Magnetic Braking & Protostellar Disk Formation

Zhi-Yun Li & Rick Mellon (Univ of Virginia)

Macrophysics of star formation: cloud and up
Microphysics: core and down (McKee & Ostriker 07)

1. Basic issue & observational motivation

   Conservation of angular momentum?

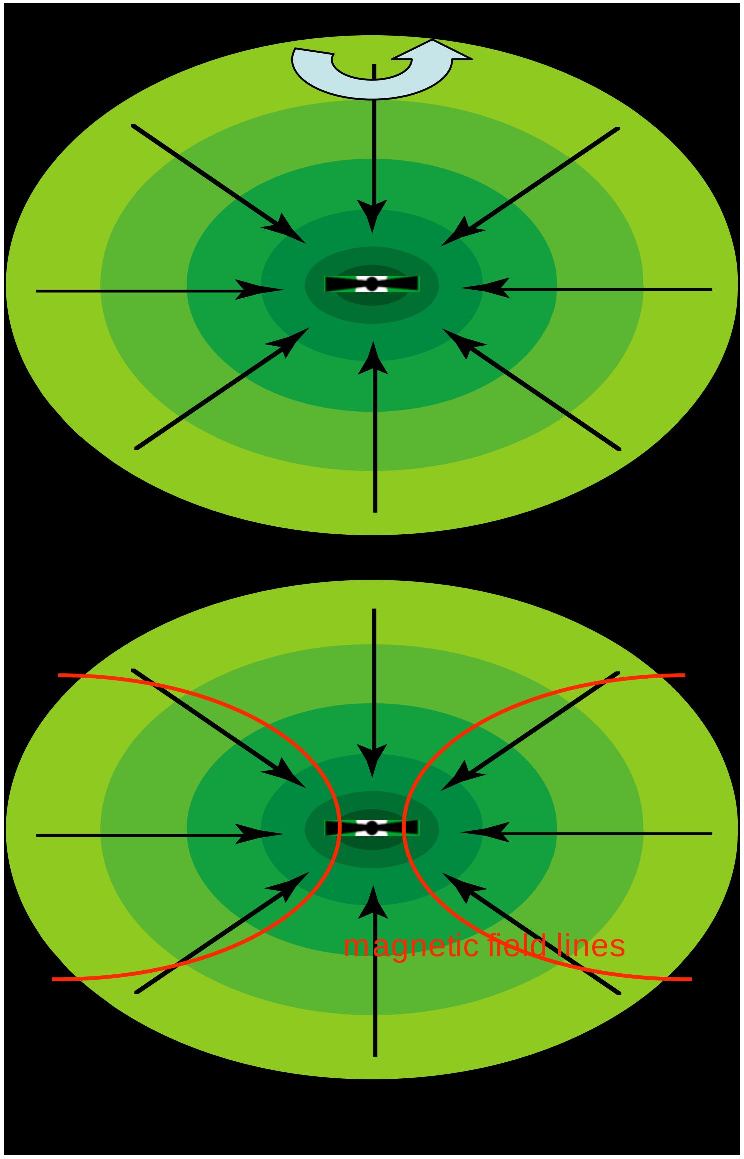
2. Ideal MHD simulations of rotating core collapse

   Can rotationally supported disks form in the presence of strong magnetic braking?

3. Speculations

   role of protostellar outflows and nonideal effects

1. Basic Issue



❑ Common view

Disks form automatically out of the collapse of rotating cores because of angular momentum conservation

