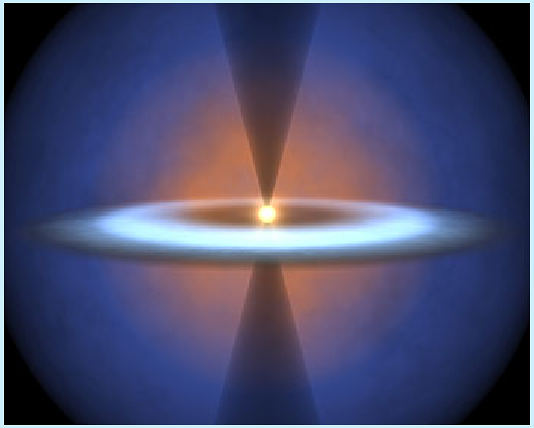
Theoretical Difficulties in Forming Rotationally Supported Disks



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Abstract

The formation of rotationally supported disks (RSDs) is a crucial event of the early times of star formation.

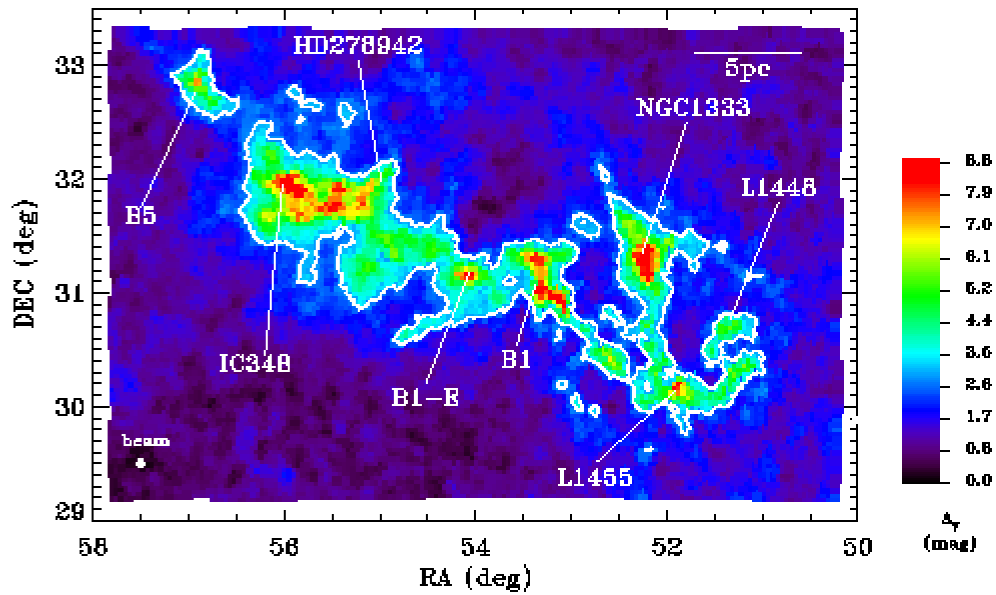
There are theoretical difficulties in forming rotationally supported disks during the protostellar collapse of magnetized dense cores. It is often expected that disks would form automatically out of the collapse of rotating cores because of angular momentum conservation.
In the presence of the observed level of magnetic fields, this simple explanation is no longer guaranteed to work, because of magnetic braking and magnetic instabilities. Indeed, in the simplest case of the ideal MHD limit, both analytic work and numerical simulations showed that RSD formation is completely suppressed by excessive magnetic braking.
Our axisymetric simulations have shown recently that non-ideal MHD effects (including Ohmic dissipation, ambipolar diffusion and the Hall effect) do not weaken the magnetic braking enough to enable RSDs to form under typical cloud conditions.
Nevertheless, RSDs are observed around at least more evolved young stellar objects and have to form sooner or later.

I will discuss possible resolutions to this problem, including non-axisymmetric magnetic interchange instabilities in 3D, misalignment of magnetic field and rotation, enhanced magnetic diffusivities (perhaps due to turbulence or reconnection), and outflow stripping of the protostellar envelope, and comment on the apparently discrepant results in the literature on this important topic of the early epoch of star formation.

Outline

- Introduction
- Enhanced Ohmic Resistivity
- Strong Hall Effect
- Collapse and Ambipolar Diffusion
- 3D Instabilities
- Current Work in 3D

The Clouds in the Galaxy where new stars are born.



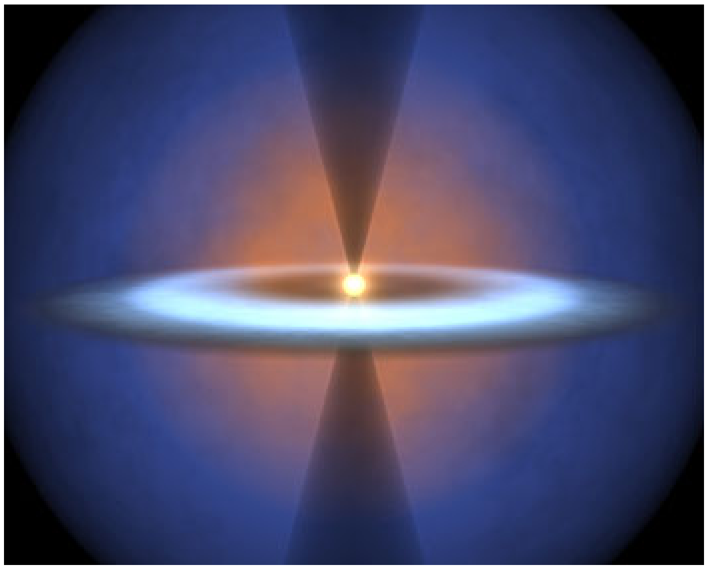
Example: the Perseus molecular cloud

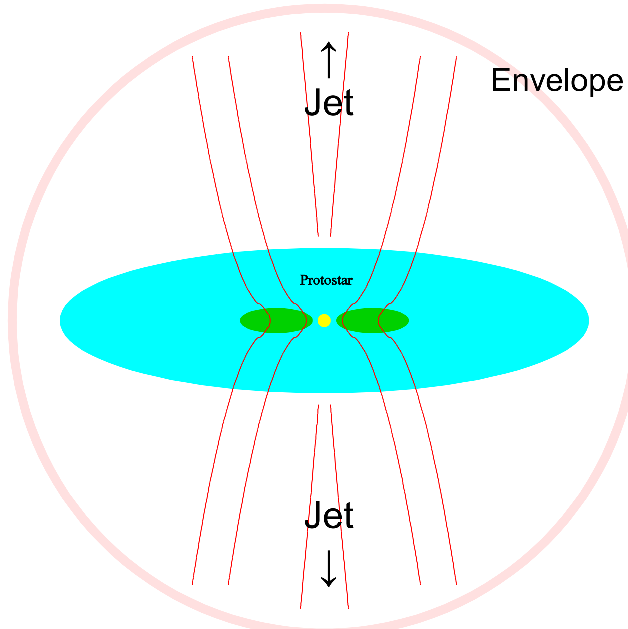
Gravity is in action, forming cores in which the density is increased.

Gas pressure, magnetism, and turbulence balance gravity and slow down core collapse – for a while.

Pre-stellar cores do not yet have a central point mass. The more evolved proto-stellar cores will form star clusters, or individual stars.

Protostars and disks





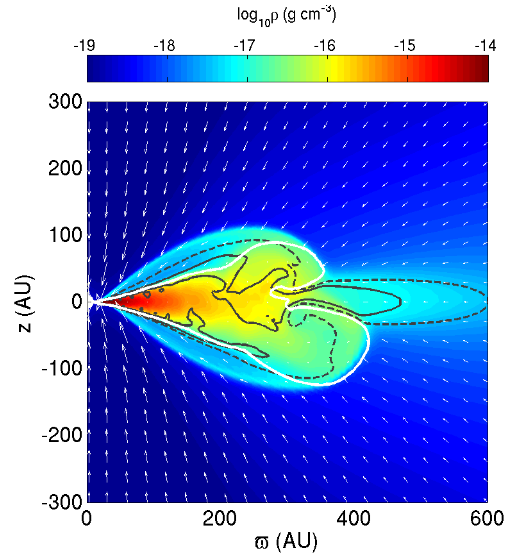
Inside a protostellar core, a star is forming – surrounded by a protostellar accretion disk, and the dense parts of the core.

Outflows – winds and jets – are also produced.

Hydrodynamic model of disk formation

Gas motions in the core have angular momentum.

Its conservation allows disk formation.



Axisymmetric hydrodynamic simulation at $t=10^{12}$ s~3×10^{4}yr

Prominent 400 AU disk of .1 Msun around a .5 Msun protostar
Rotationally supported – Keplerian. Subsonic, very dense.
Surrounded by a rapidly accreting supersonic flattened structure.

Angular momentum transport is a problem in this model

Magnetized Models

- Necessary: Dynamically significant **B** fields are observed

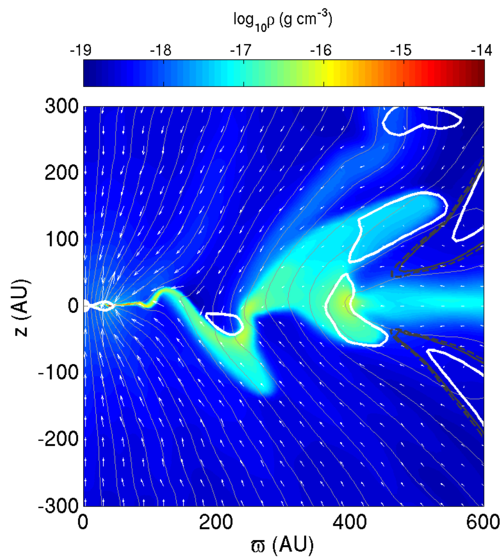
- Magnetism solves some problems

- It provides a mechanism for outflows – winds and jets (Blandford & Payne 1982). Simulations show this magneto-centrifugal mechanism works (e.g. Ustyugova et al 1999, Krasnopolsky et al 1999)
- Magnetism can provide the torques needed for angular momentum transport – magnetic braking – allowing accretion of mass to the central object (e.g., Basu & Mouschovias 1995, Krasnopolsky & Königl 2002)

- However, magnetic braking can become excessive – leaving too little angular momentum for a disk to form (Mellon & Li 2008, 2009). "Magnetic Braking Catastrophe"

Example of Excessive Magnetic Braking in 2D Ideal MHD

Magnetic braking acts the strongest in a model without explicit diffusion



Powerful supersonic accretion takes place in blobs and rings.
Not equatorially symmetric, not rotationally supported.
Dominated by magnetic reconnection events – numerically mediated.

