Evolution of the Parker Instability: MHD Flows, Shock Waves, and Other Consequences

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We perform a two-dimensional MHD calculation of the nonlinear evolution of the Parker instability, with particular application to a galactic gas layer supported by thermal-pressure and magnetic forces. We study modes with linear perturbations having both odd and even symmetry about the galactic plane. The initial rapid expansion of the magnetic field leads to rapid flows along the arched field lines, resulting in shock fronts near the valleys of the curved field lines. Eventually, the system settles into final (two-dimensional) equilibrium states. Modes which allow the field lines to cross the galactic plane evolve more rapidly than modes which preserve reflection symmetry about the galactic plane, and enable the system to more greatly reduce its gravitational potential energy. These modes also result in diffuse gas concentrations that are spaced half as far apart as in the cases with reflection symmetry. For typical interstellar conditions, the separation of these gas concentrations is 0.5 - 1 kpc.

1. INTRODUCTION

The large scale galactic magnetic field is inferred to lie predominantly parallel to the galactic plane (Mathewson and Ford 1970) and to have strength $2-5\mu$G (Manchester 1974; Heiles 1987); hence, the magnetic pressure is comparable to the thermal pressure of the highly conducting interstellar gas. Parker (1966) showed that an equilibrium state in which the gas is partially supported against gravity by a horizontal (parallel to the galactic plane) magnetic field is unstable with respect to deformations of the field lines. Mouschovias (1974, 1975) argued that the instability would reach a final equilibrium state after nonlinear evolution, and calculated the final equilibrium states for modes whose (mirror) symmetry leaves the field line on the galactic plane undeformed. The nonlinear evolution of the instability has been investigated recently in a series of papers by Matsumoto and collaborators (e.g., Matsumoto et al. 1988, 1990; Matsumoto and Shibata 1992). Their model is most applicable to accretion disks, and only some large-scale, qualitative features of the results can be relevant to galactic disks (see review by Mouschovias 1996). In our study, we concentrate on building a realistic model of the galactic gas layer and focus on the implications of the instability for the formation of large-scale gas concentrations.

2. MODEL

We use a newly developed two-dimensional MHD numerical code. The equations of ideal MHD for an isothermal gas are solved on a nonuniform grid using second-order differencing. The magnetic field components are evolved at grid points which are staggered relative to those of the density and momentum. This allows the magnetic induction equation to be differenced in such a way that $\nabla \cdot \mathbf{B} = 0$ at all times. The spatially discretized partial differential equations are treated as a large system of ordinary differential equations (ODE's) and solved using an implicit, variable time step ODE solver. The initial state is in magnetohydrostatic equilibrium, with magnetic and thermal-pressure forces supporting the gas against a constant gravitational field $-g\hat{\mathbf{z}}$. The ratio of magnetic to thermal pressure $\alpha \equiv B^2/(8\pi P)$ is initially constant and equal to 1. We solve the problem using dimensionless variables for which the unit of velocity $[v]$ is C, the isothermal sound speed, the unit of time $[t]$ is C/g, and the unit of length $[L]$ is C^2/g. For typical values of $g = 3 \times 10^{-9}$ cm^2 s^{-1} and temperature $T = 6000K$, the units are $[v] = 6.2$ km s^{-1}, $[t] = 6.5 \times 10^6$ yr, and $[L] = 41$ pc. The evolution is initiated by a sinusoidal perturbation in the vertical velocity v_z in a (y, z) coordinate system. This perturbation has odd symmetry about $z = 0$ for the midplane symmetric mode, which preserves reflection symmetry about $z = 0$, and even symmetry about $z = 0$ for the midplane crossing mode, which allows motions that cross the galactic plane.

3. RESULTS

Figure 1 shows the magnetic field lines and velocity vectors at three different times in the evolution of a midplane symmetric (hereafter MS) mode run. The vertical half-wavelength $\lambda_z/2 = 25$ is large enough that the presence of the top boundary $z = 25$ (where the initial density drops to 3.73×10^{-6} of its value at $z = 0$) does not affect the dynamics of most of the matter. The horizontal half-wavelength $\lambda_y/2 = 12$ gives, for the chosen λ_z, the maximum growth rate in the linear regime. The linear growth time is 5.77.

