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Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
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THREE-DIMENSIONAL SIMULATIONS OF THE PARKER INSTABILITY IN A UNIFORMLY-ROTATING DISK

Jongsoo Kim,[1] Dongsu Ryu,[2] and T. W. Jones[3]

RESUMEN

Investigamos, mediante simulaciones de alta resolución, los efectos no lineales de la rotación uniforme en la inestabilidad de Parker para un disco estratificado exponencialmente. Durante la etapa lineal, la velocidad del gas es subsónica y la evolución es similar al caso sin rotación. Esto es debido a que la fuerza de Coriolis es pequeña. Durante la etapa no lineal, los flujos supersónicos que se mueven en direcciones opuestas cerca de los valles magnéticos sienten la fuerza de Coriolis en sentido invertido y enrollan las líneas de campo en esos lugares. Las láminas de gas formadas, que quedan inclinadas respecto a la dirección inicial del campo, tienen una densidad columnar 1.5 veces mayor al valor inicial. Aunque cuando la rotación no tiene mucha influencia sobre el aumento en densidad, genera campos con enrollamiento helicoidal que pueden dar soporte adicional a las nubes resultantes.

ABSTRACT

We investigate the nonlinear effects of uniform rotation on the Parker instability in an exponentially-stratified disk through high-resolution simulations. During the linear stage, the speed of gas motion is subsonic and the evolution with the rotation is not much different from that without the rotation. This is because the Coriolis force is small. During the nonlinear stage, oppositely-directed supersonic flows near a magnetic valley are under the influence of the Coriolis force with different directions, resulting in twisted magnetic field lines near the valley. Sheet-like structures, which are tilted with respect to the initial field direction, are formed with an 1.5 enhancement of column density with respect to its initial value. Even though uniform rotation doesn't give much impact on density enhancement, it generates helically twisted field lines, which may become an additional support mechanism of clouds.

Key Words: **INSTABILITIES — ISM: CLOUDS — ISM: MAGNETIC FIELDS — ISM: STRUCTURE — MHD**

1. INTRODUCTION

It has been considered that the Parker instability (Parker 1966) is one of plausible mechanisms for the formation of the giant molecular clouds (GMCs). The conjecture is mainly based on the results from linear analyses that the minimum growth time and its wavelength along the magnetic field direction are comparable to the life time and the inter-distance of GMCs. However, it is already known that the instability initiated by three-dimensional perturbations grows at the maximum growth rate with infinite wavenumber along the third dimension perpendicular to both the gravity and field directions (Parker 1967). This means that one dimension of the structures formed by the instability should have a very small scale, which is an obstacle for the GMC formation scenario.

Linear analyses have the inherent limitation that they are no longer valid in the nonlinear region. In order to see the nonlinear effects, Kim et al. (1998) followed the evolution of the Parker instability without rotation

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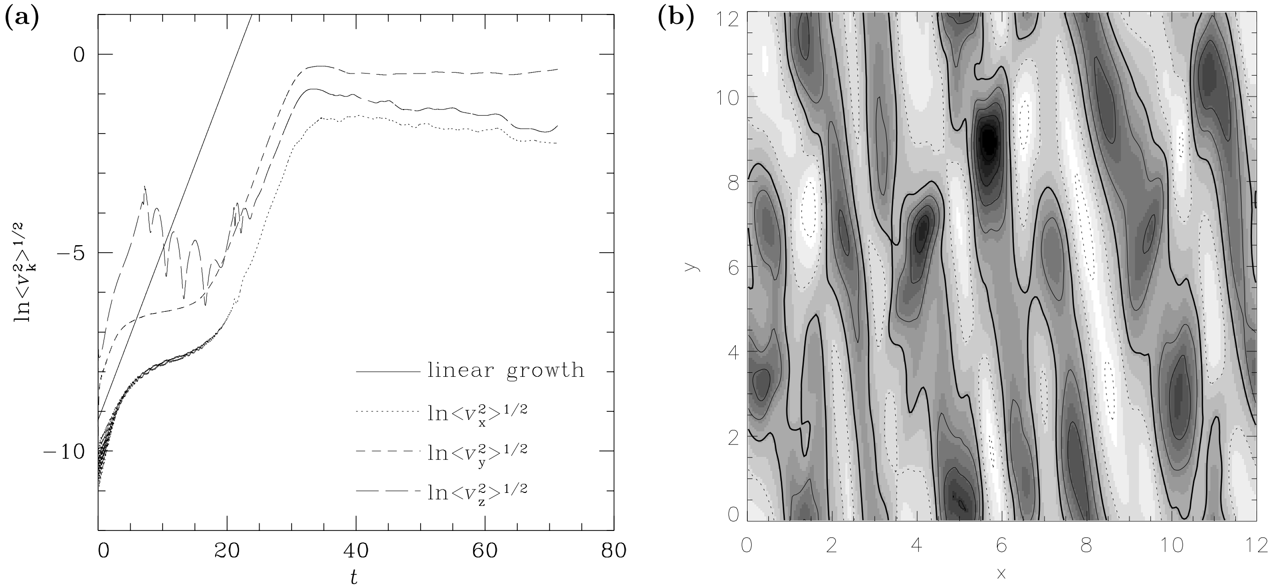