NO KEPLERIAN DISK

Need to weaken magnetic braking

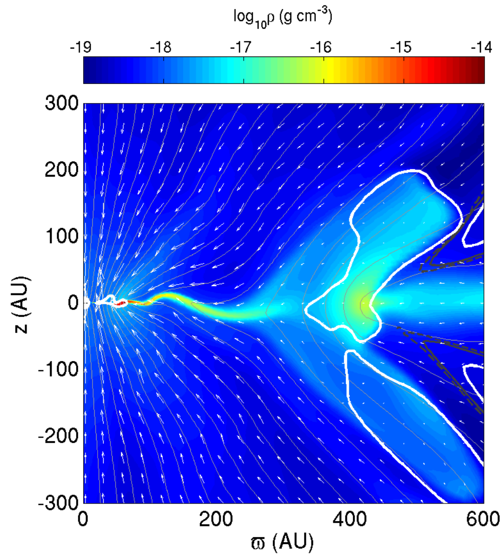
- How?

- Reducing the **B** field? It will not help by much: the simulation used a field that is pretty typical (B_o=35μG, dimensionless mass-to-flux ratio λ ~ 3).

- We can try to weaken the coupling of the magnetic field to matter, utilizing non-ideal MHD effects. These effects allow matter to fall in without having to drag all of the magnetic field with it. As a bonus, the non-ideal MHD effects also avoid the so-called “Magnetic flux problem”.

- We will consider three non-ideal MHD effects: Ohmic resistivity, the Hall effect, and ambipolar diffusion.

Classical resistivity



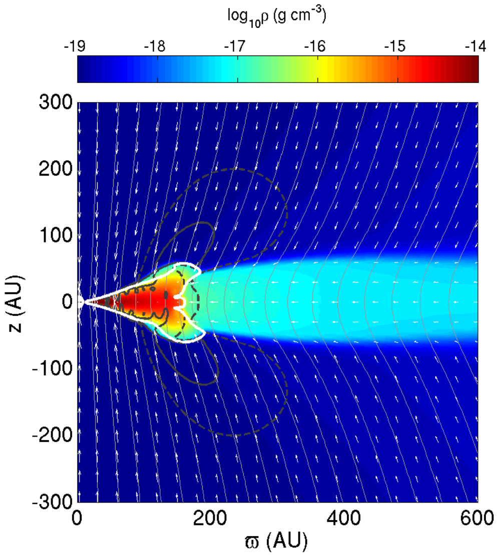
An inner, denser flattened structure forms.
Fragmented, and far from being rotationally supported.
Accretion is mostly supersonic.
Magnetic tension allows for some subsonic accretion rings.
Inner structure still dominated by not well-resolved reconnection events.

NO KEPLERIAN DISK

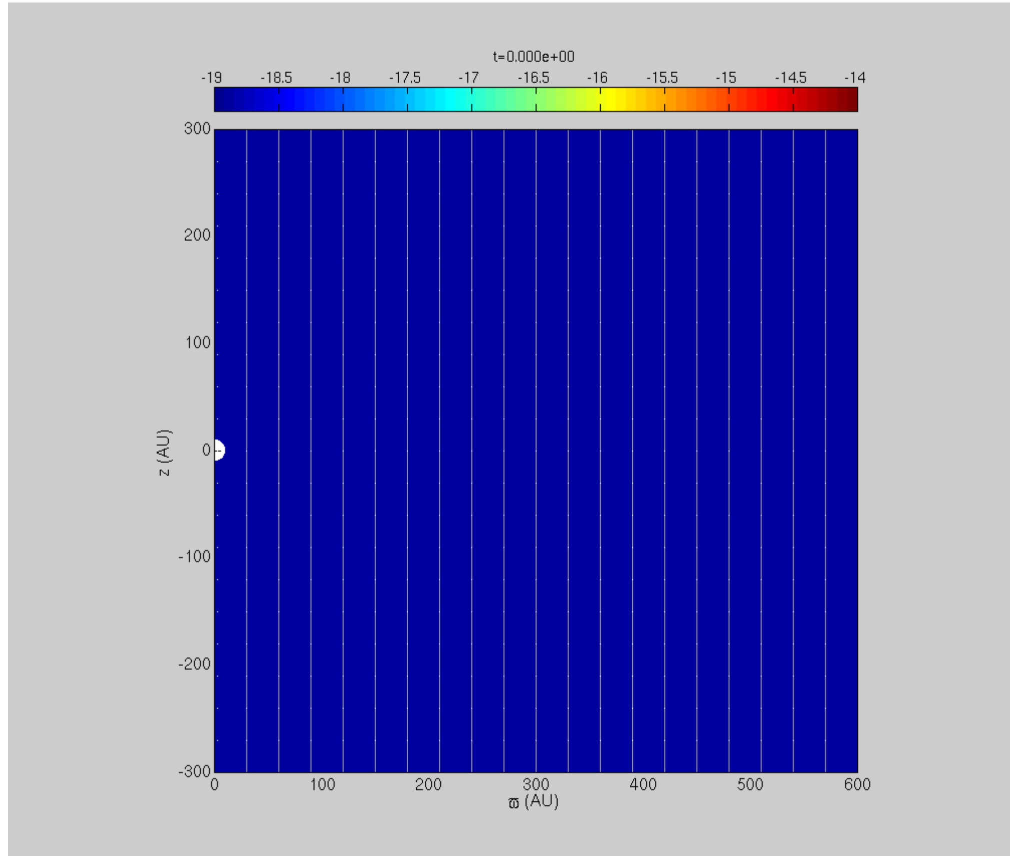
Need to try with enhanced resistivity

Enhanced Ohmic Resistivity

Enhanced resistivity enables disk formation



t=10^{12} s
DISK
Bo=35μG

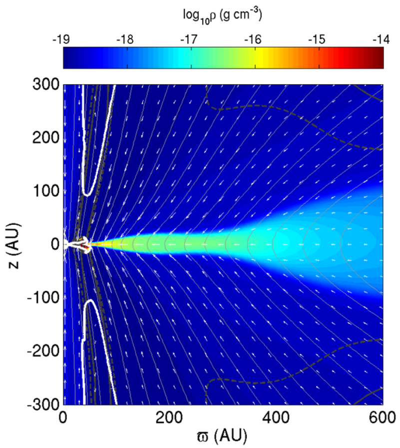


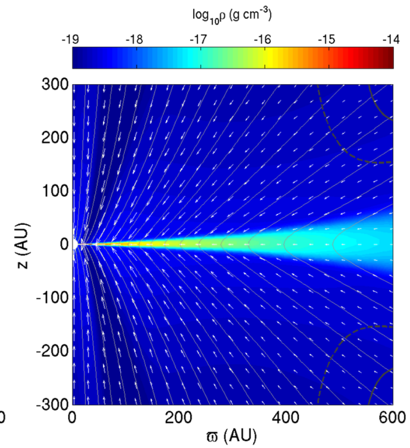
Enhanced resistivity, $\eta=10^{20}$cm^2/s
Result: Very dense Keplerian disk, growing with time.
Surrounded by a pseudodisk supported by magnetic tension.

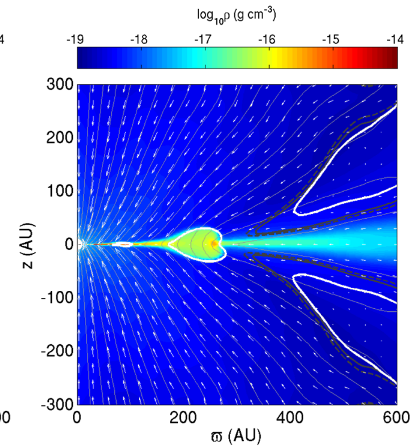
How much resistivity η do we need?

