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# PCELL: A 2D PROGRAM FOR VISUALIZING CONVECTIVE PLASMA CELLS

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OVER THE PAST 50 YEARS, HUGE DEVELOPMENTS HAVE OCCURRED IN THE INTRIGUING FIELD OF *MAGNETOHYDRODYNAMICS*, WHICH DESCRIBES THE GENERATION AND PERSISTENCE OF MAGNETIC FIELDS IN THE COSMIC SOURCES THAT TAKE their energy from fluid mechanical energy. Currently, the magnetic field intensity of most celestial bodies and regions of the universe are known; they range from $10^{-9}$ G in the intergalactic plasma to $10^{12}$ G at the surface of neutron stars.[1]

The approach most researchers use to understand this dynamo mechanism is to consider a cosmic plasma with a stationary motion, which leads to an induction problem where the goal is to find stationary states as solutions of the induction equation. Nowadays, this kind of equation is easily solved via a computer. W.M. Elssaser, N.O. Weiss, and E.N. Parker performed the first two-dimensional simulations by using velocity fields with symmetry.[2–4] More recent simulations by Weiss and P.A. Galloway include dynamical effects and are generalized to three dimensions for the kinematic case.[5–7]

By choosing convective velocity fields, we can simulate convection cells, which in turn help us understand the behavior of the photosphere, the chromosphere, the sun's convective zone, and laboratory plasmas. We can also investigate the not-well-understood phenomena of reconnection in this way.[8]

The PCell program helps visualize the magnetic field's evolution in different convective plasmas. We wrote the program in C (part of the program was translated from Fortran to C); it runs on Linux or Unix. Any interested user can download it from our Web site: http://bellatrix.efis.ucr.ac.cr/astromod/convection.

## The Induction Equation

Maxwell's equations determine electromagnetic field behavior in cosmic fluids. The induction equation reads

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{curl}(\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \quad (1)$$

where $\eta = 1/\mu\sigma$ is magnetic viscosity, and $\mu$ is magnetic permeability. We can obtain the induction equation under certain special conditions:

- The plasma is assumed to be an isotropic, homogeneous medium of constant conductivity $\sigma$.
- The effects produced by the temperature gradient and charged particles' density fluctuations are neglected.
- The velocity of the charged particles (mechanical velocities) are considered much slower than the electromagnetic field velocity, meaning the

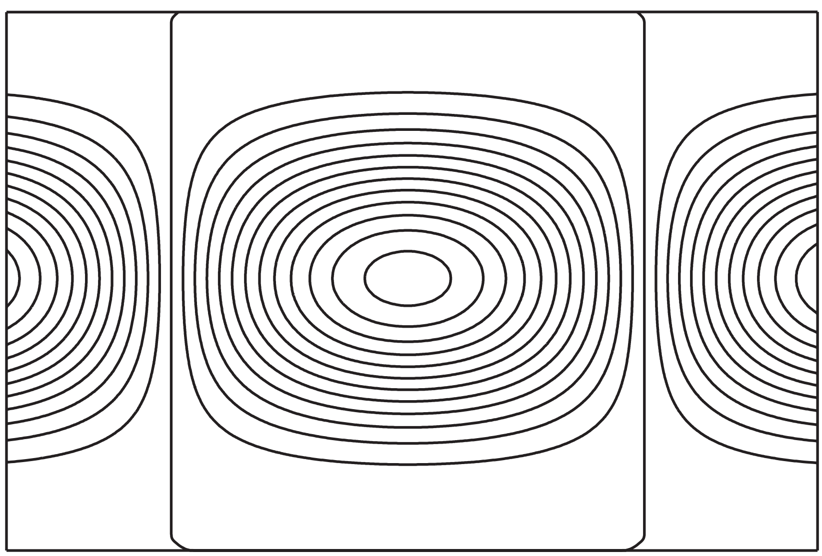

**Figure 1. Stream function in which $m = 0.25$. We can obtain a wide variety of velocity fields by changing the parameter $m$; in this case, we see one central eddy and two emerging eddies on both sides of the central eddy.**