Fig. 1. *(a)* Rms of each velocity component as a function of time. The maximum linear growth rate (0.41) of the Parker instability in uniformly-rotating, exponentially-stratified disk is represented by a solid line. *(b)* Normalized column density at $t = 40$ (eq. 1). Gray-scales (where black represents the highest) and contours (0.8, 1.0, 1.2, 1.4) of column density are overlaid. The units of length, time and velocity are H, H/a and a, respectively.

using three-dimensional numerical simulations. Sheet-like structures formed at the developing stage of the instability persist during the nonlinear stage, which confirms the above linear analysis result. Furthermore, the density enhancement factor near the midplane was about 2, which is too small, and becomes another obstacle for the GMC formation scenario.

It is also known from linear analyses (Shu 1974; Zweibel & Kulsrud 1975) that uniform rotation reduces the growth rate of the instability. It is the Coriolis force that prevents the lateral motion and reduces the growth rate. The purpose of this paper is to investigate the nonlinear effects of uniform rotation on the Parker instability. Based on numerical simulations, we discuss structural deformation due to the rotation and re-address the possibility of GMC formation by the Parker instability.

2. THREE-DIMENSIONAL SIMULATIONS

In order to describe the Parker instability at the solar neighborhood, we introduce a Cartesian coordinate system (x, y, z), whose axes are parallel to the radial, azimuthal, and vertical directions of the Galaxy, respectively. As a model for the initial distributions of gas and magnetic field, we choose magnetohydrostatic equilibrium, which was originally used by Parker (1966). With downward gravity $(-g\hat{z})$ and a horizontal magnetic field $(B_0[z]\hat{y})$, gas and magnetic pressures are described by an exponential function. Its scale height is defined by $H = (1+\alpha)a^2/g$, where α is the ratio of magnetic to gas pressure and a is the isothermal sound speed. The solar neighborhood, as a whole, is assumed to rotate with a constant angular speed $(\Omega\hat{z})$ around the Galactic center. A computational cube, $0 \le x, y, z \le 12H$, is placed at the solar neighborhood. To initiate the instability, random velocity perturbations are added. The standard deviation of each velocity component is set to be $10^{-4}a$. A periodic condition at the radial and azimuthal boundaries and a reflection condition at the vertical boundaries are enforced. Isothermal MHD equations, which take into account the Coriolis force, are solved by the MHD TVD code (Kim et al. 1999). We have done high-resolution (256^3) simulations with $\alpha = 1$ and $\Omega a/(2H) = 1$. In what follows, we use normalized quantities with respect to H and a.

If two-dimensional (y and z) perturbations are considered, uniform rotation reduces the growth rates of the

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undular mode (Zweibel & Kulsrud 1975). If additional radial perturbations are given, not only the undular mode but also the interchange mode come into existence. When they work together, the mixed mode (undular + interchange) is more unstable than the undular mode alone. However, the interchange mode generates vertical motions, which are not affected by the rotation. For the extreme case with infinite radial wavenumber, the growth rates do not depend on angular speed. The most unstable growth rate is 0.41 (Shu 1974). Figure 1*a* represents the rms of each velocity component as a function of time. After the magnetized gas system adjusts itself to the random perturbations, the rms velocities grow with the maximum linear growth rate 0.41 from $t \simeq 20$ to $t \simeq 30$. When the rms of the y-velocity is comparable to the isothermal sound speed ($t = 30$), the evolution enters into the nonlinear stage.

The normalized column density is defined by

$$N(x,y;t) = \int_0^{12H} \rho(x,y,z;t)dz \Bigg/ \int_0^{12H} \rho_0(z)dz, \tag{1}$$

where $\rho_0(z)$ and $\rho(x,y,z;t)$ are the densities at initial and specific time epochs. The column density at $t = 40$ is shown in Figure 1*b*. Sheet-like structures are formed, whose long dimension is slightly tilted with respect to the initial field direction due to rotation. The maximum enhancement of the column density is attained around $t \simeq 40$ and its value is about 1.5.

Evolution of the Parker instability without rotation is described in Kim et al. (1998). Here we mention briefly the effects of rotation. Since the speed of gas motion during the linear stage is less than the isothermal speed, the Coriolis force is not important and the evolution with rotation is not much different from that without rotation. As the instability fully develops during the nonlinear stage, magnetic arches and valleys form. The speed of gas falling toward magnetic valleys becomes comparable or larger than the isothermal speed. Now the Coriolis force becomes important. Oppositely-directed flows near the magnetic valleys are under the influence of the Coriolis force with different directions. For this reason, the magnetic field lines in the valley regions become twisted.

In our previous study of the Parker instability without rotation (Kim et al. 1998), we concluded that it is difficult to regard the Parker instability alone as the formation mechanism of GMCs. The inclusion of rotation does not change this conclusion. The density structure is still sheet-like and the density enhancement factor is small. Nevertheless, rotation generates helically twisted field lines, which may become an additional support mechanism of clouds.

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