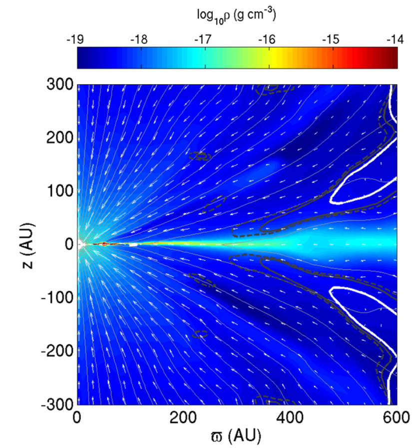
Enhanced Ohmic Resistivity

Exploring enhanced η and **B**







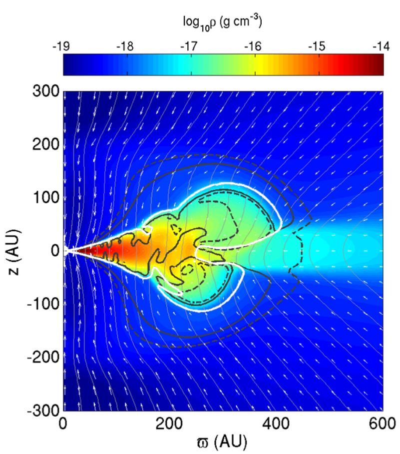


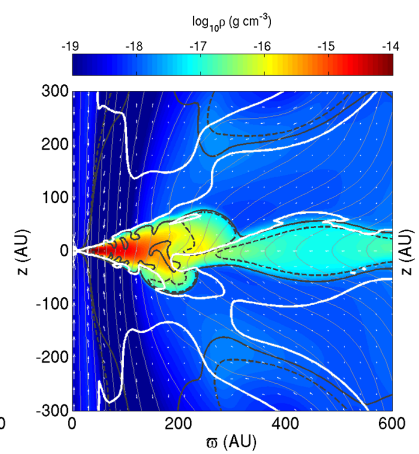
η=3×10^{19}cm^2/s
Bo=35μG: TINY

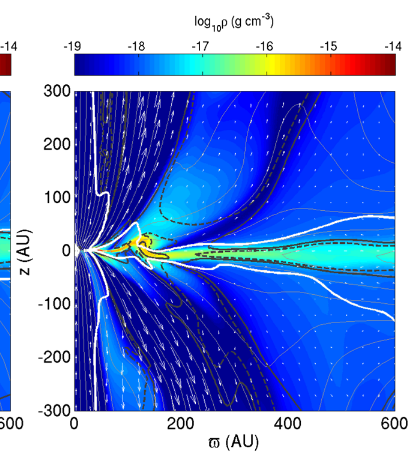
η=10^{19}cm^2/s
NO DISK

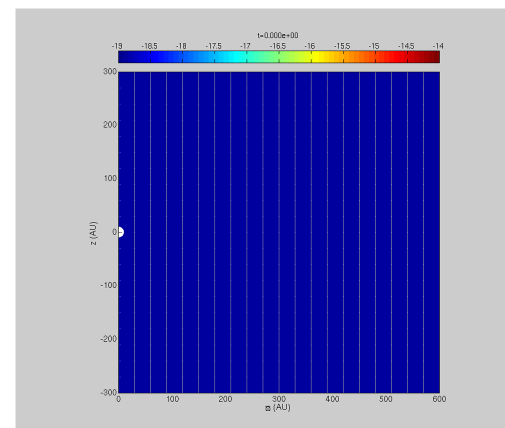
η=3×10^{17}cm^2/s
Magnetic Blob

η=10^{17}cm^2/s
NO DISK









η=3×10^{19}cm^2/s
Bo=10μG

η=10^{19}cm^2/s
Bo=10μG
DISK

η=10^{18}cm^2/s
Bo=10μG
TINY

η=3×10^{17}cm^2/s
Bo=35μG: Blob Movie

Enhanced Ohmic Resistivity

Ohmic Resistivity: Summary

- Classical resistivity is unable to weaken magnetic braking enough to allow a rotationally supported disk (for a realistic magnetization).

- **Enhanced resistivity allows disk formation**

- Need about $\eta=3\times10^{19}cm^2/s$ to form a disk larger than 10AU for $\lambda \sim 3$, and about $\eta=10^{18}cm^2/s$ for $\lambda \sim 10$.
- Need to explore mechanisms that produce enhanced resistivity. Turbulent resistivity (e.g. Lubow et al. 1994, Guan & Gammie 2009). Current-driven instabilities (e.g. Norman&Heyvaerts 1985). Reconnection diffusion in turbulent flows (e.g. Lazarian 2012). Interactions between magnetic tension and turbulence (unexplored idea, suggested by the blob movie).

- **Results published in Krasnopolsky, Li, & Shang (2010) ApJ, 716, 1541**

Non-ideal MHD: Generalized Ohm's Law

- $\partial_t \mathbf{B} = -c \nabla\times\mathbf{E}$
- $\boldsymbol{c}\,\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta\mathbf{J} + Q\,\mathbf{J}\times\mathbf{B} - \alpha(\mathbf{J}\times\mathbf{B})\times\mathbf{B}$

- **v**: velocity of the fluid (ideal MHD term)
- η: resistivity (Ohmic term)
- *Q*: Hall coefficient
- *α*: Ambipolar diffusion coefficient
- more terms: electron inertia and pressure, multifluid, etc.

Hall Effect

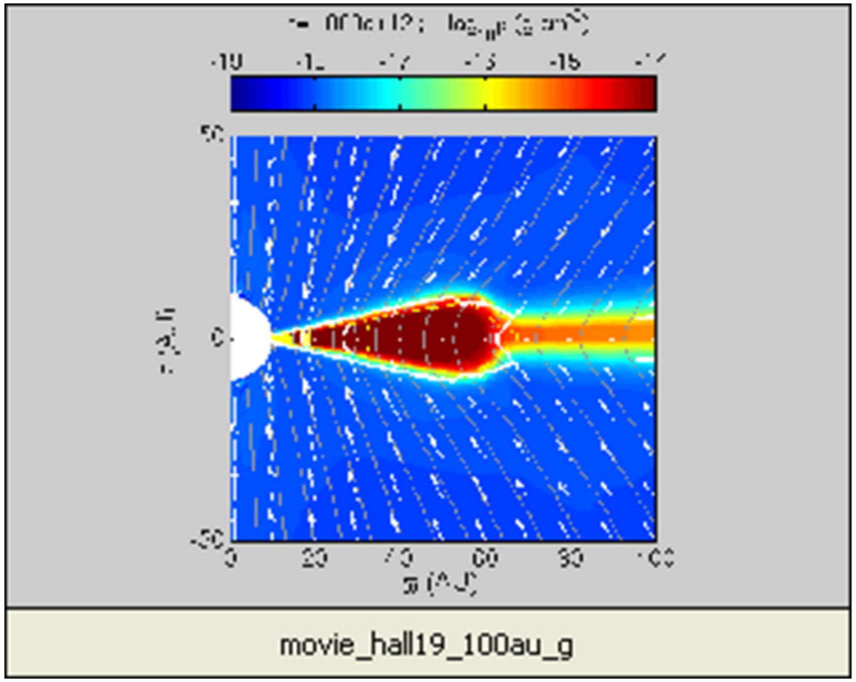
- The Hall effect arises because a current needs a charged species in motion. For instance, in the case of electrons, $\mathbf{J} = -n_e e \mathbf{V}_e$, and $Q = -1/n_e e$. In general, charged species will have different speeds, particle masses, and tying to the magnetic field. Hall Q comes from multi-fluid effects.
- **Hall effect depends on sign of charge carriers, giving it unusual symmetries.**

Hall Effect and Torques

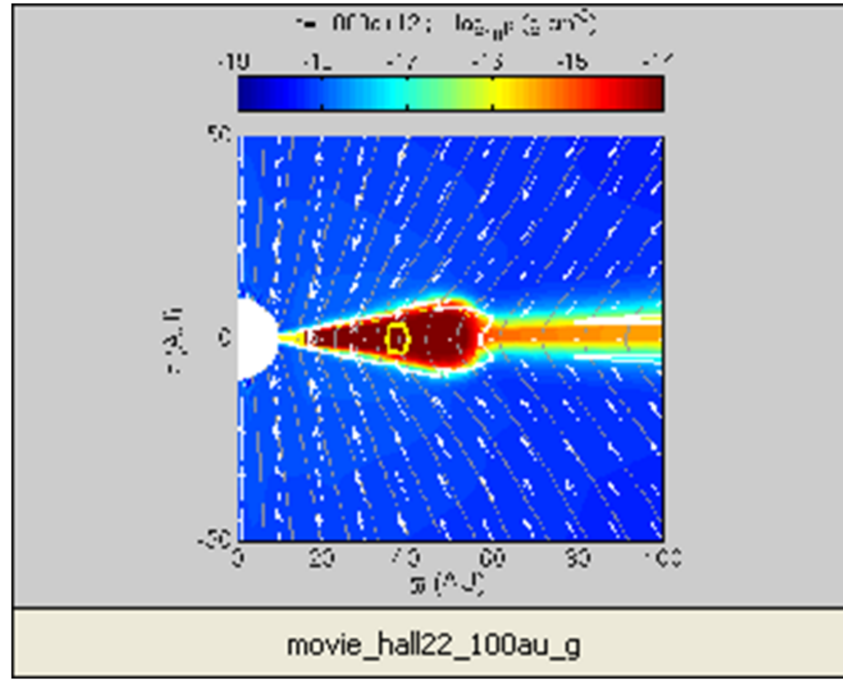
- The Hall effect is expected to be large where current densities are large, such as in the pseudodisk, which is supported by the magnetic tension created by a sharp kink in the poloidal field $\mathbf{B_p}$, which produces a large current component $\mathbf{J_\varphi}$: that current makes the charge carriers move with a Hall velocity –Q $\mathbf{J_\varphi}$ in the φ(toroidal) direction. As the field is tied to the charge carriers on the thin pseudodisk, a $\mathbf{B_\varphi}$ is generated, which can introduce a $\mathbf{J_p} \times \mathbf{B_p}$ force, which has a toroidal component.