❑ Role of magnetic fields

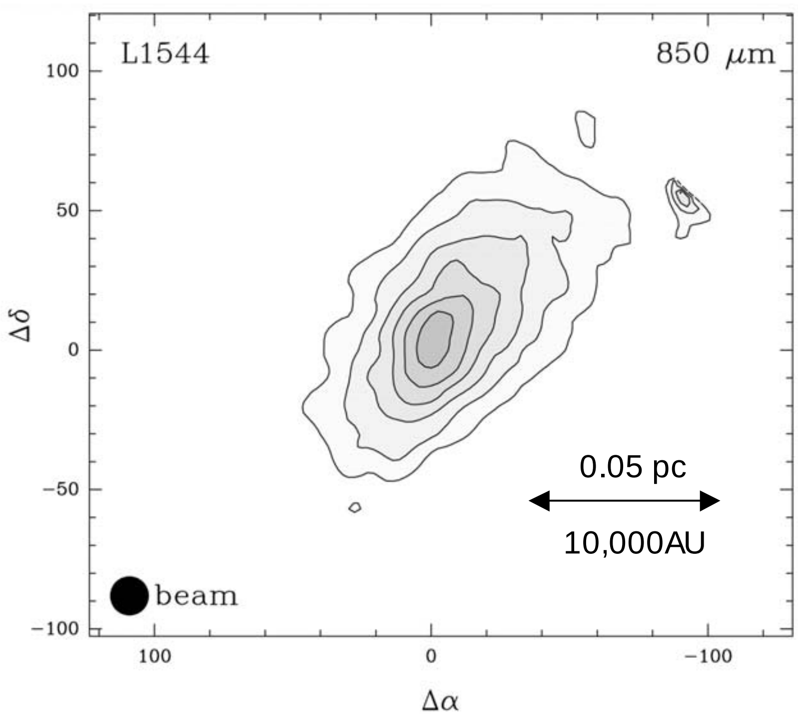
Fast rotating disk and slowly rotating massive envelope magnetically linked

⟹ magnetic braking

1. rotationally supported disks
   not guaranteed
2. disk-envelope transition region
   dominated by magnetic fields & rotation -- ALMA?

Observed Initial Condition for Star Formation

Prestellar core L1544



Shirley et al. (2000)

- Rotation (Caselli et al. 02)

  ~6km/s/pc ~ $2x10^{-13}s^{-1}$

- Magnetic field

1. Ordered magnetic field from polarized submm emission (Ward-Thompson et al. 00)
2. Field strength from OH Zeeman measurements (Crutcher & Troland 00)

   B_{los} ~ 11μG

- Mass-to-flux ratio

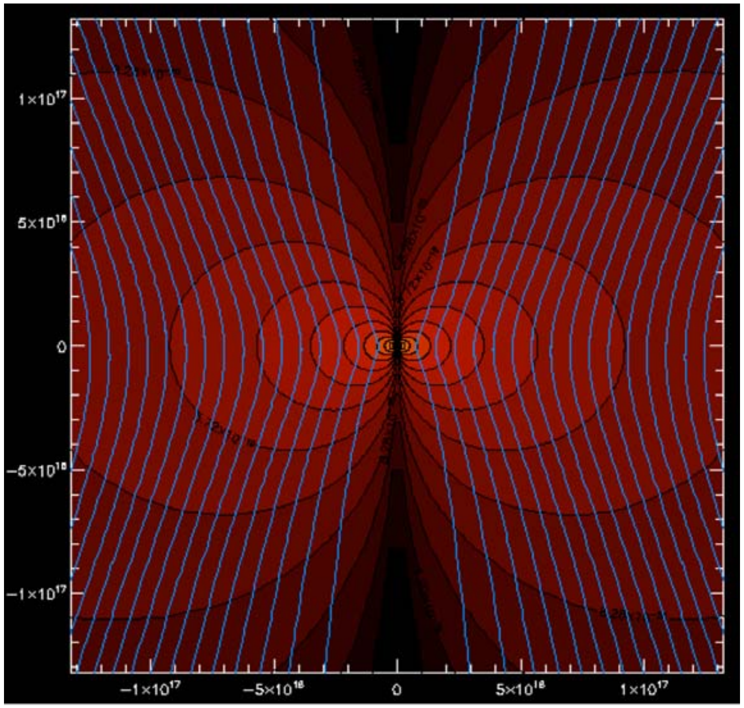
  If λ=∞, non-magnetic core

  If λ=1, magnetic force ~ gravity

  Inferred λ=M/Φ~8, smaller if deprojected

  Fiducial value λ=4 chosen

Initial Condition for Protostellar Collapse Calculations



(Mellon & Li 2007, Allen, Li & Shu 2003, see also Galli et al. 2006)

