time to generate any condensations in the magnetic valley. The Galactic ISM, therefore, should be shredded into thin sheets by the convective instability before large-scale structures fully grow in the disk (Asséo et al. 1978; Lachiéze et al. 1980). Through a 3-D MHD simulation, Kim et al. (1998) confirmed that the large-scale 2-D structure generated by the classical Parker instability driven by an externally given uniform gravity eventually evolves into chaotic features.

On the other hand, the Galactic gas disk experiences the gravitational accelerations generated by the Galactic stars and the ISM as well. The self-gravity of the interstellar gas accounts only one fifth of the external gravity that is induced mostly by the stars (Bienaymé et al. 1987). As a driving agent of the Parker instability, the self-gravity may not be so important as the externally given one. However, once the gas is perturbed by the Parker instability, the Jeans instability could eventually control the generation of large-scale condensations in the disk.

Hence, for a full investigation on the evolution, it is necessary to study the Galactic disk under gravities of both origins. In most of the previous studies, however, externally given gravity was taken as a sole source of the driving agent. From a linear stability analysis on a self-gravitating magnetized gas disk, Lee & Hong (1999) suggested that the convection could be suppressed by the combined action of the Jeans and Parker instabilities (the Jeans-Parker instability). To investigate how the Jeans-Parker instability competes with the convection in the nonlinear stage, we have simulated the evolution of an isothermal magnetized gas disk under the self-gravity. This is a brief summary of the simulations, and full report will be made in a forth coming paper.

II. Linear Analysis

We have performed a linear stability analysis onto an isothermal vertical equilibrium model of self-gravitating magnetized gas disks. Magnetic field lines are taken initially along the y direction. The disk extends infinitely in the x and y directions, and over a finite thickness, z_a, in the z direction. The system is fully described by *i)* the ratio of magnetic to gas pressure α, *ii)* the adiabatic index γ of the perturbed material, *iii)* the thickness parameter $\zeta_a = z_a/H$, where H is the pressure scale height, *iv)* boundary conditions, and finally

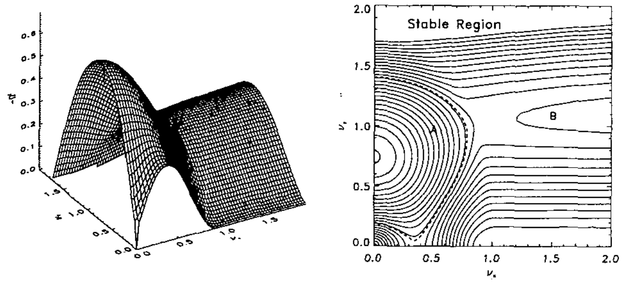

Fig. 1.— Dispersion relation for the case with ζ_a=5.0, α=1.0, γ=1.0, and odd symmetry at the mid-plane. On the left is shown the 3-D surface plot of the growth rate, and on the right is the contour map of equal growth rate. The ordinate of the left frame represents the growth rate squared, and the two abscissae do the horizontal perturbation wave numbers. Model A is a representative of the perturbations that will make the Jeans-Parker instability dominate over the convection, while in Model B the Parker and convection do over the Jeans instability.

v) the perturbation wave numbers ν_x and ν_y. Aiming at the gravitational instability, we have assigned an odd symmetry to the perturbations at z=0. Fig. 1 illustrates how the growth rate varies with $\nu_x(\equiv 2\pi H/\lambda_x)$ and $\nu_y(\equiv 2\pi H/\lambda_y)$ for the case with ζ_a=5.0, α=1.0, and γ=1.0. There are the features of all the Jeans, Parker and convective instabilities. In the left frame of the figure the two peaks in the growth rate, which are induced by the Jeans instability, can be located: one with ν_x=0 is higher than the other with ν_y=0. In the former the Parker instability have assisted the gravity to trigger the Jeans instability, while in the latter the magnetic fields render a resistance to the action of gravity. The long ridge along $\nu_y \simeq 1$ is due to the Parker instability. The convection makes the ridge slightly incline as ν_x gets larger but it attains a finite height at $\nu_x = \infty$.

In order to determin the perturbation wave numbers for simulations, equal growth rate contours are plotted in the (ν_x, ν_y) plane in the right frame of Fig. 1. The dash line is the contour corresponding to the highest ridge level. Any perturbations whose wave numbers are within the dash line boundary would grow faster than the ones outside. Therefore, there is a good chance for the Jeans-Parker instability to suppress the convection. We have selected two models along the ridge, inside and outside the boundary. The perturbation parameters (ν_x, ν_y) for Model A and Model B are (0.5, 1.0) and (1.5, 1.1), respectively.