- **The Hall effect can introduce a torque**

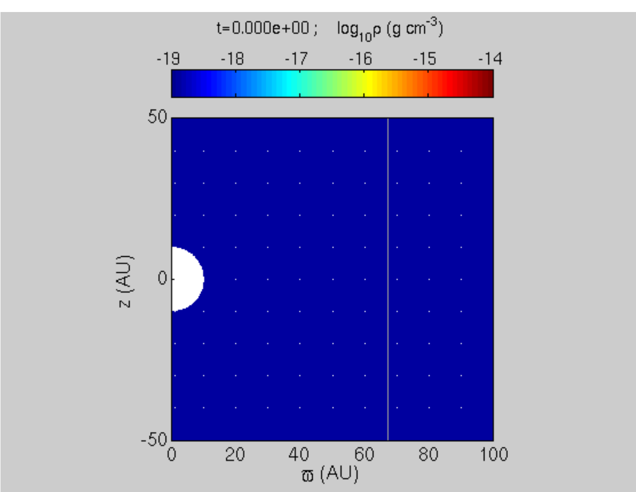
Hall Effect in Disk Formation



Run plus: Bo=35μG



Run minus: Bo = – 35μG



Both: $Q=3.5\times10^{12}$(cgs) ($n_e=6\times10^{-4}$ cm^{-3}), $v_{\varphi o}$=0.2km/s (initial rotation)

Both runs form nearly Keplerian disks:
but they spin in opposite directions.
These disks are not due to $v_{\varphi o}$ (initial)
They come from Q and Bo.

Strong Hall Effect

Hall Effect: Spin-Up

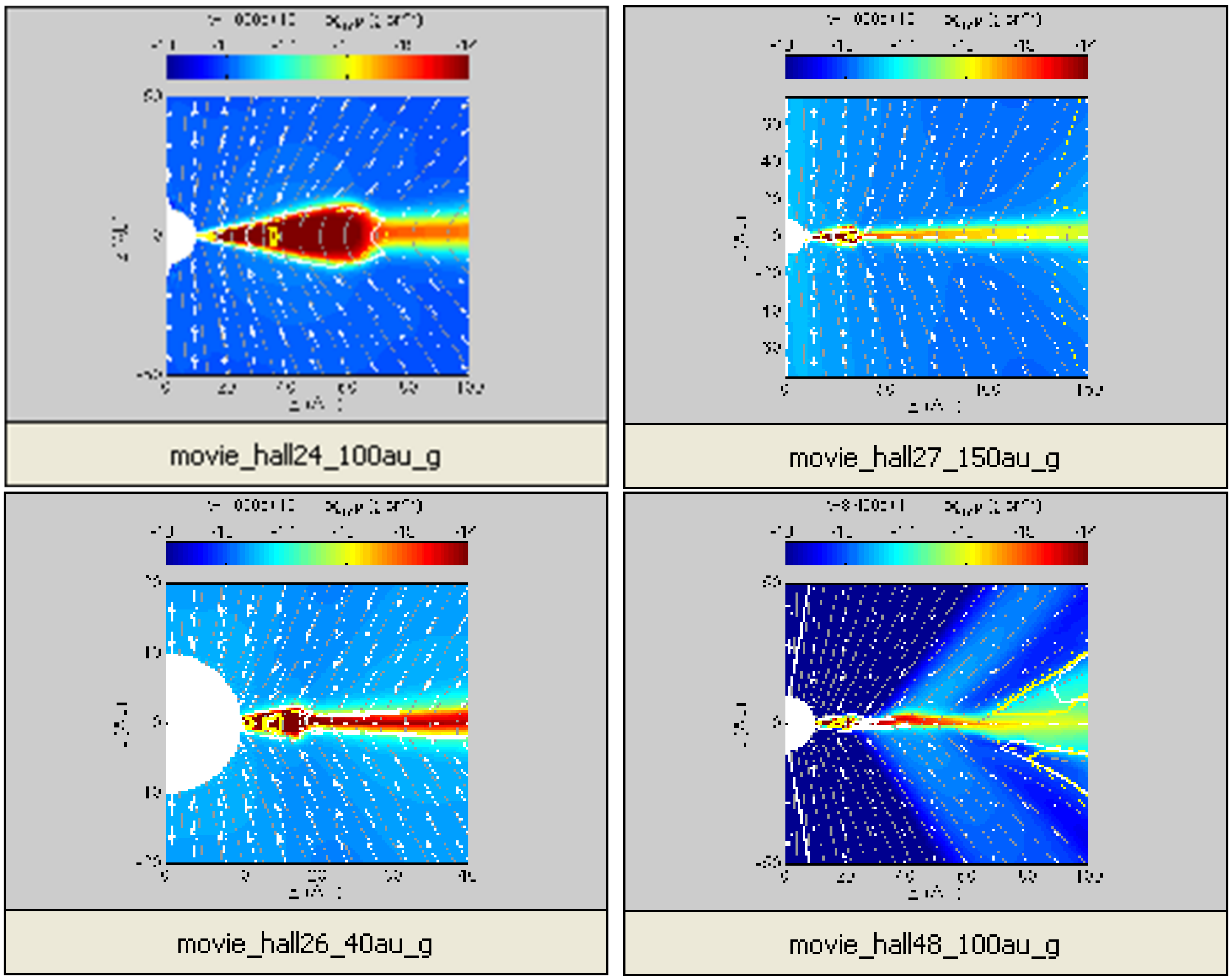
- **The Hall effect can introduce a torque: so we start without rotation**

Bo=35μG | Bo=10μG

Q=3.5×10[12]

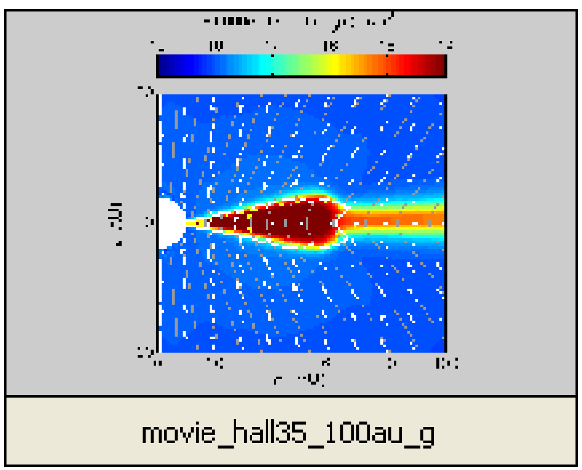
Q=3.5×10[11]

Strong Hall Effect

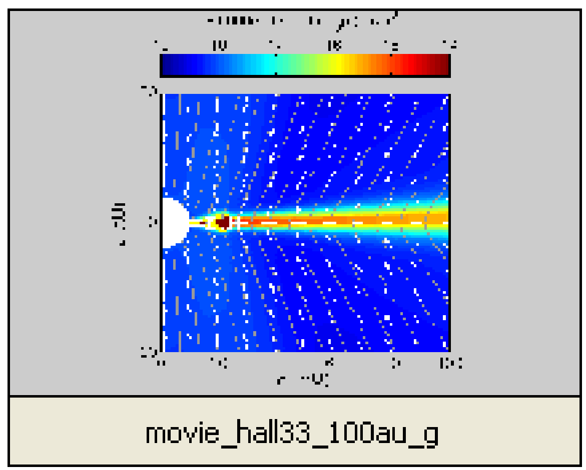


Hall Effect + Ohmic Resistivity

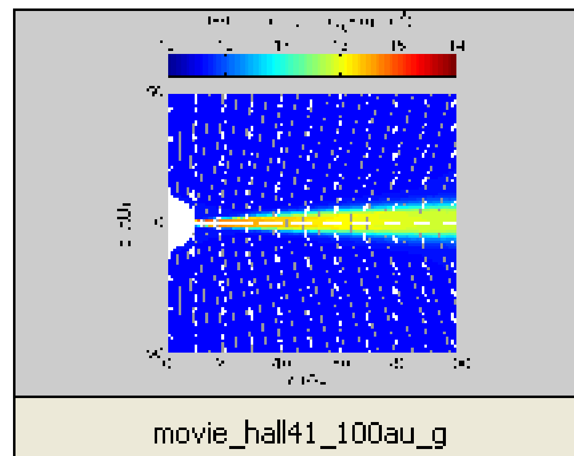
- We combined both effects in a few runs. If classical resistivity is used, it has little effect. If enhanced resistivity is used, it can reduce disk size – and even prevent disk formation. The cutoff is near the same value needed for η to enable disk formation. It seems to be the η value necessary to reduce magnetic torques – either IMHD braking, or Hall spin-up.



$\eta=10^{18}cm^2/s$



$\eta=10^{19}cm^2/s$



$\eta=10^{20}cm^2/s$

Strong Hall Effect

Hall Effect: Summary

- Hall effect can spin up a pseudodisk to Keplerian speeds – even if the pseudodisk is not rotating.
- Increasing magnetization can help: enhanced resistivity can be counterproductive.
- Looking into the literature (e.g, Nakano et al. 2002), the values of Q adopted are on the high side by one or two orders of magnitude. This could be addressed by moderately increasing magnetization, or by considering conditions of especially low ionization.
- **Strong Hall effect allows disk formation**
- **Not by weakening braking, but by its own magnetic torque**

A STRONG HALL EFFECT CAN SPIN DISKS UP

[Krasnopolsky, Li, & Shang (2011) ApJ, 733, 54]

Collapse and Ambipolar Diffusion

- Ambipolar diffusion (AD) is the non-ideal effect expected to appear earliest in the collapse process forming the protostar and the protostellar disk.