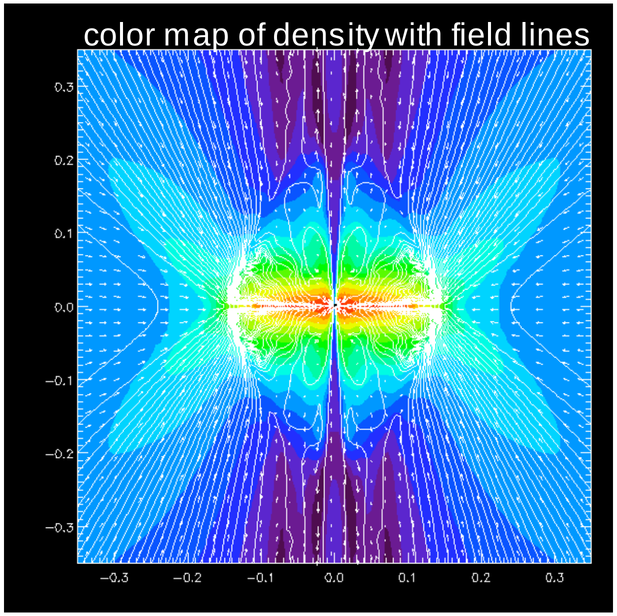
- Self-similar isothermal toroid
  - Sound speed=0.3 km/s
  - Volume density $\propto r^{-2}$
  - Field strength $\propto r^{-1}$
  - Rotation speed=0.15 km/s
- Axisymmetry in r-θ coordinate
  - Inner radius=10^{14}cm=6.7AU
  - Stress-free condition on B field
  - Outer radius=$2\mathrm{x}10^{17}$cm=0.065pc
  - Uniform grid in θ, log in r (Zeus2D)
  - 3.8$M_\odot$ enclosed
- Model parameters

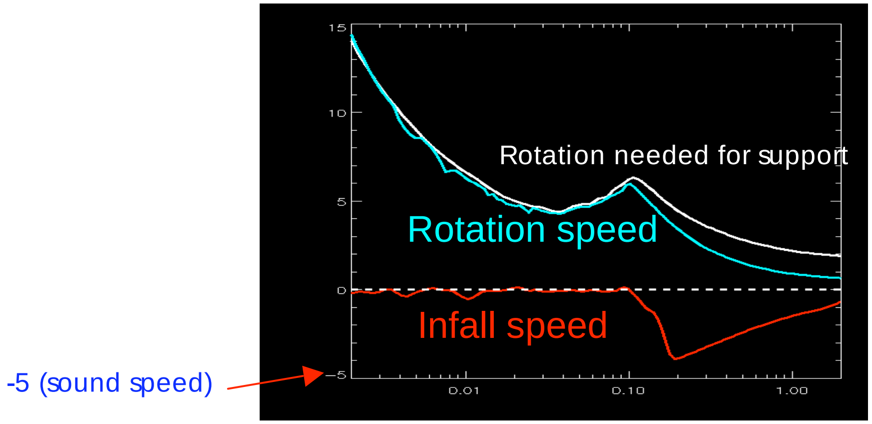
fiducial, λ=4, B_{eq}=24.5(.05pc/r)μG

- λ=400, extremely weak field
- λ=80, weak field
- λ=13, moderately weak field
- λ=4, moderately strong field

Formation of Rotationally Supported Disks in Extremely Weak Fields

λ=400, B_{eq}=0.25(0.05pc/r)μG « 6 μG for atomic CNM (Heiles & Troland 2005)