III. Nonlinear Simulations

The MHD equations have been solved with a TVD scheme (Ryu et al. 1998; Kim et al. 1999), and the gravitational potential has been computed with a fourth-order accurate Fourier method and the Green function. The computation box has 256 or 128 grids for each of the three Cartesian coordinates, and its size is fixed by the chosen perturbation wavelengths along the x- and y-axes and 10 times the scale height, H, over the z-axis. The periodic boundary condition has been used in the x and y directions, while the reflecting condition has been applied in the z direction.

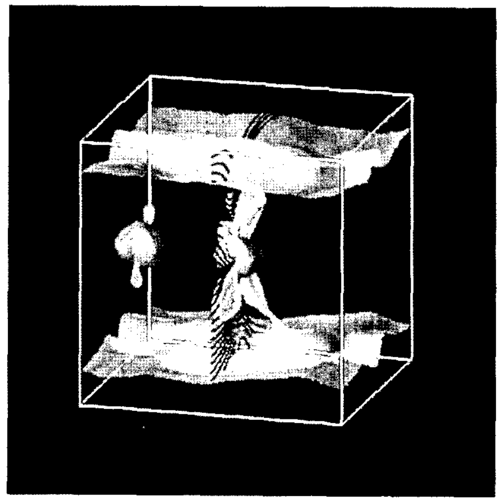

Fig. 2.— Final configuration of Model A. The x-, y-, and z-axes run to the right, far side, and top, respectively. From the gray level of the iso-density surfaces one may notice density contrast. The magnetic field lines are shown in dark lines only in the yz-plane at x=0, and the filaments are aligned with the curved field lines which are anchored in the core. Shape of the dense core can be noticed from the one at the left wall of the box.

The Jeans-Parker instability is expected to override the convection in Model A, and a random perturbation has been applied in this model. The smallest scale would trigger the convection first, but the Jeans-Parker instability would dominate the convection later. In the early stage of the simulation, gravity waves emerge from the mid-plane and propagate to the upper boundary. After the waves sweep over the whole disk, convective features develop predominantly from the upper region. At this stage the iso-density surfaces are just like shingles with their crests being parallel to the initial magnetic fields. The height of the shingle crests becomes smaller toward the mid-plane. As time goes on, the Parker instability collects material in the magnetic valley and begins to form a cylindrical bar, whose axis is perpendicular to the initial magnetic fields. And then the Jeans instability takes an action to transform the bar into a dense prolate core. At this stage the magnetic field lines are anchored in the core almost radially and become highly curved. Along the curved field lines, we see rope-like filaments. The shingles in the upper diffuse region have now been flattend. The

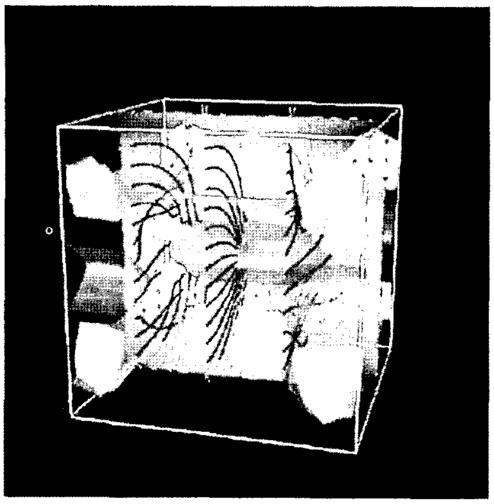

Fig. 3.— Final configuration of Model B. The magnetic fields are shown in dark lines in the yz-planes at x=0 and $\pm\lambda_x/2$. Others are same as in Fig. 2. This model reaches a final equilibrium state, which differs from its initial equilibrium configuration.

filaments run from the mid-plane core to the upper region. By this time of final evolution the core density has reached $\sim 10^2 \rho_o(0)$. Fig. 2 illustrates the final stage of the simulation.

In Model B the Jeans instability is expected to play a less significant role. To discern operations of the Parker and convective instabilities, a sinusoidal perturbation is applied with the wavelength same as the size of the computation box. After the vertically propagating gravity waves die out, the Parker instability generates magnetic valley in the central plane and buckles up the field lines in the upper region. As time goes on, the velocity field in the valley disappears slowly, although the flow activity in the upper region is still active. At least in the region of the magnetic valley, the system attains a quasi-equilibrium, which is different from the initial equilibrium configuration. Fig. 3 illustrates the final state of Model B. The new equilibrium is reminiscent of Mouschovias's (1974) non-linear equilibrium of the classical Parker instability.

IV. Conclusion

Our findings are summarized as follows: When large wavelength perturbations are applied to a self-gravitating disk of magnetized isothermal gas, a cooperative action of the Jeans and Parker instabilities suppresses the development of the convection and leads the system to develop large scale structures of high density. When small wavelength perturbations are applied, the disk attains an equilibrium state by balancing the self-gravity with magnetic tension. This is just like the case of the classical Parker instability under the external gravity. We conclude that the Jeans-Parker instability can be a viable mechanism for the formation of the GMC scale structures in the Galaxy.

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