At early times (e.g., $t = 10$) the instability manifests itself in the higher, low inertia region. The initially exponential atmosphere (see Fig. 2a) means that 95% of the matter is found between $z = 0$ and $z = 6$. There are relatively large upward velocities where the magnetic arches are rising, and downward velocities where the magnetic valleys are being created. However, in the region where most of the magnetic flux is located, the field lines still nearly retain their initial straight-parallel configuration. By $t = 25$, the bulk of the system has entered its rapid nonlinear growth phase. The field lines are sufficiently steepened that a rapid downflow along them creates a shock (of maximum strength Mach 3) near the valleys of the curved field lines. The shock front subsequently moves to lower heights (but always

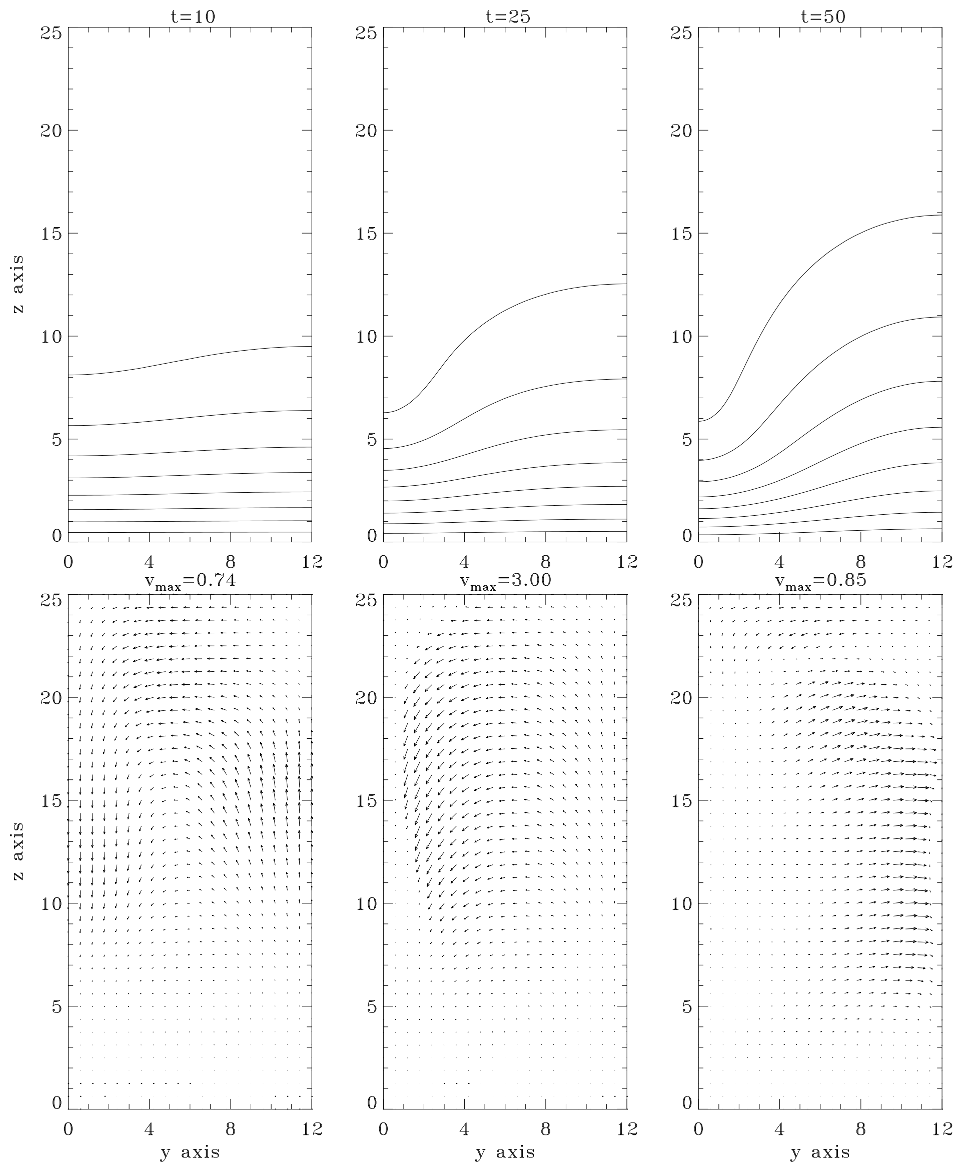

FIGURE 1. The midplane symmetric (MS) case. Magnetic field lines (initially parallel to $\hat{y}$) at three different times, and, immediately below them, the velocity vectors at the same times. The maximum speed is given above each velocity figure.

above $z = 6$) as the field lines there become more arched. Later, the shock front moves upward along field lines and weakens in strength as matter accumulates below (behind it). Finally, an equilibrium state is reached (due to the confining magnetic tension of the field lines) and overshot slightly, so that by $t = 50$ the pressure gradient drives a reverse, upward flow along field lines.

