THE ROLE OF MAGNETIC FIELDS

IN STAR FORMATION

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OUTLINE

I. Historical introduction

II. Observations of magnetic fields in molecular cloud cores

III. Observing interstellar magnetic fields on a computer (P-S Li+ in prep.)

IV. The Protostellar Accretion Disk Crisis (Myers+ 13)

V. What Accounts for Violations of Magnetic Flux Freezing?

I. Historical Introduction

Seminal theory papers (before any direct measurement of interstellar B):

Mestel & Spitzer (1956)

Mestel (1965)

Strittmatter (1966)

Spitzer (1968)

Mouschovias & Spitzer (1976)

Key idea: Magnetic energy scales as gravitational energy, so there is a magnetic critical mass:

$$\frac{\text{Gravitational energy } E_G}{\text{Magnetic energy } E_B} \propto \frac{GM^2/R}{B^2R^3} \propto \frac{M^2}{\Phi^2/G}$$ independent of scale

where $\Phi = \pi R^2 B$ is the magnetic flux

Hence magnetic energy = gravitational energy for $M = M_\Phi \sim \Phi / (2\pi G^{1/2})$

(Numerical coefficient gives condition for instability for a magnetized sheet)

The Two Classical Problems in Star Formation

1. The two magnetic flux problems:

   How can the mass to flux ratio increase so that $M > M_{\Phi} \sim \Phi / (2\pi G^{1/2})$, allowing gravitational collapse to occur? (Mestel & Spitzer 1956)

   How can the mass to flux ratio increase by a further factor $10^5 - 10^8$, as observed in stars? (Not discussed here)

2. The angular momentum problem

   How can interstellar gas lose the 99% of its angular momentum required to form a star? (Mestel 1965, Spitzer 1968)

Magnetic torques can solve the angular momentum problem (Spitzer 1968)

Can be so strong that they prevent disk formation (Mestel & Spitzer 1956):

The protostellar accretion disk crisis

We shall see that loss of magnetic flux (solution of first problem) can resolve this crisis

The Magnetic Flux Problem - I

Normalized mass-to-flux ratio $\mu_\Phi = M / M_\Phi$

Magnetic critical mass: $$M_\Phi = \frac{\text{Magnetic flux } \Phi}{2\pi G^{1/2}}$$

$$\mu_\Phi = \frac{M}{M_\Phi} = 2\pi G^{1/2} \left(\frac{M}{\Phi}\right)$$

Magnetically supercritical: $E_G > E_B$, $\mu_\Phi > 1$ => Cloud can collapse

Magnetically subcritical: $E_G < E_B$, $\mu_\Phi < 1$ => Cloud cannot collapse

In ideal MHD, mass-to-flux ratio can increase only due to mass flow along the magnetic field; mass transport across the field is impossible

The Magnetic Flux Problem - II

The diffuse ISM is magnetically subcritical => cannot form stars (Mestel & Spitzer)

Their argument with modern data:

Let N = nL = column density along the field

$$\frac{\mu_\Phi}{2\pi G^{1/2}} = \frac{M}{\Phi} = \frac{N m_H \times \mathrm{Area}}{B \times \mathrm{Area}} = \frac{nL\, m_H}{B}$$

$$\Rightarrow L \simeq \frac{500}{n}\left(\frac{B}{6\ \mu\mathrm{G}}\right)\mu_\Phi \quad \mathrm{pc} \gg$$ size of 1 M_{sun} cloud for $\mu_\Phi > 1$

Hence magnetic fields exceed gravity on stellar mass scales in diffuse ISM

And, the length scale required for flow along the field to change this is too large to be effective in forming stars

(In fact, this is the length scale for formation of Giant Molecular Clouds, which were not discovered until 20 years later)

Role of Ambipolar Diffusion

Mestel & Spitzer: since impossible to gather enough gas along the field to overcome the magnetic field, neutrals must undergo gravitational contraction by slipping through the ions and the magnetic field in shielded regions---ambipolar diffusion

This became the standard paradigm for low mass star formation:

Ambipolar diffusion enables gas to evolve from magnetically subcritical ($\mu_\Phi < 1$) to magnetically supercritical ($\mu_\Phi > 1$) (Shu+ 87)

