Hourglass magnetic field from a survey of current density profiles [2022]

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Keywords:

- Magnetic Fields
- Analytical Models
- Star-Forming Regions

Background

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The hourglass shape of magnetic fields are formed when magnetic pressure cannot balance gravity and the material carrying the field is pinched inwards near the core.

The happens as the flux freezes with the fluid.

If the flux is partially fixed, then the pinching is significantly less than normal observed.

There has been ongoing research work to study this hour-glass shape.

Researchers are using analytical models, simulations and direct observations to study the magnetic properties around these star-forming core.

Introduction

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1. Previous work has been done to create a mathematical model that fits the simulation data. [Ewertowski and Basu (2013)]

2. The work was then extended to the polarimetric observations of the prestellar core 'FeSt 1-457'. Although the model fit well, it provided limited information on actual magnetic fields.

3. In Ewertowski and Basu (2013) a gaussian distribution was adopted for the vertical direction of magnetic fields (not taking radial fields explicitly).

4. Extending the 2013, here current density distributions are assumed for radial components and hour-glass pattern is studied.

To calculate magnetic-field strengths, first the large-scale ordering of magnetic field is determined.

Then the fluctuations of polarization vectors relative to the mean is used to calculate magnetic field strengths using the DCF method. [Pattle et al. (2017)]

Analytical Method

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Boundary Conditions:

- Background magnetic field is assumed to be constant at large Z and outside **core** radius.

Assumptions:

- A purely poloidal magnetic field is assumed with components only in r and z directions.

- The vertical magnetic field component has gaussian distribution.

- **Current density** is separable for both directions.
  $j(r,z) \equiv f(r)g(z)$

Methodology:

1. Magnetic field vector potential A, is analytically formulated and previous solution is applied.

2. The gaussian distribution of vertical direction is used.

3. The coefficient k present in the solution is then derived which depends on current density along radial direction.

4. Hence, a radial current density distribution is used which is then put into to solve integral of the coefficient k and get magnetic field distributions near core.

There are the following functional distributions discussed in the literature:

$$f(r) = \begin{cases} e^{-r^2/l^2} & \text{Gaussian,} \\ J_0(\alpha_{0,1} r/R) & \text{Bessel,} \\ 1/(1 + r^2/l^2) & \text{power law.} \end{cases}$$

The integral is solved numerically using various quadrature techniques.

Results

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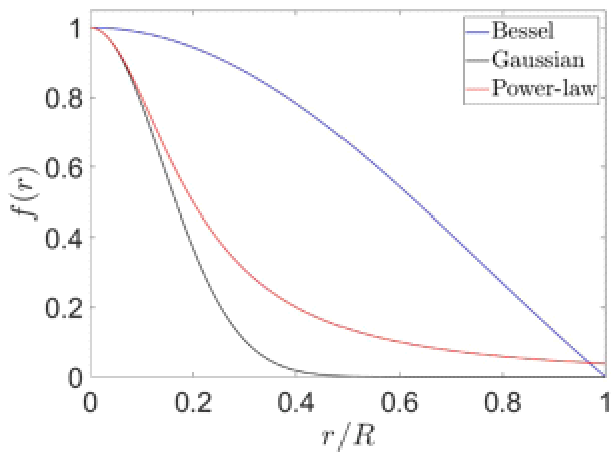
All the distributions applied on radial direction were assumed centrally peaked such as below:



- The Bessel function converges the most delayed compared to gaussian and power-law.
- Gaussian is the most centrally concentrated among all.

Parameters varied and studied:

- Scale length along r-direction --> l
- Scale length along z-direction --> h
- Background magnetic field
- Ratio of Central magnetic field to Background magnetic field

For the gaussian model:

- If the scale length ratio (h/l) is kept constant, with increasing central magnetic field strengths the magnetic field pinches in with forming loops for the highest values.

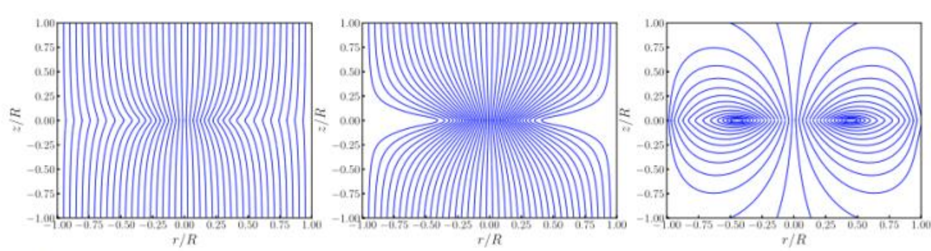


Fig. 2. Magnetic field line morphology for model 1 (Gaussian radial and Gaussian vertical distributions) demonstrated for increasing central-to-background field ratio $B_c/B_0 \in [4.36, 16.16, 1475.56]$ (from left to right), with fixed ratio of vertical and radial scale length, $h/l = 0.02$.