Figure 2a shows how the density changes from the initial to the final equilibrium

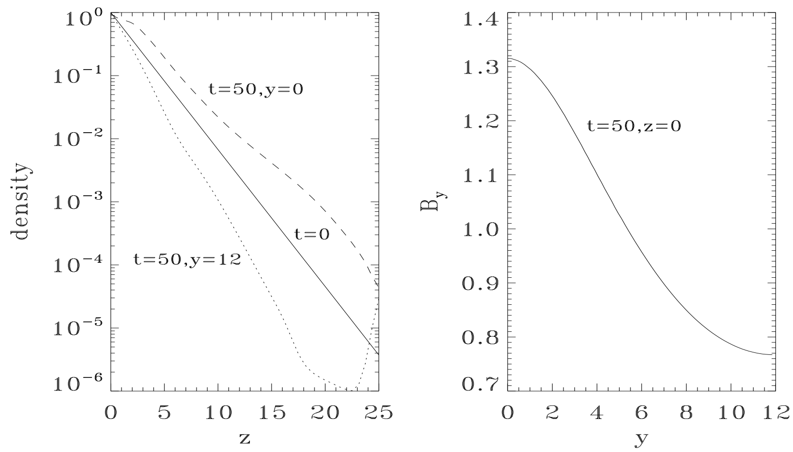

FIGURE 2. (a) The density versus z at $t = 0$ and along $y = 0$ (magnetic valleys) and $y = 12$ (magnetic arches) at $t = 50$. (b) The horizontal magnetic field component B_y along $z = 0$ at $t = 50$. Both the density and B_y are normalized to their initial value at $z = 0$.

states. There is an enhancement in the density at $y = 0$ for all $z > 0$ since matter has slid down into the valleys of the field lines, and a decrease everywhere along $y = \lambda_y/2 = 12$, from where matter has slid downwards. For the MS mode, there is no density enhancement at $z = 0$ itself, since the field line there remains straight and parallel. The scale height of the gas increases slightly at $y = 0$ but decreases at $y = 12$. Along $y = 12$, the presence of the top boundary at $z = 25$ (whih acts as a lid) creates a density inversion in an extremely low-inertia upper boundary layer. Comparison with runs with higher lids show that this layer has negligible effect on the dynamics below. Figure 2b shows that, unlike the density, B_y does change significantly from its initial value along $z = 0$. By $t = 50$, it increases by 32% at $y = 0$ where field lines are compressed by the weight of the accumulated gas, and decreases by 23% at $y = 12$ where the field lines tend to rise. The parameter α is no longer constant at $t = 50$. Along the galactic plane, it has a value of 1.8 at the point (0,0), and decreases monotonically to 0.6 at the point (12,0). Above the galactic plane, it is much larger than its initial value in the magnetic arches (along $y = 12$), reaching values as large as 1.7×10^3.

We also evolved a midplane crossing (hereafter MC) mode case with the same horizontal half-wavelength $\lambda_y/2 = 12$. The evolution was much more rapid than the MS case, and achieved a stronger (maximum Mach number 3.7) shock. The system evolves much more rapidly in the nonlinear regime because the flux tubes which cross the galactic plane (1) allow matter to fall closer to the plane and thus greatly reduce its gravitational potential energy, and (2) contribute additional magnetic pressure to drive the expansion of field lines on the other side. Figure 3a shows the field lines at $t = 40$, by which time they have reached their equilibrium positions. A greater plotting range is used than in Figure 1 to illustrate the unique symmetry of this mode. The positions of the arches at $y = \lambda_y/2 = 12$ show that the field lines have expanded farther than in the MS case. The field line initially along $z = 0$ now extends as far as $z = \pm 3$. A new feature of the MC mode equilibria is that the