Mouschovias and his students have done the most work on this

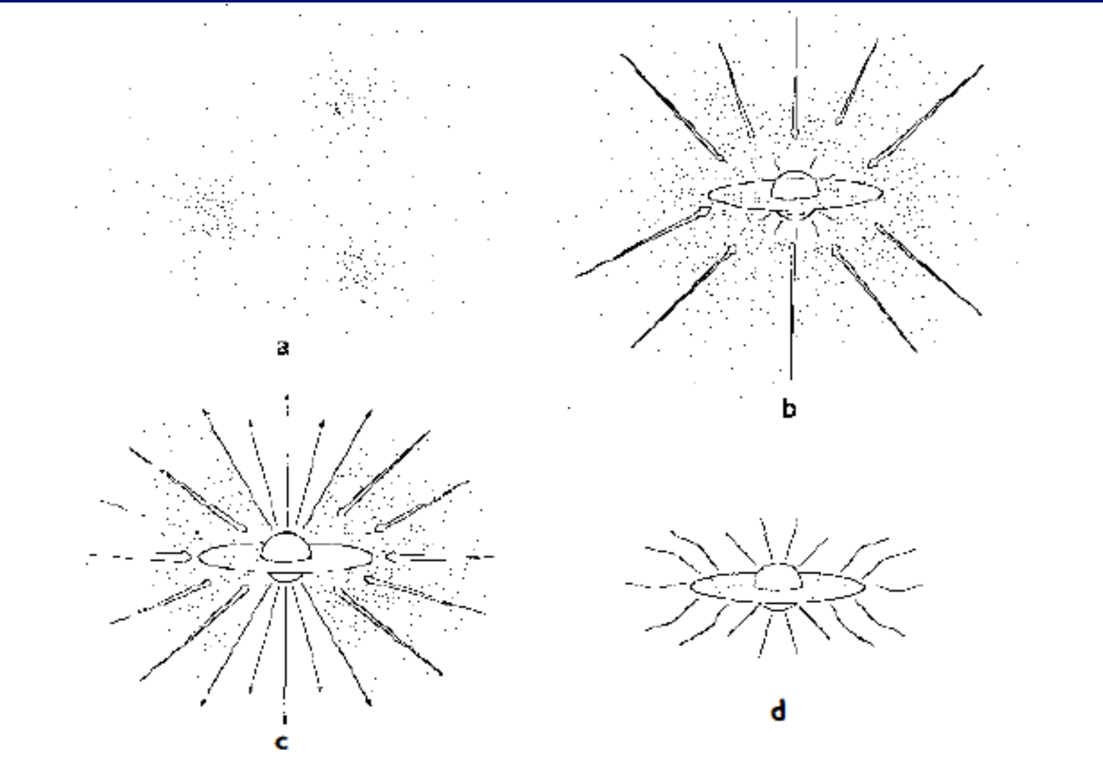


Figure 7 The four stages of star formation. (*a*) Cores form within molecular clouds as magnetic and turbulent support is lost through ambipolar diffusion. (*b*) A protostar with a surrounding nebular disk forms at the center of a cloud core collapsing from inside-out. (*c*) A stellar wind breaks out along the rotational axis of the system, creating a bipolar flow. (*d*) The infall terminates, revealing a newly formed star with a circumstellar disk.

(Shu, Adams & Lizano ARAA 1987)

II. Observations of Magnetic Fields in Molecular Clouds

Zeeman observations of N B_{los} = column density x los field in HI, OH and CN

Let B_{tot} = magnitude of the density-weighted total magnetic field from Zeeman observation, before projection along the los (line of sight)

Then, since median cos theta=0.5, median B_{tot} = 2 x median B_{los}

Atomic ISM is magnetically subcritical (as Mestel & Spitzer inferred)

Heiles & Troland (2005) find normalized mass/flux $\mu_\Phi < 1/6$: very subcritical

But molecular cloud cores are magnetically supercritical

Theory: GMCs have $\mu_\Phi \sim 2$ (McKee 1989)