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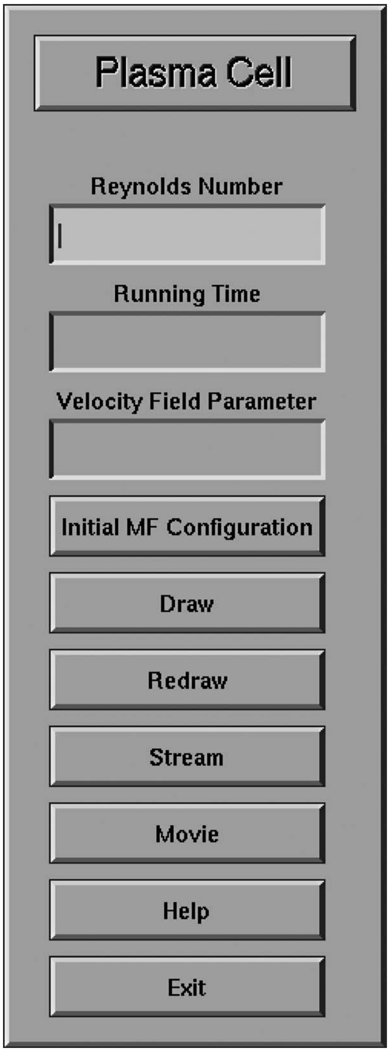


**Figure 2. PCell's control panel. The user can enter parameters and click on the control panel interactively with keyboard and mouse. The first three input fields (Reynolds number, running time, and velocity field) should be set first (before initial magnetic field configuration, draw, redraw, stream, movie, help, and exit).**

relativistic effects are not present.

- The magnetic energy dominates over the electric energy, which means that the force is mainly magnetic.
- The rate of the convection current (or the displacement current) to the conduction current is very small.

We can simplify the induction equation (Equation 1) for the two-dimensional case if we write it as a function of the vector potential. We take the magnetic field and the velocity field limited to the $(x-y)$ plane, then we obtain the magnetic field from the $z$-component $A$ of vector potential $\mathbf{B} = \text{curl}\,\mathbf{A}$:

$$\frac{\partial A}{\partial t} = -\mathbf{v} \cdot \nabla A + \eta \nabla^2 A. \tag{2}$$

Let's look at how we can use PCell to solve this equation.

## The Visualization Program

We can solve Equation 2 by using a fourth-order difference scheme in a two-dimensional cell that has perfect conducting upper and lower walls (the magnetic field lines always remain tied to them) and periodic conditions at the lateral walls—for example, each cell is surrounded by similar cells.

The velocity field is taken to be incompressible, which lets us define a stream function from which it can be obtained. We prefer the following stream function (see Figure 1):

$$\psi = -\frac{1}{4\pi}\left(4(1-m)\left(x-\frac{1}{2}\right)^2 - m\right) \times \left(1-4\left(y-\frac{1}{2}\right)^2\right)^4 \cos\pi\left(x-\frac{1}{2}\right); \tag{3}$$

with $(0 \le x \le 1,\ 0 \le y \le 1)$, $m$ is an adjustable parameter $(0 \le m \le 1)$ that lets us select different velocity fields. When $m = 1$, it describe a single eddy;[3] as $m$ decreases, two new symmetrical eddies emerge from each side, compressing the original eddy. At one point, we have three eddies, but as $m$ gets closer to zero, the central eddy disappears and just two eddies remain, rotating in opposite directions.

The PCell program is intended for visualizing not only this stream function, but also simulations of magnetic-field evolution. Users can find it on our Web site under the compressed file pcell.tar.gz. As we mentioned earlier, we originally wrote part of the program in Fortran, but translated it into C with the help of F2C (this means that potential users need the LIBF2C library). Users also need the XFORMS library, which we used to design the control panel. The data generated by the program is processed by gnuplot to produce the simulation; gnuplot is a plot program found in almost all Linux or Unix distributions.