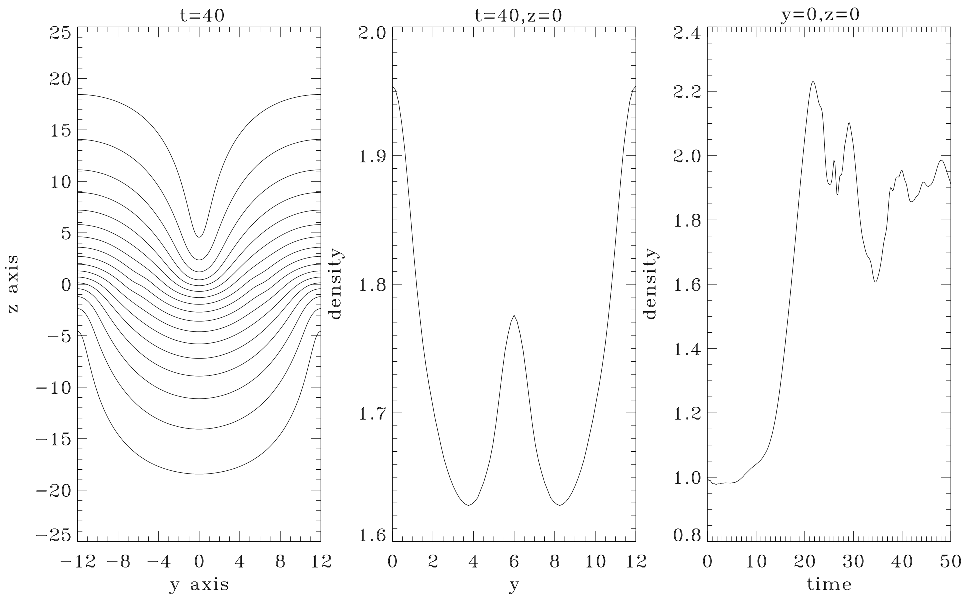

FIGURE 3. The midplane crossing (MC) case. (a) A full wavelength of the magnetic field lines near the end of the run. (b) The density along $z = 0$ at $t = 40$ normalized to its initial value. (c) Time evolution of the density in the magnetic valley at $y = 0, z = 0$.

density along $z = 0$ can increase above its initial value. Figure 3b shows the density along $z = 0$ at $t = 40$. There is an enhancement over the initial value at all positions, with maxima at $y = 0$ and $y = 12$, where matter accumulates from above and below the galactic plane, respectively. There is a secondary maximum at $y = 6$, where the field line initially at $z = 0$ now intersects the galactic plane. The enhancement of density along $z = 0$ coupled with a decrease of magnetic field strength there means that the parameter α is everywhere less than 1 by $t = 40$. It is equal to 0.36 at the points (0,0) and (12,0), dropping to 0.15 at the point (6,0) where the magnetic field strength has its smallest value. The time evolution of the density at point (0,0) shown in Figure 3c reveals that most of the density enhancement takes place in a brief nonlinear phase between about $t = 10$ and $t = 20$. The early evolution of the system takes place in the higher, low inertia region, as in the MS mode. Figure 3c also shows that the system overshoots its equilibrium density before coming back down. The maximum density enhancement possible due to the two-dimensional Parker instability (without the effect of cosmic rays) is a little over a factor of 2.

Figure 4 shows the column density versus y at the end of both the MS and MC mode runs. The MS mode results in a gas concentration at $y = 0$ both above and below the galactic plane. The next concentration is located at $y = \lambda_y$. The MC mode results in one concentration at $y = 0$ due to matter that accumulates from above the galactic plane, and one at $y = \lambda_y/2 = 12$ due to matter from below the galactic plane. In both cases, the final column density as a function of y varies by about a factor of 2.

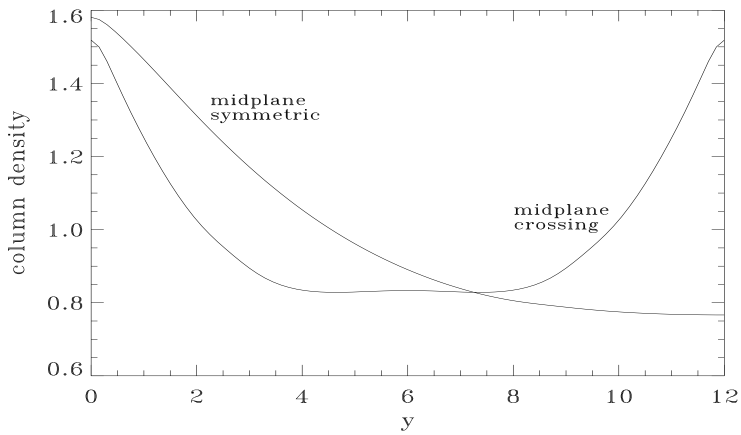

FIGURE 4. Final column density versus y, normalized to the initial value, for both the midplane symmetric (MS) and midplane crossing (MC) mode runs.

4. SUMMARY

Our simulations of the Parker instability in a galactic gas layer reveal that the initial linear phase of the instability is characterized by rapid motions only in the higher (greater than three initial scale heights) low-inertia atmosphere. The system then enters a rapid nonlinear growth phase in which most of the system mass is redistributed. This phase sets in earlier for the MC mode, and results in greater expansion of the field lines and stronger shock fronts in the low-inertia region. In addition, study of models with different wavelengths reveals that the shock fronts are present for models with all unstable wavelengths when α is initially equal to 1. The MC mode also deposits mass directly onto the galactic plane, with maximum density enhancement at the galactic plane a little over a factor of 2. The expansion of field lines is eventually halted mainly because of the magnetic tension force, and a reversal of the downflow along the magnetic field lines is seen. The column density in the final states shows roughly a 2 to 1 contrast along the magnetic field direction (coincident with the spiral arm direction in our galaxy) with spacing of about 0.5 kpc (MC mode) or 1 kpc (MS mode).

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