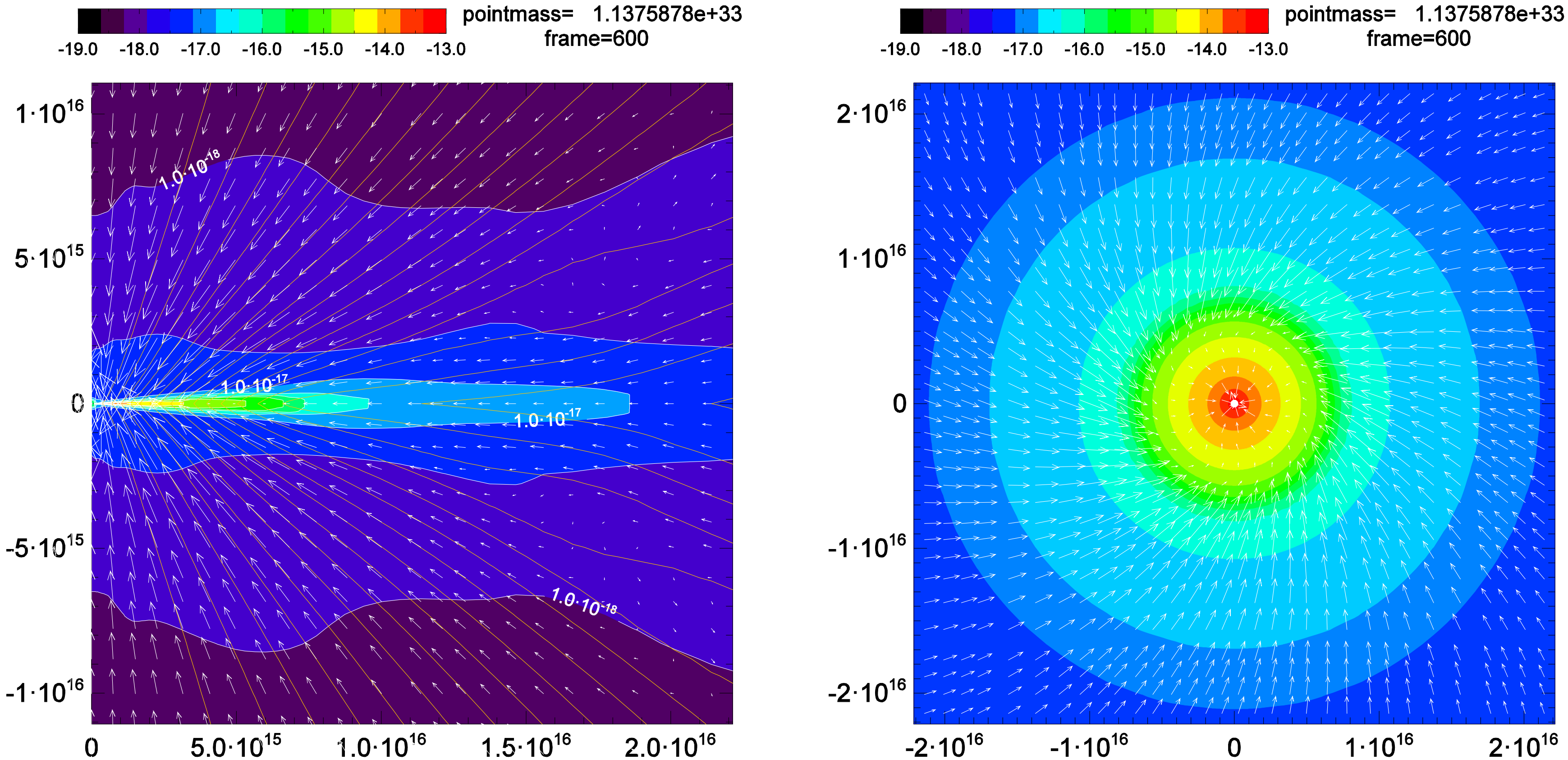
- Ambipolar diffusion is the non-ideal effect widely expected to solve the so-called “Magnetic flux problem”
- Will it also solve the excessive magnetic braking problem?
- How will it interact with other non-ideal MHD effects during the collapse phase?
- We addressed those questions in Li, Krasnopolsky, and Shang 2011 (ApJ, 738, 180)

Collapse and Ambipolar Diffusion

To address the challenges of disk formation during collapse, these AD simulations included:

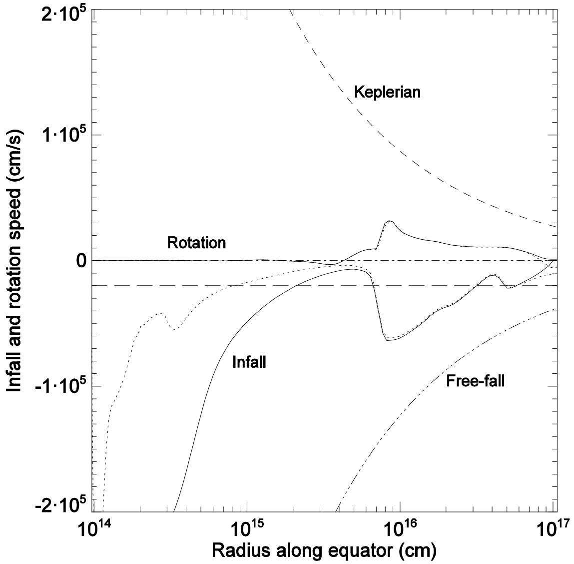
- All three major non-ideal effects
- Non-ideal coefficients calculated from a simplified chemical network (Nakano, Nishi, & Umebayashi 2002) including different kinds of charged species (grains, electrons, metal ions, molecules).
- Self-gravity
- An accreting central point mass, starting from zero, and growing in mass due to core collapse

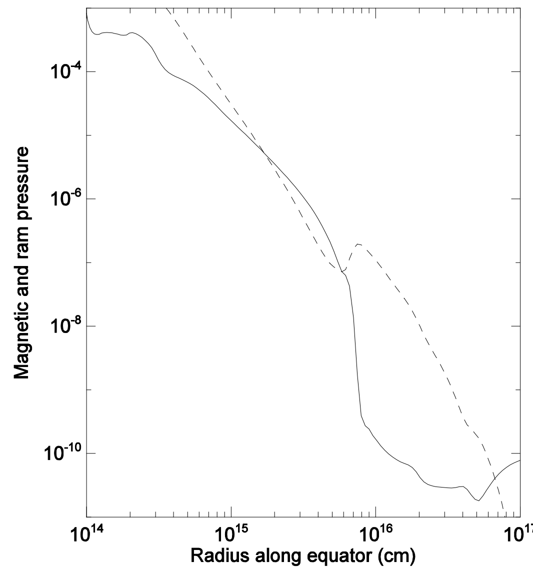
AD reference model



Colormap of log(ρ) in the reference model, including AD, at $t=6\times10^{12}$s, when the central mass was 1.1×10^{33}g=.57Msun (57% of the initial core mass). The highly flattened, dense equatorial structure is a nearly non-rotating pseudodisk.