- If we take different scale length ratios the magnetic field lines morphology is like

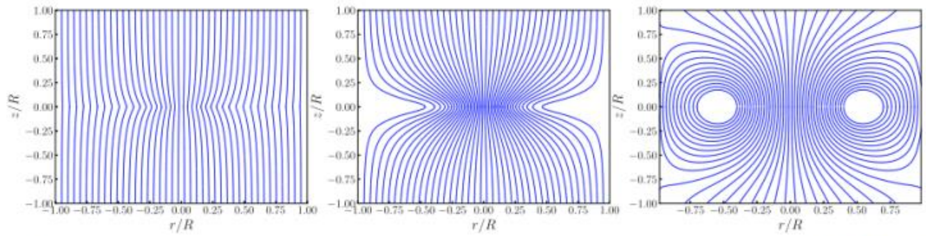


Fig. 3. Magnetic field morphology for model 1 (Gaussian radial and Gaussian vertical distributions) demonstrated for the scale length ratios $h/l \in [0.01, 0.1, 0.75]$ (from left to right) with respective $B_c/B_0 \in [2.63, 13.69, 51.95]$.

For Bessel Model:

The scale length ratio is assumed as h/R here.

When the scale length ratio is increased we see more curvature here at values around 0.1

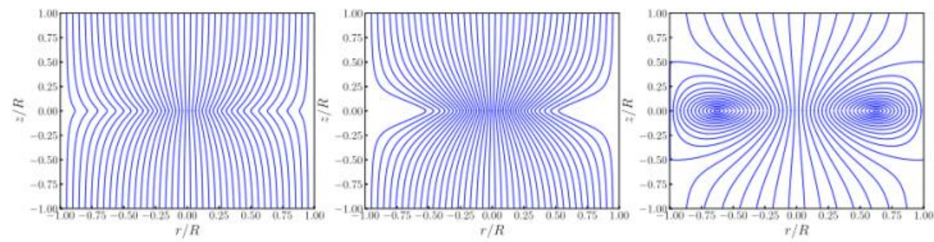


Fig. 5. Magnetic field morphology for model 2 (Bessel radial and Gaussian vertical distributions) demonstrated for increasing vertical scale length $h/R \in [0.01, 0.025, 0.1]$ (from left to right) with respective $B_c/B_0 \in [5.07, 10.53, 32.71]$. The characteristic radial scale length for the Bessel function in this model is taken as the core radius itself and remains unchanged.

For Power-Law Model:

Again the scale length h/l is increased and we see an increase in pinched structure.

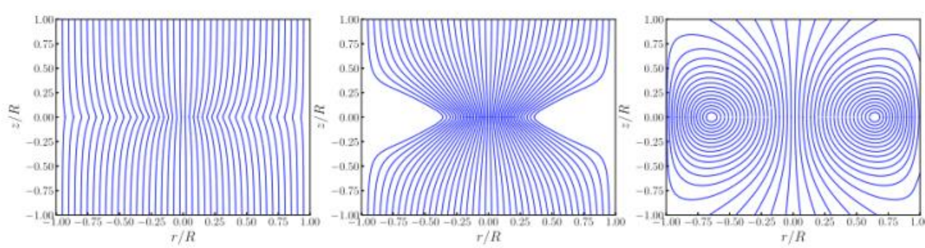


Fig. 7. Magnetic field morphology for model 3 (power-law radial and Gaussian vertical distributions) demonstrated for the scale length ratio $h/l \in [0.01, 0.1, 0.75]$ (from left to right) having respective $B_c/B_0 \in [3.07, 17.21, 61.93]$.

Discussions

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- Simulations suggest that relatively low scale-length ratios shall be used because gravitational contraction is slow and gives enough time for gas to settle along field lines.
- However, if dynamical contraction is fast enough we might see high h/l ratios as gas couldn't settle around field lines in enough time. This can happen during rapid-core formation scenarios.
- Weak Bo means that there has been sufficient contractions that the induced currents overpower external currents.
- Weak Bo and high scale length ratios could signify that the contraction happened from a larger distance
- Also, flux-freezing breakdown can occur, resulting in loops because of this fast contraction.
- This happens because of high magnetic diffusion (Ohmic diffusivity) near the core which causes field lines to curve so much that they reconnect and form loops.

Thus while weak background magnetic field can be a reason of hour-glass magnetic field profiles, but the core morphology (the scale length ratio) can also significantly change the field lines curvature. Hence, the current density distribution can impact magnetic field line shape.

Advantages:

As we solved the integral here, the number of free parameters reduced to 4 as compared to 2013 analysis.

This is because at that time a series solution was applied and some order of terms were considered.

This optimized our problem.

Any Future Work?

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As there is a sudden increase in polarimetry measurements of star-forming regions, we have more cope for better analytical solutions to fit and understand.

We can use current density profiles other than the ones discussed here in the paper for radial distributions.

Assuming distributions where hour-glass shape does not appear.

Also, we need to find current density distributions where the coefficient can be analytically solved rather than numerically.

Questions

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