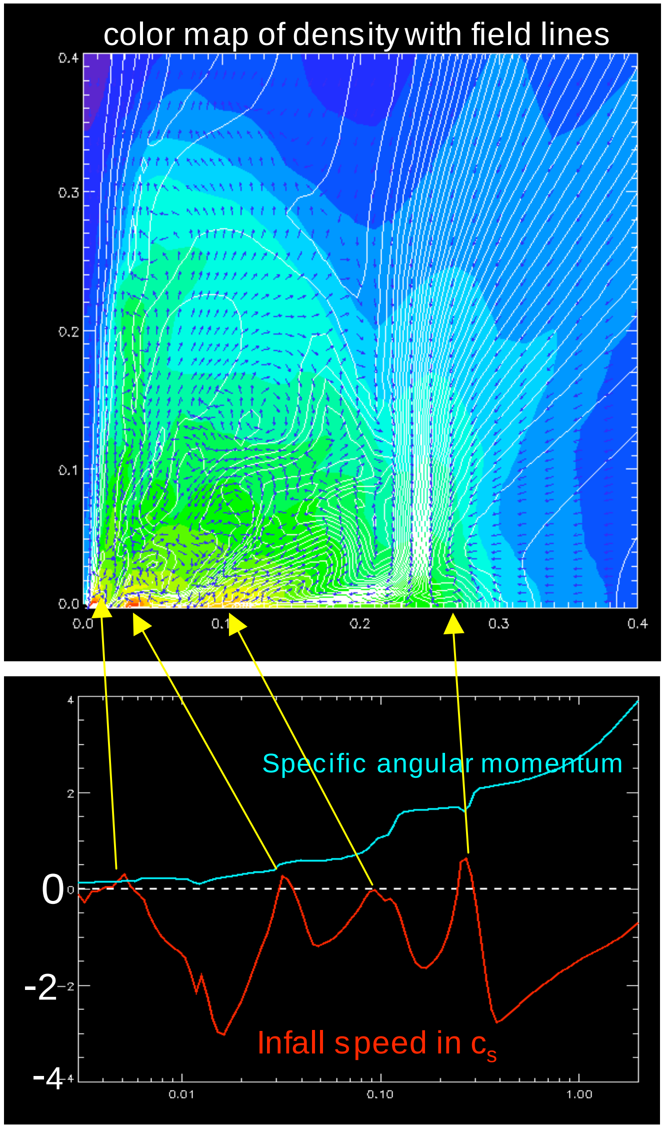


- ❑ Rotationally supported disk
  - R_d~500AU (time/2x10^{12}sec)
  - Self-gravitating in the outer region
  - Fragmentation in 3D? (Begelman & Pringle07)
- ❑ Magnetic pressure dominated
  - Ratio of thermal & magnetic pressure <β>~0.4
  - "Corona" in place of "accretion shock"
  - Field amplified in collapse & by rotation

$\Rightarrow$ Weak field important for disk dynamics

Disruption of Equilibrium Disk by Weak Field

λ=80, B_{eq}=1.25 (0.05pc/r) μG ~ Galactic mean B



- ❑ Beginning of disk disruption

Best evidence from infall speed on equator

Supersonic infall at most radii

Multiple centrifugal barriers w/ enhanced braking

- ❑ Region dominated by B field & rotation

Radius ~ 10^3AU (time/$2\text{x}10^{12}$sec)