Crutcher (1999): Cores typically have $\mu_\Phi = 2\pi G^{1/2} (M/\Phi) > 1$

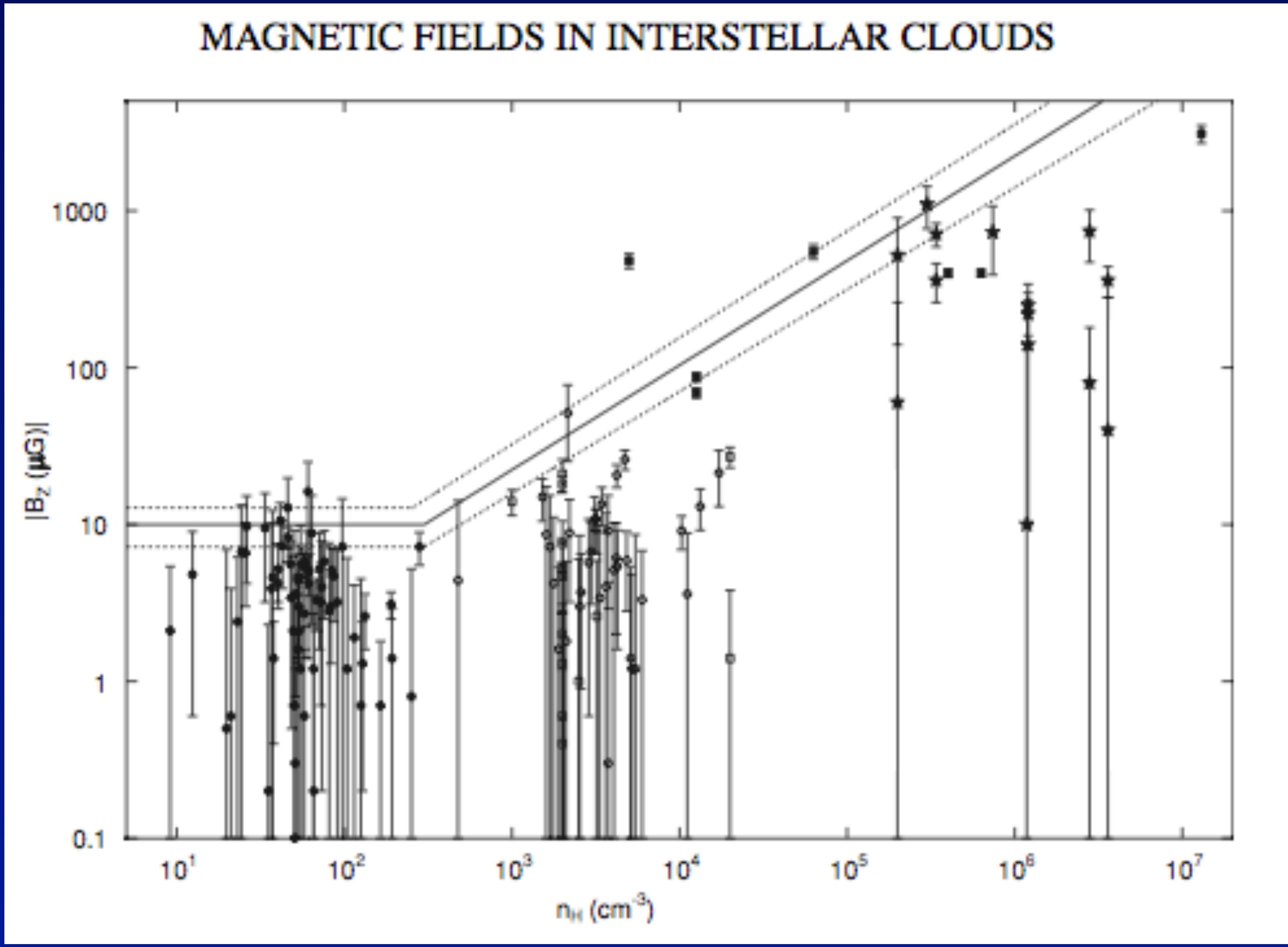
Alfven Mach number $\mathcal{M}_A \sim 1$