Results: AD reference model



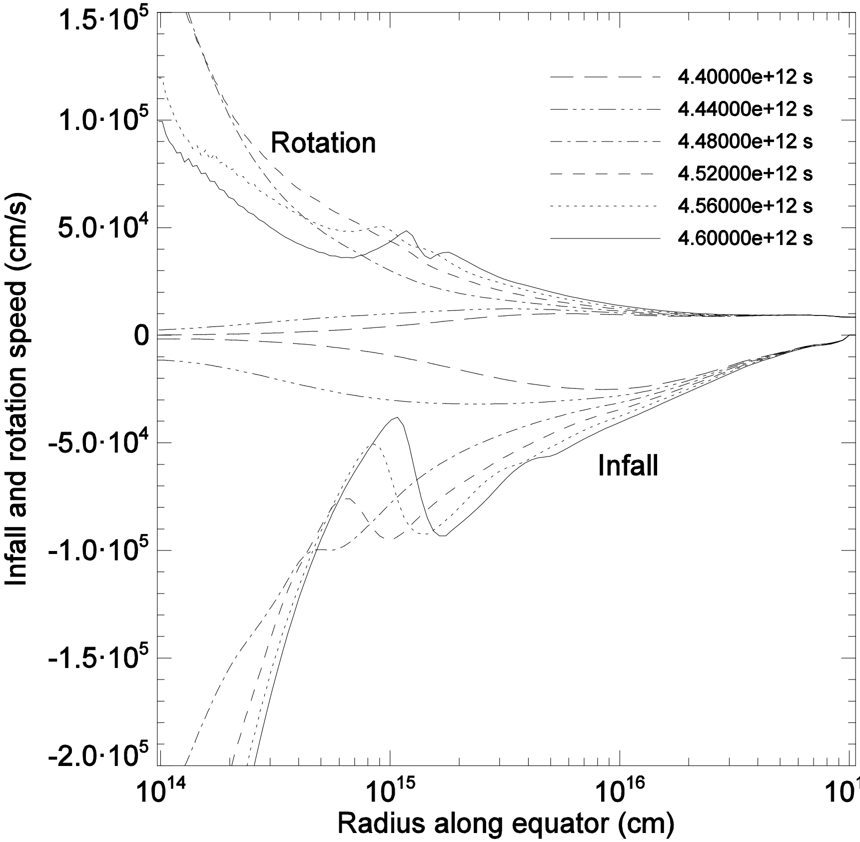


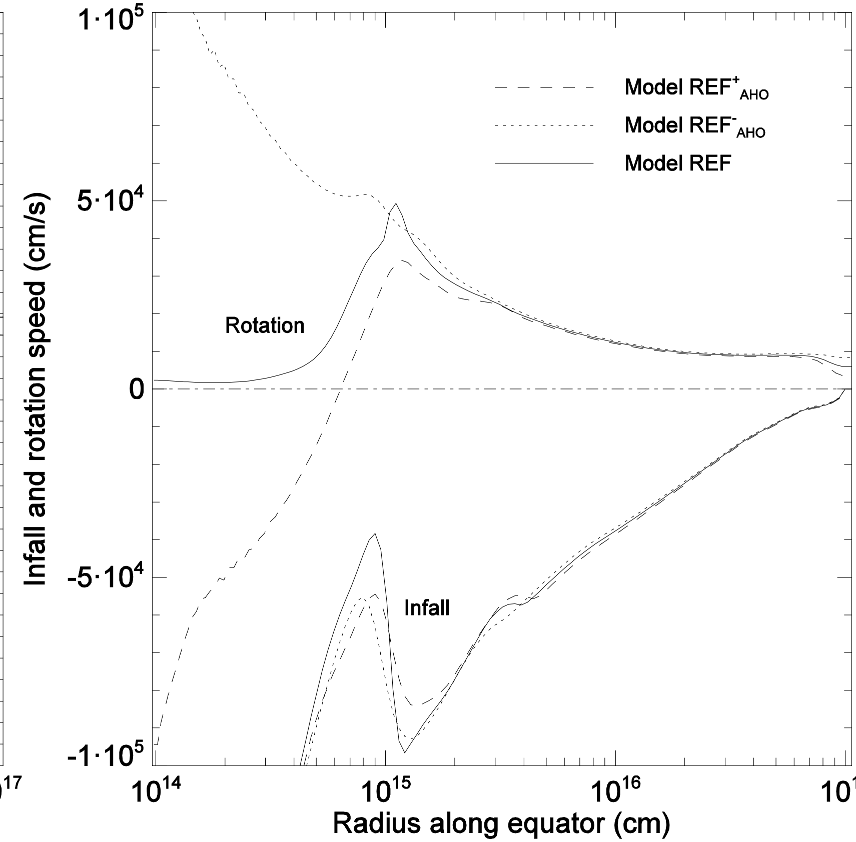
Due to AD, while neutral particles fall in, the charged particles do not fall in at the same speed, and so the magnetic field is not advected all the way to the center together with the mass. The central split-monopole is avoided.

Magnetic flux is redistributed: however, magnetic braking can be **increased**, because field “piles up” near the AD shock (Li & McKee 1996, Krasnopolsky & Königl 2002).

Supersonic rotation was observed earlier in the run (about $t=4.5\times10^{12}$s), but it was later suppressed by AD-increased magnetic braking; no rotationally supported structure was observed (run ended at $t=9\times10^{12}$s).

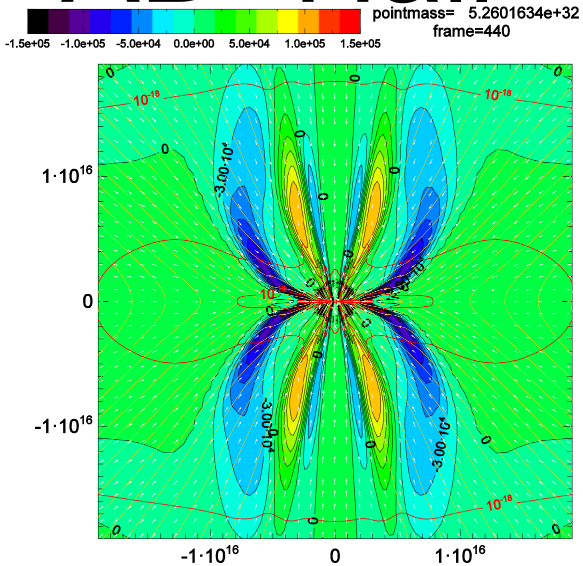
AD+Hall+Ohmic during collapse

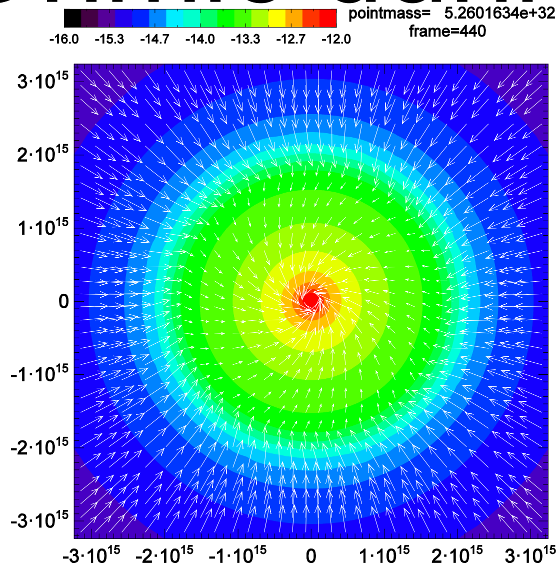


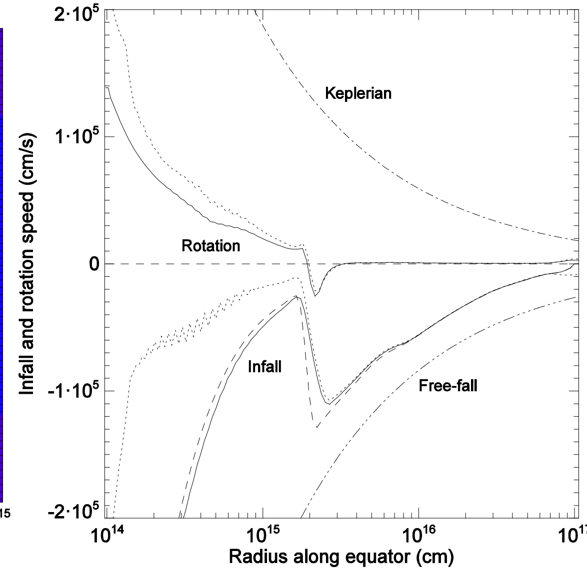


- Simulation with all three effects.
- The Hall effect is able to spin up the nearly completely non rotating, post-AD shock material, up to supersonic speeds. However, rotation is still far below Keplerian; infall speeds are barely slowed down.
- Changing the direction of magnetic field, the Hall effect can induce counterrotation (frame taken at $t=4.55\times10^{12}$s)

AD+Hall+Ohmic during collapse

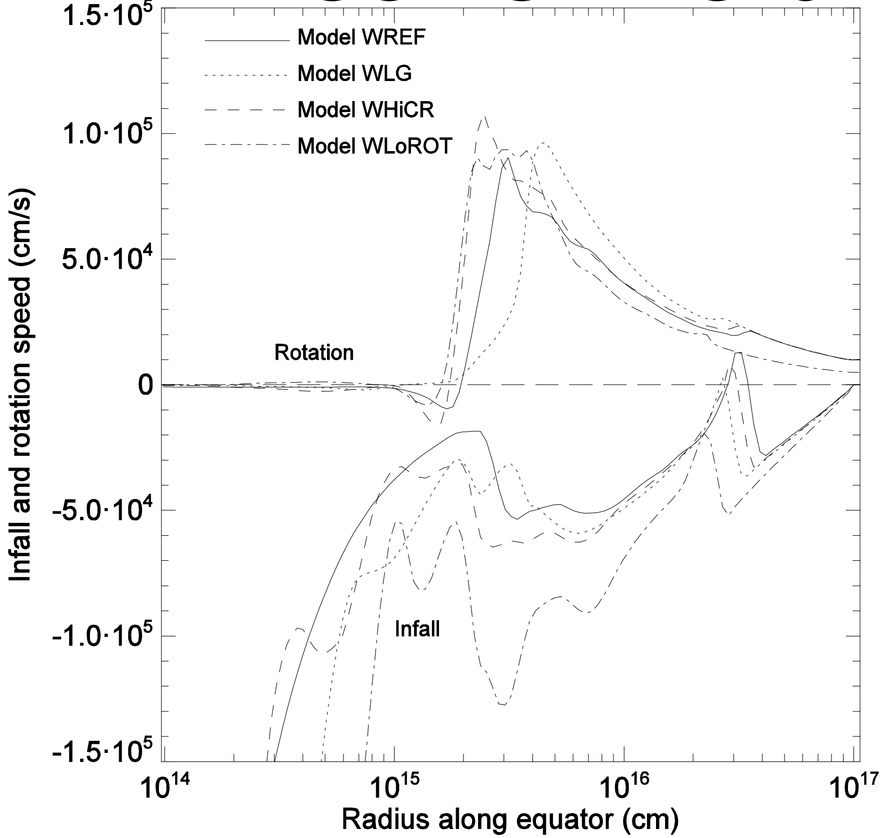


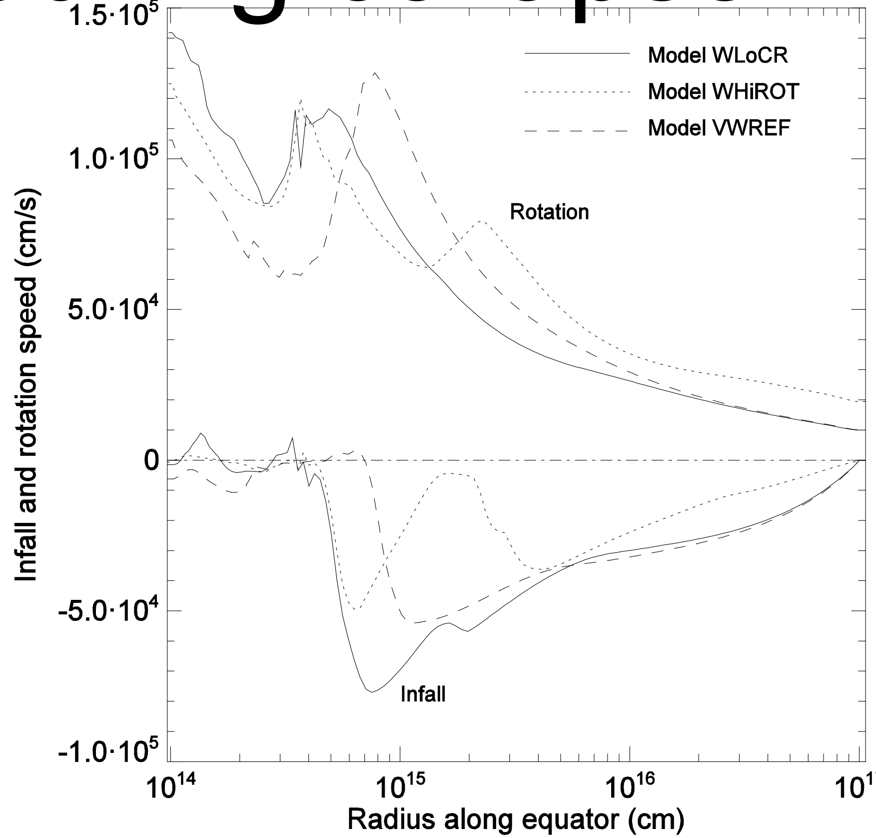




- Hall effect spin-up can be illustrated more clearly by showing the collapse of an initially non-rotating core, where any rotation that develops must come solely from the Hall effect.
- Supersonic rotation speeds are achieved inside a flattened, equatorial region of about 2×10^{15} cm at $t=4.4\times10^{12}$s.
- This rotating region is falling in. Rotation is far below Keplerian.