Chaotic (subsonic) flow pattern in meridional plane

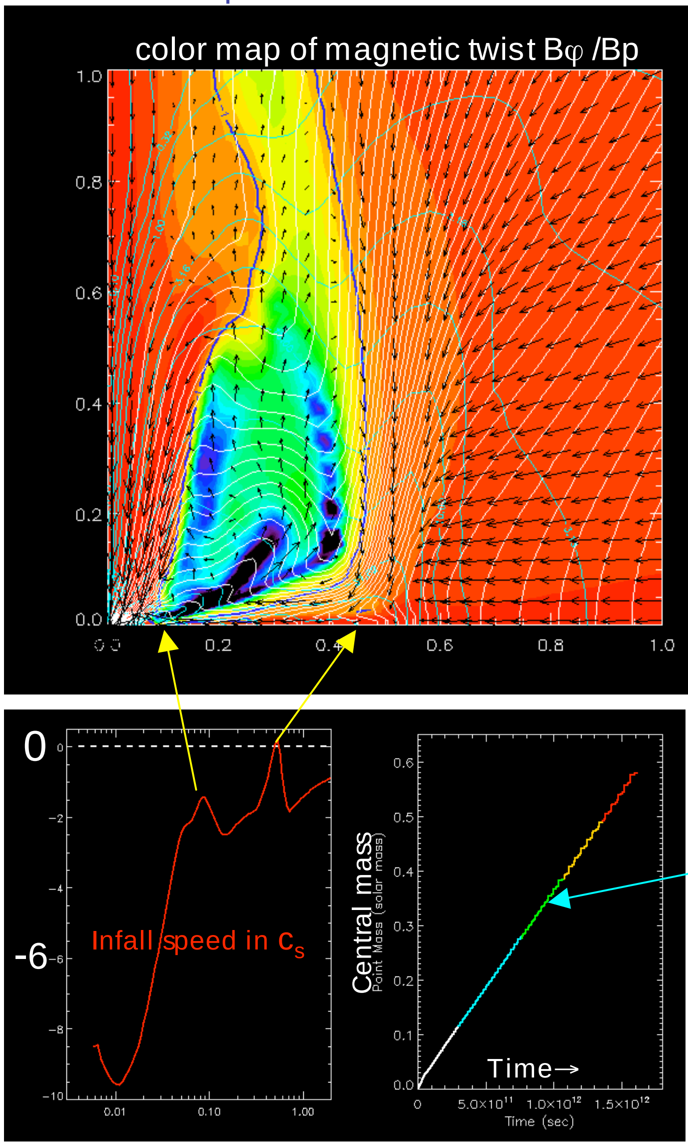
Velocity dominated by supersonic rotation