Troland & Crutcher (2008): OH observations with Arecibo

Cores magnetically supercritical: median μ_Φ = 1.7-2.6

Median $\mathcal{M}_A$ =1.5

Comprehensive study of Zeeman observations, including upper limits on B_{los}



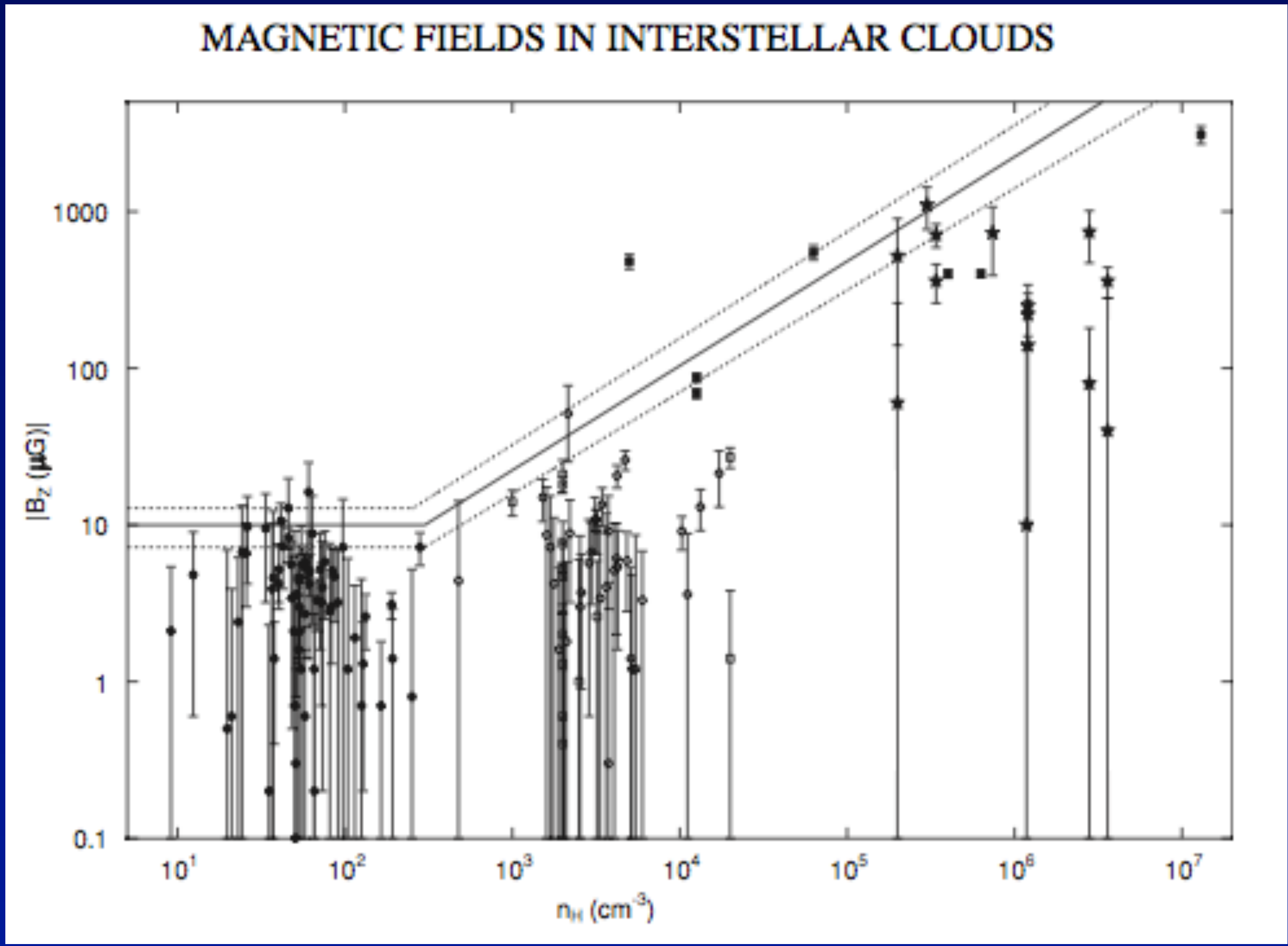
HI: Mostly $n_H < 300$ cm^{-3}

(Crutcher + 2010)