When the program starts, it creates a window: the PCell control panel. With the mouse, the user can adjust the parameters interactively by clicking. The control panel has the following items (see Figure 2):

- *A magnetic Reynolds number input*. The user selects the magnetic Reynolds number $(0 < R_m \le 1{,}000)$.
- *A running time input*. The user enters the running time in units of $\tau_0 = L/U$, where $L$ is the characteristic length, and $U$ is maximum velocity. The values of $U$ and $L$ are chosen equal to one, thus the magnetic Reynolds number $R_m = LU/\eta$ equals the reciprocal viscosity. At this time, the program stops.
- *A velocity field parameter input*. The user chooses the velocity field by selecting a value of the $m$ parameter $(0 \le m \le 1)$.

The user clicks on the following buttons after entering values for the just-described inputs:

- The *initial magnetic field configuration button* sets the initial form of the magnetic field. It is not fully implemented; at the moment, we have only one initial magnetic field configuration, which is the homogeneous one.
- The *draw button* starts the program

that calculates the magnetic field at each time interval (this data is stored in the files pcell1.dat, pcell2.dat, and so on); after a short time, when data generation is finished, the display window opens (see Figure 3). The *display window* shows the evolution of the magnetic field lines by calling the gnuplot program.

- The *redraw button* displays the simulation of previously obtained data, to avoid repeating an already existing calculation.
- The *stream button* displays plasma's mechanical motion (see Figure 1).
- With the *movie button*, users can create their own movies, and with XANIM or an MPEG player, they can display these movies. The name of the created movie is convection.mpg.
- The *help button* gives the user a program guide.
- The *exit button* lets the user leave the session, but the data created is not removed automatically. The user can remove all pcell*.dat files by typing rm -rf pcell*.dat at the prompt.

If a user wants to make a movie, we recommend using the movie button instead of the draw button. These buttons are independent of each other, which means that you can't automatically create a movie after seeing the simulation by using the draw button. However, you can see the simulation after creating a movie simply by clicking on the redraw button.