Weaker field during collapse





Weakening Bo to 10μG (λ ~ 10), or even smaller, has allowed small RSD to appear in a few of the runs. Run WREF has a ~20AU RSD at $t=3.68\times10^{12}$s, but it is completely gone by $t=5\times10^{12}$s ($M=5.7\times10^{32}$g), due to strong magnetic braking producing a transient outflow. Early disks are also observed in run WLoCR (with a lower ionization rate), WHiROT (faster initial spin), and VWREF (Bo=3.5 μG), at a time when M<0.018Msun. Each of the disks drives a strong, sometimes chaotic outflow. It is unclear if these early disks will survive braking.

Collapse and AD: Summary

- In axisymmetric ideal MHD, collapse creates a central split monopole, which induces catastrophic braking.
- AD is able to eliminate the split monopole; however, the field that would be trapped inside a point is now concentrated inside the AD shock. Braking is enhanced. For a realistic $\lambda \sim 3\text{-}4$, braking is strong enough to remove essentially all of the angular momentum of the material accreting into the central object under a wide range of conditions in two dimensions.
- Unenhanced Ohmic diffusivity was unable to allow disk formation in the scale explored here ($>10^{14}$cm).
- Hall effect can spin up the post-AD shock material to a supersonic speed; for the parameters studied, it is still strongly sub-Keplerian.
- For large $\lambda \sim 10$, a small RSD forms early during collapse, when the central mass is still small. In most cases, this early RSD was observed to disappear, braked by the powerful outflow it drives. However, when ionization is unusually low or core rotation is unusually high, the fate of this disk is still unknown.

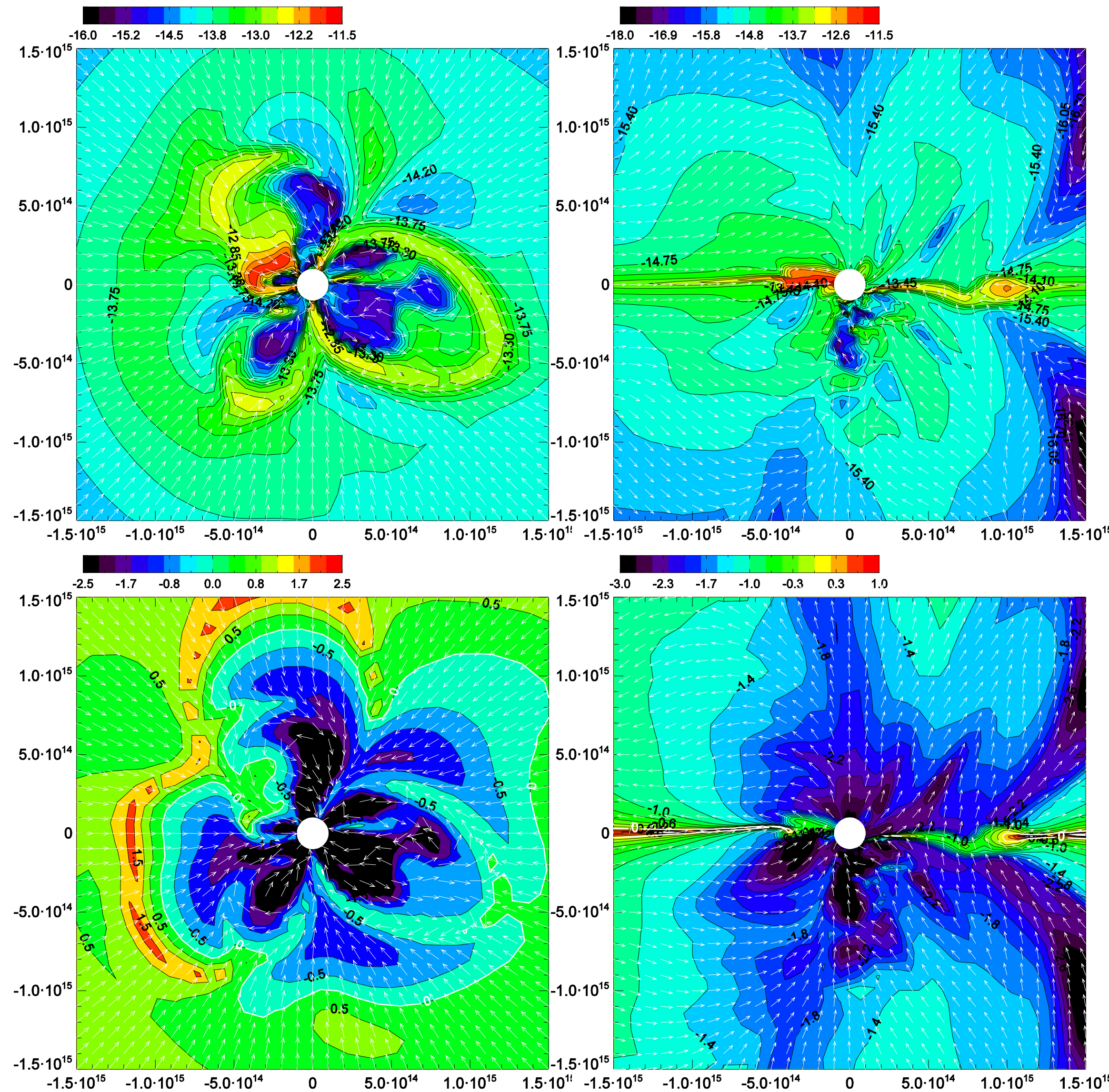
[Li, Krasnopolsky, & Shang (2011) ApJ, 738, 180]

3D Instability

We carried out 3D simulations of collapse including three non-ideal processes: AD, enhanced Ohmic dissipation, and decoupling at the inner boundary at r=10^{14} cm.

Result: the inner protostellar accretion flow is driven unstable by the magnetic flux decoupled from the matter that enters the central object. When this interchange instability is fully developed, the flow structure becomes highly filamentary, as a result of the interplay between gravity-driven infall and magnetically-driven expansion.

In particular, the AD shocks found in 2D are unstable.

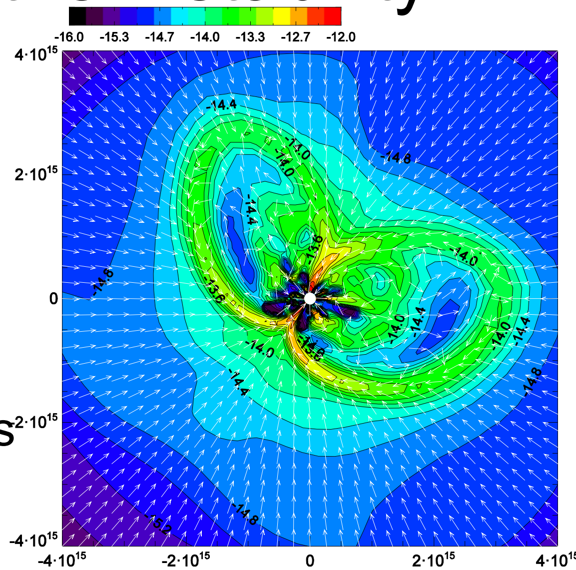


3D collapse simulation with AD ($\zeta=9\times10^{-17}$/s), at a time when M=0.092Msun. Left panels: equatorial plane (unit **v** vectors in white); right panels: a meridian plane (with unit **B** vectors). Top panels: log(ρ); bottom panels: log plasma β, with β=1 in white.

Growth of the instability

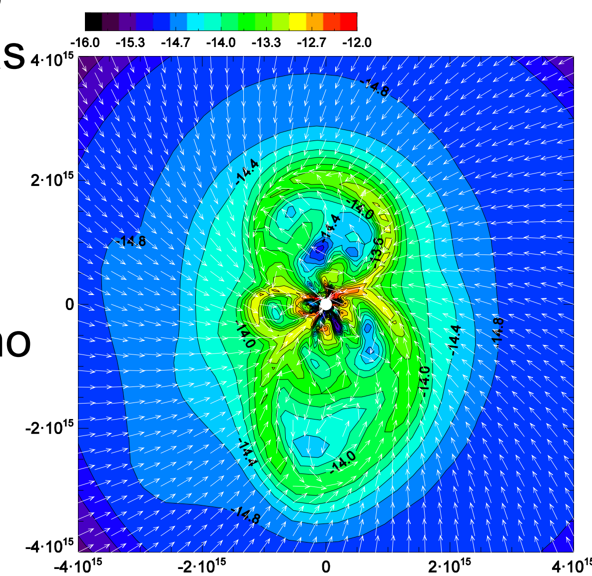
Growth of the instability is clearly seen in these models including a step-function resistivity (η goes from 1 to 10^{19} cm^2/s for $r<2\times10^{14}$ cm).