OH: Mostly 1×10^3 cm^{-3} $< n_H < 2 \times 10^4$ cm^{-3}

CN: 2×10^5 cm^{-3} $< n_H < 4 \times 10^6$ cm^{-3}

Comprehensive study of Zeeman observations, including upper limits on B_{los}



OH: Mostly 1×10^3 cm^{-3} < n_H < 2×10^4 cm^{-3}

CN: 2×10^5 cm^{-3} < n_H < 4×10^6 cm^{-3}

27 of 68 molecular cores have detected B (i.e., $B_{los} > 2\sigma_B$)

Analysis of Zeeman observations suggests uniform distribution of B_{tot}

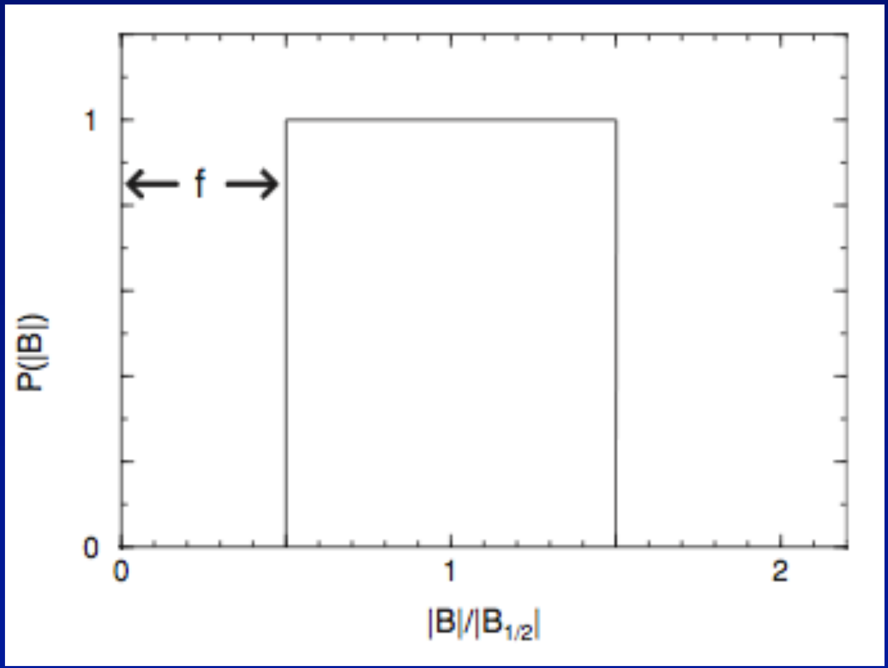
(Crutcher+ 2010)

Use Bayesian analysis to include the majority of points with only upper limits on B_{los}

Results:

For $n_H > 300\ cm^{-3}$ (ie., excluding most HI data), B_{tot} varies as n_H^{α} with $\alpha \approx 0.65$

Median μ_Φ consistent with previous results ($\mu_\Phi \approx$ 2-3)



$B_{tot}/n_H^{0.65}$ uniformly distributed from f $B_{max}/n_H^{0.65}$ to $B_{max}/n_H^{0.65}$ with f ≈ 0.03