Pressure dominated by toroidal magnetic fields

⇨Disk dwarfed by an extended rotating magnetized region

Magnetic Bubble and Efficient Braking

λ=13, B_{eq}=7.35 (0.05pc/r) μG ~ median B field of atomic CNM

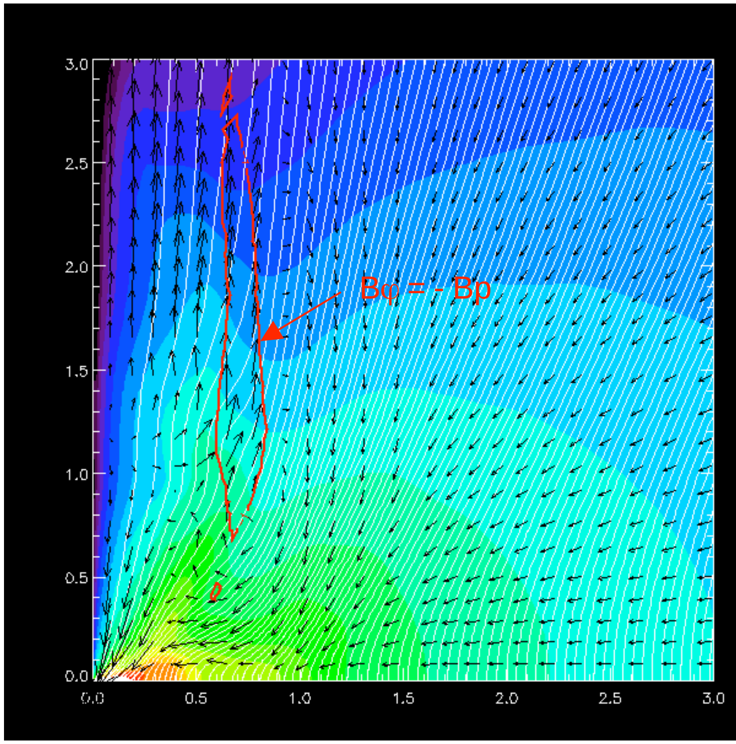


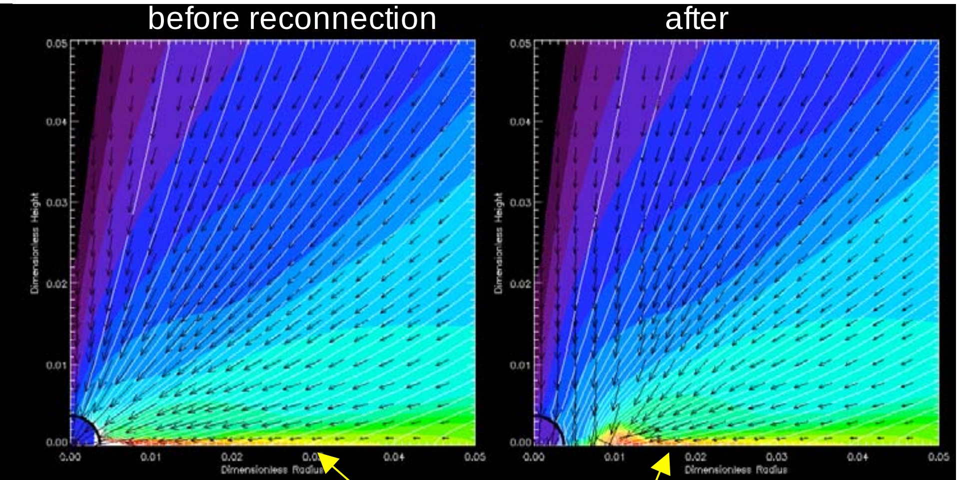
- No rotationally supported disk
  - Collapsing envelope ⇒ pseudodisk
  - Severe braking at the centrifugal barrier
  - Magnetic bubble inflated
  - Remaining material straight to the center
- Magnetic bubble
  - Pressure dominated by toroidal field
  - Velocity dominated by rotation
  - Slow ordered expansion
  - R~2000AU (time/2x10^{12}sec)
- Mass accretion to center
  - Nearly constant rate on average
  - Expected from self-similar initial condition

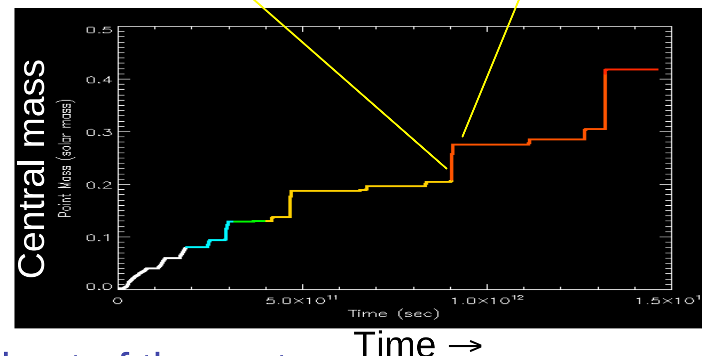
⇒Mass to center & angular momentum to bubble

Reconnection and Episodic Mass Accretion

λ=4, B_{eq}=24.5 (0.05pc/r) μG ~ typical core field strength?