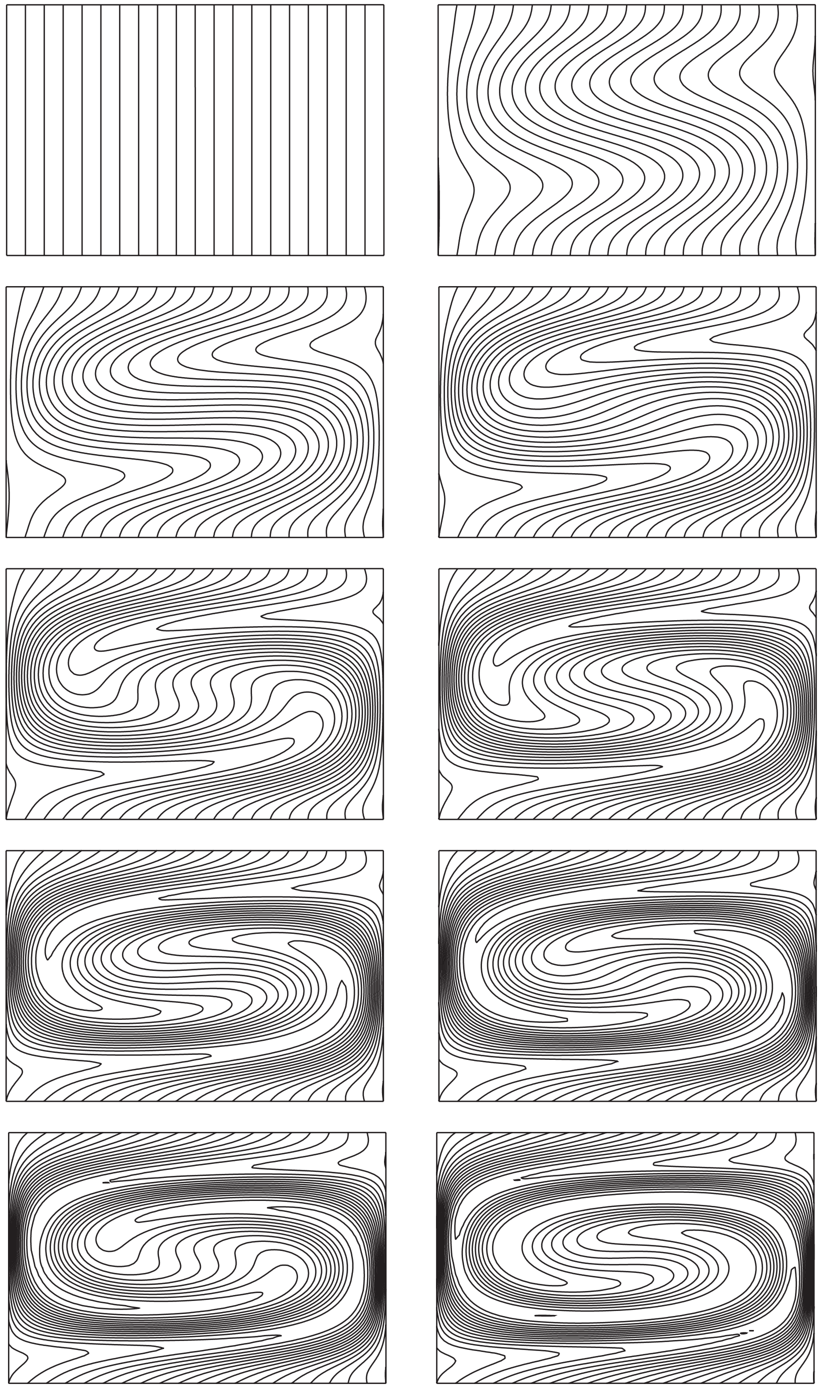

**Figure 3. Pictures of a sequence obtained with PCell for $R_m$ = 1,000 and $m$ = 0.25. At the beginning, the magnetic field is homogeneous. The pictures that follow show the twisting of the magnetic field. Reconnection of the magnetic field appears in the last picture.**

## Applications

The user can explore some interesting applications with PCell:

- the evolution of the magnetic field lines as a function of the magnetic Reynolds number;
- the mechanism of magnetic field dissipation and the reconnection phenomena;
- the evolution of the averaged magnetic density as a function of the magnetic Reynolds number;
- the maximum averaged magnetic density as a function of the magnetic Reynolds number;
- the stationary state of the averaged magnetic density and the way it is reached as a function of the magnetic Reynolds number; and
- the time it takes to reach the maximum

and the stationary state of the averaged magnetic density as a function of the magnetic Reynolds number.

The capability to easily create movies is one of PCell's main features.

As a didactical tool, a program to visualize the magnetic field in a plasma confined to a cell is very useful, especially if the user can create movies by changing the parameters involved in the induction equation. The versatile program we've described functions quickly and interactively with the keyboard and mouse, but there is room for improvement. We still need to

- include more velocity fields;
- add magnetic density averaged over the cell, represented as a function of time;
- expand to three-dimensional cells and other shapes such as hexagonal cells (this shape appears as stable patterns in some fluids);
- consider mechanical–electromagnetic interaction between the plasma and the field;
- explore more complex behaviors such as chaos;
- use a contour subroutine; and
- improve the program to avoid having to use the F2C library.

We are implementing a contour subroutine under Open GL to run the program faster. We hope to finish the implementation of the initial magnetic field configuration and revise help buttons soon. Keep visiting our Web site for these modifications.

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