Much better fit than delta function distribution for $B_{tot}/n_H^{0.65}$

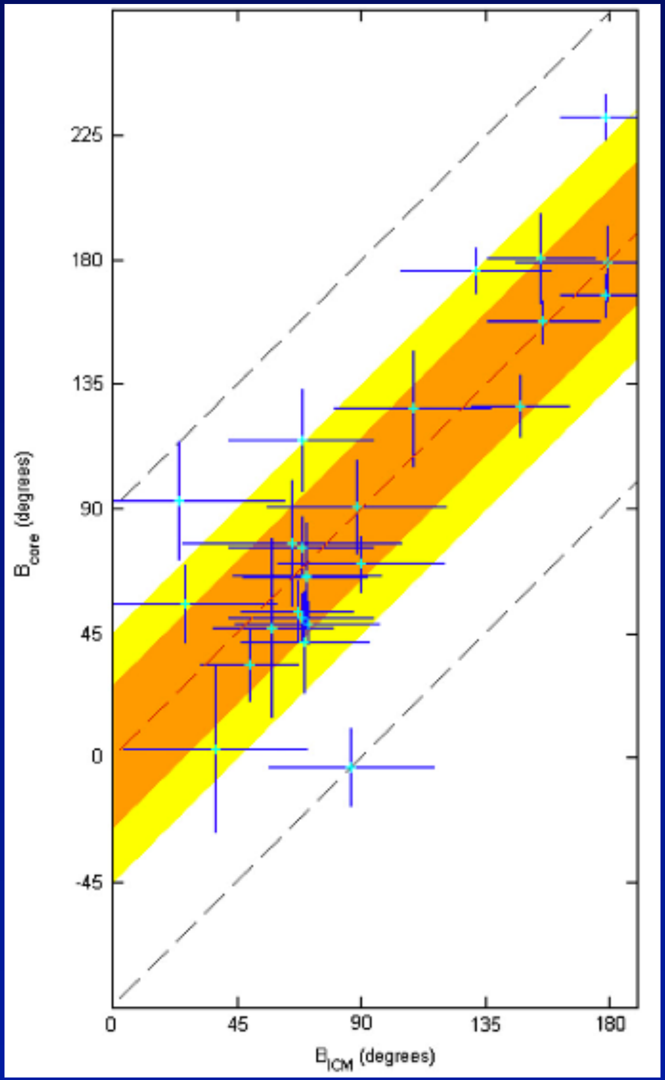
Implies significant fraction of volume of ISM has low magnetic field

Zeeman observations refer to clumps on scales ~ < few pc

What about the field structure on large scales—how is it related to the small scale field?

Magnetic field structure on 200 pc scale in diffuse ISM correlated with that on < 1 pc scale in molecular clouds --- (Hua-Bai Li + 2009)

Orientation of field in molecular cloud cores determined via submillimeter polarimetry (0.1-0.3 pc)



Orientation of field in surrounding intercloud medium on 200 pc scales determined by optical polarization

90% of cores have B within 45 degrees of that in ambient medium => turbulence does not dominate the field

Cores may be magnetically supercritical, but not too much

Conclusions on Observations

Zeeman observations, which measure $\int nB_{los}d\ell$, show molecular gas is magnetically supercritical: gravity dominates

No OH cores, and only one CN core, are subcritical based on the line-of-sight field, B_{los}

Crutcher+ (2010) infer that B_{tot} varies as $n^{0.65}$ in molecular gas

They also infer that $B_{tot}/n^{0.65}$ is uniformly distributed from a very small value to $B_{max}/n^{0.65}$

H.-B. Li+ (2009) find that the orientation of the field on scales less than 1 pc in molecular cores is correlated with that on 200 pc scales in the surrounding ISM => Alfven Mach number is not large

III. Observing Interstellar Magnetic Fields on a Computer

(P-S Li, McKee, & Klein in prep)

Observations:

Zeeman observations give the density-weighted line-of-sight component of the field, $\int nB_{\rm los}d\ell$

Polarization gives direction of B in plane of sky

Chandrasekhar-Fermi method: estimate magnitude of B_{pos} from fluctuations in direction and measurement of turbulent velocities

Numerical simulations give full 3D field

High-Resolution Turbulent Box Simulation

Code: ORION2 ideal MHD with adaptive mesh refinement (AMR) (P-S Li + 12)

Simulation:

- Physics included in simulation: Ideal MHD, self-gravity
- Periodic boundary conditions
- Drive turbulence at large scales (k=1-2) throughout simulation
- Turn on gravity after 1 free-fall time, when turbulent density field established
- Resolution: 512^3 base grid with 2 levels of refinement (max. resolution 2048^3)

Dimensionless parameters:

- Mach numbers: Sonic $\mathcal{M} = 10$, Alfven $\mathcal{M}_{\mathcal{A}} = 1$
- Gravitational energy ~ turbulent energy: $\alpha_{vir} = 5\sigma^2 L/(2GM) = 1$
- Magnetically supercritical: $\mu_\Phi = 1.62$

Setting the Scale

Isothermal MHD simulations are scale free: mass, length, time arbitrary

With self-gravity, one dimensional relation set by G:

$$\alpha_{vir} = 5\sigma^2 L / (2GM) = 1$$

Second dimensional relation set by k_B T :

Assume T = 10 K, the typical temperature in molecular gas

Final dimensional relation set by assuming that the turbulence obeys the relation between the line width and size observed in molecular clouds:

Set $v_{rms} = 0.85\, L_{pc}^{0.5}$ km s^{-1} in the simulation box

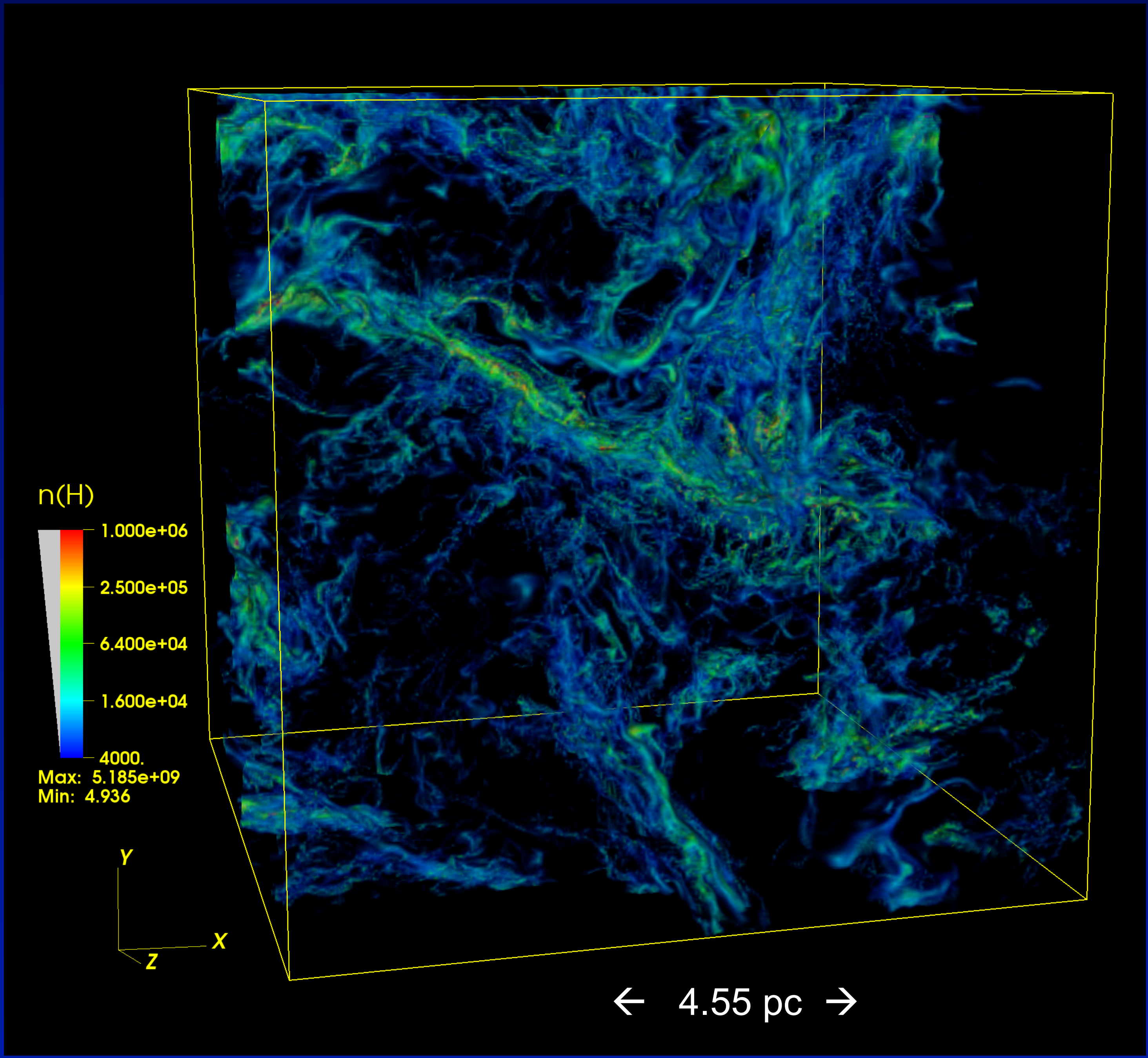
=> $M = 3100\, M_{sun}$, L = 4.55 pc, n = 960 cm^{-3}, B = 32 μG, Δx = 500 AU