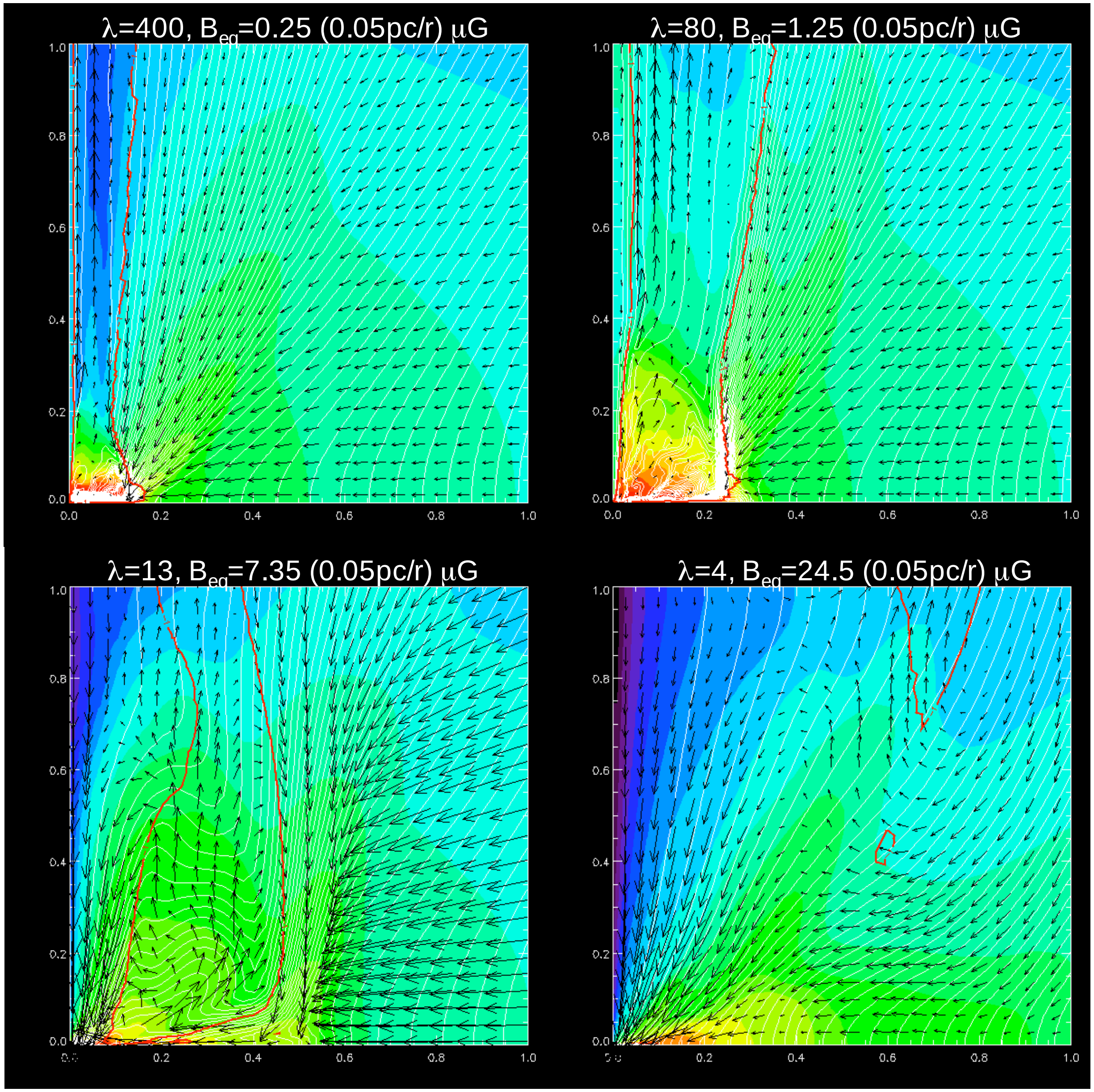




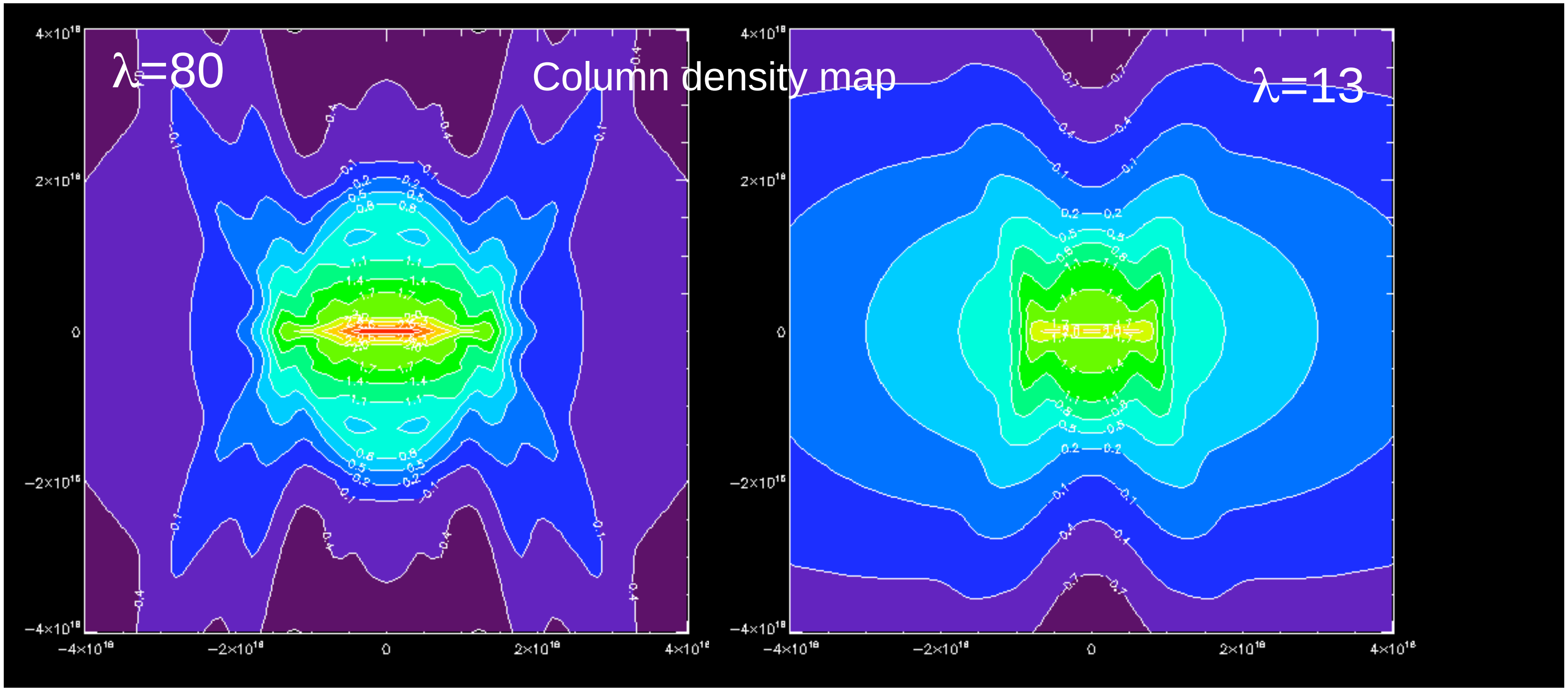
- ❑ No rotationally supported disk
  - Less twisted field lines, stronger outflow
  - Majority of angular momentum transported out of the system
- ❑ Strong pinched field near equator ⇒ magnetic reconnection
  - Accretion shuts off after reconnection, until enough mass is accumulated for gravity to overwhelm magnetic tension
  - Unsteadiness in mass accretion on top of disk instability? (Basu's talk yesterday) (see also Tassis & Mouschovias 2005)

Summary of Ideal MHD Calculations

Early universe?



Magnetogyrosphere?



- Bound circumstellar structure
  - B field strong enough to extract angular momentum from disk, too weak to drive L out of system
  - Dominated by a combination of (toroidal) magnetic field & rotation ⇒ magnetogyrosphere
  - Densest region not a rotationally supported equilibrium disk---alternating infall/spinup & slowdown/braking , to be probed by ALMA?
- Possible role of protostellar winds (Arce & Sargent 06, Shu et al. 87, Nakano et al. 1995, Matzner & McKee 00)
  - Typical core mass ~ a few $M_{\odot}$, typical stellar mass ~ 0.5 $M_{\odot}$ ⇒ most core mass removed by winds?
  - Most of the magnetogyrospheric material removed by winds as well? Most angular momentum?
  - Remaining material falls back to form a disk, when envelope (& braking) gone ⇒ fallback disk?

Future Directions

- Non-ideal effects, particularly ambipolar diffusion (second part of Rick Mellon's thesis)

  (see also Basu & Mouschovias 1994, Krasnopolsky & Konigl 2002)

- 3D simulations, with AD eventually

  fragmenation during protostellar mass accretion phase

- Inclusion of fast protostellar winds

  stellar mass and disk angular momentum at same time?

Summary: Magnetized Rotating Core Collapse & Disk Formation

- Formation of rotationally supported disks not guaranteed

  Disk disrupted by relatively weak fields in the ideal MHD limit

  Microphysics of magnetic decoupling and/or wind interaction needed

- Magnetogyrosphere should exist in some form

  Extended region dominated by magnetic fields & rotation

  Should be searched for with current & future instruments