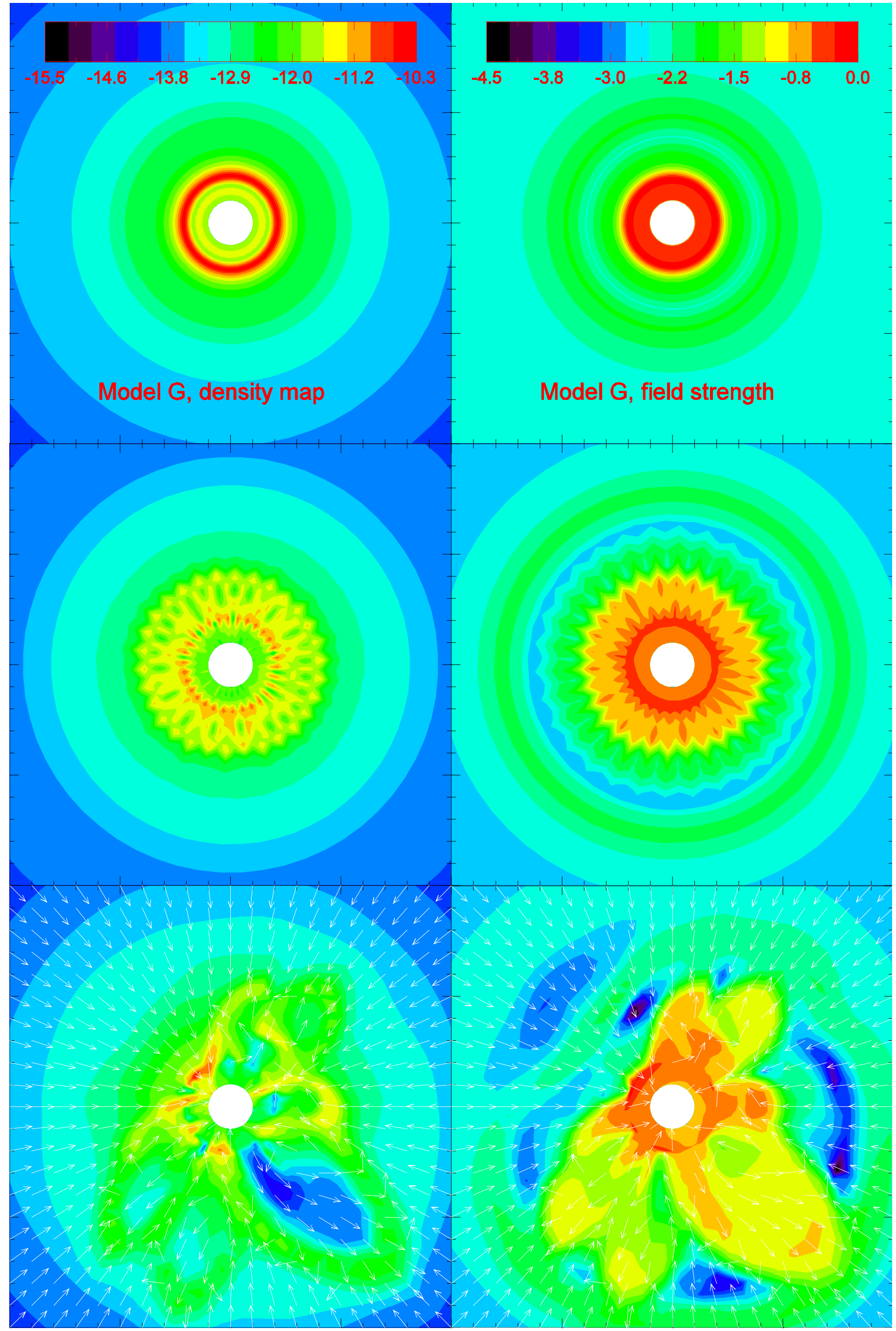
Models I and J incorporate also AD. Model J has initial rotation; that does not change the outcome of the instability, and no RSDs are seen.



Models G & I (Ω=0)

Model J (Ω= 10^{-13}/s)





3D Instability

3D Instability: Summary

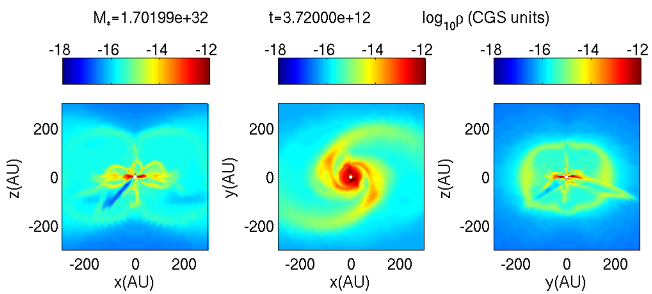
- Magnetic interchange instabilities are seen to take place during collapse once the axisymmetry assumption is released.
- Magnetic flux is transported by macroscopic advection, in addition to microscopic diffusion.
- Diffusive processes are important to this process, in that they provide the initial decoupling needed for the instability to start; after decoupling, more strongly magnetized regions expand away along some azimuthal directions, while less magnetized regions sink in.
- The instabilities lower B close to the protostar; however, magnetic braking is still efficient, and no RSDs were observed in this set of simulations.

[Krasnopolsky, Li, & Shang (2012) ApJ, 757, 77]

[also: Zhao, Li, Nakamura, Krasnopolsky, & Shang (2011) ApJ, 742, 10]

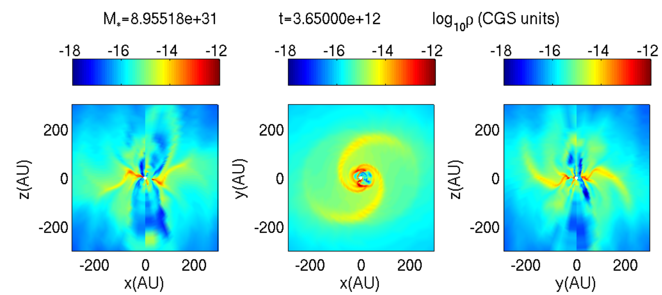
3D asymmetric configurations

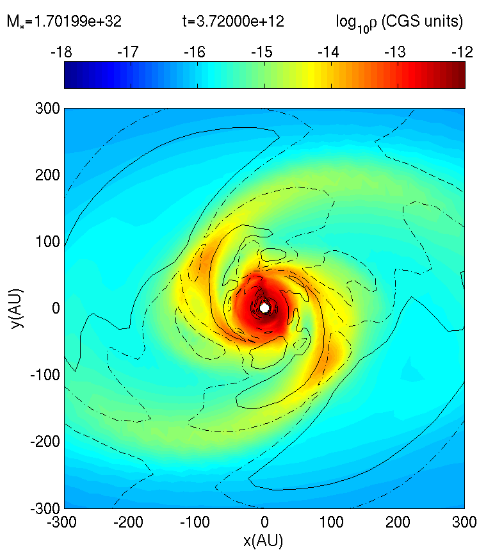
RSDs are formed in some ideal MHD simulations (e.g., Machida et al. 2011), particularly when the rotation and magnetic axis are misaligned (Joos et al. 2012) or in the presence of a strong turbulence (Seifried et al. 2012, Gouveia dal Pino et al. 2011). Having explored the axisymmetric conditions in detail, we are now studying these asymmetric configurations.



Simulations with $\lambda \sim 10$.

B- Ω tilt angles of 90° and 30°.





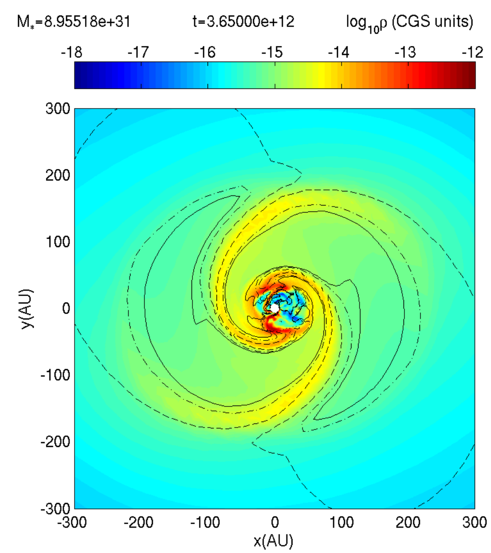
Contours of $v_{\varphi}/v_{RotSupport}$:

Solid:1.0

Dash-dot:0.9

Dashes:0.7

Dots:0.5



Current work

Summary

- For the observationally inferred level of magnetization in dense cores, disk formation is difficult in the axisymmetric, ideal MHD limit, because of magnetic braking (Allen+2003, Galli+2006, Seifried+2011, Hennebelle&Fromang2008).
- **Classical non-ideal MHD effects might be not strong enough in 2D.** Machida+(2007) and Dapp+(2012) showed that Ohmic dissipation can enable small (AU scale) disks. Enhanced resistivity can allow 100AU scale disks (KLS2010); large disks can also be formed through a strong Hall effect (KLS2011). However, the microscopic values of η and Q do not seem large enough (LKS2011), while AD acts to increase magnetic braking (Mellon&Li2009, Krasnopolsky&Königl2002).
- The interchange instability produces complex flows of varying magnetization (KLS2012), including blobs and filaments (which may help to solve the flux problem) but which could compromise disk growth and stability.
- Asymmetric effects, such as a tilted magnetic field (Hennebelle&Ciardi 2009), and different kinds of turbulence, may weaken braking and help disk formation in various plausible conditions, such as a sufficiently large tilt angle, favorable patterns of turbulent flow (Seifried+2012), and turbulent enhancement of magnetic reconnection (Santos-Lima, Gouveia dal Pino, & Lazarian 2012)
- Our current work shows that rotationally supported structures can be formed in the tilted scenario.