Volume Rendering of Density in the Magnetized Turbulent Box

$t=0.5\ t_{ff}$ after gravity on

Mean density: 960 cm^{-3}

Half mass above 5300 cm^{-3}



Sample of Molecular Cloud Cores from Simulation

Analyze data at t=0.57 free-fall times ($t = 8x10^5$ yr) after gravity turned on

16% of mass has density high enough to have formed stars

Find cores with Clumpfind (Williams + 1994)

Merge all cores separated by < 0.06 pc, the smallest separation permitted in the observations

Choose the 100 most massive cores (minimum M is 1.2 M_{sun})

For comparison with observation, consider a central beam with radius 0.3 r, the median value for observed clouds

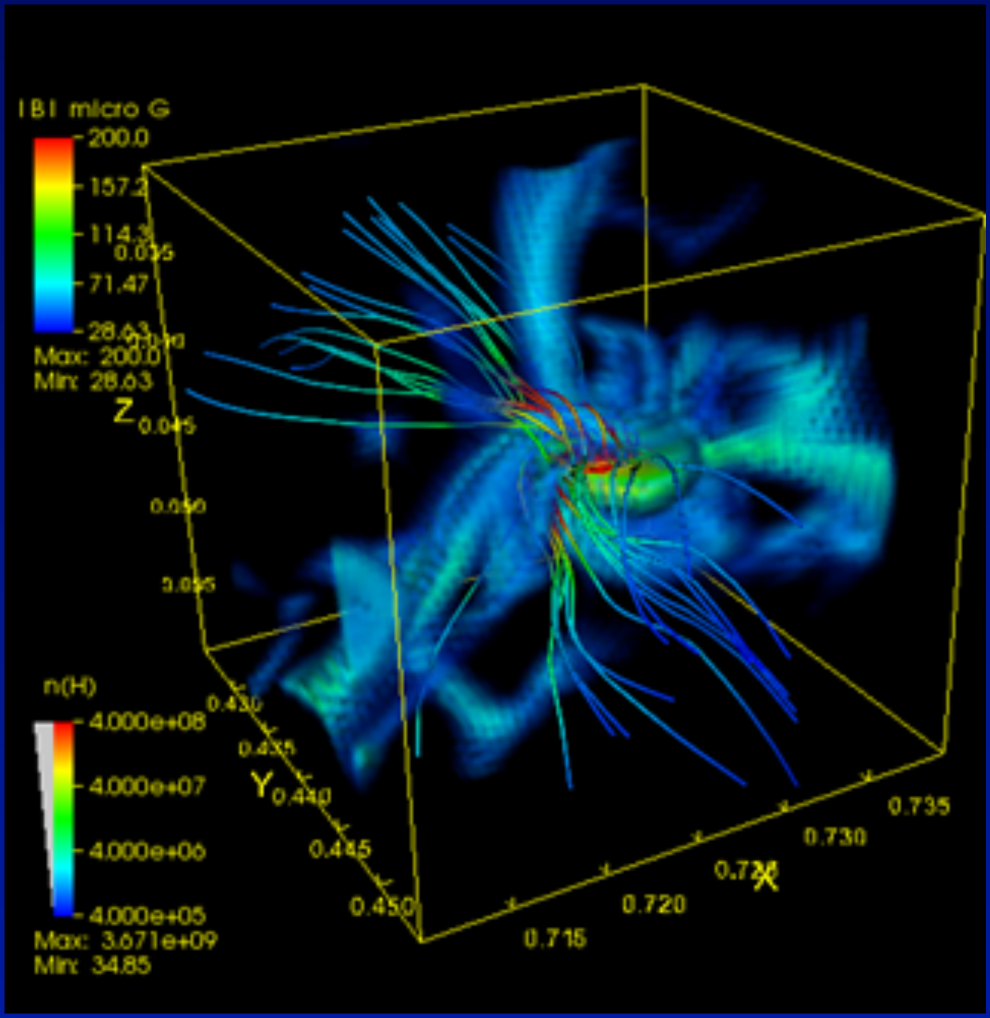
These regions are well resolved, with > 10^4 cells, median 47000 cells

A close-up view of one of the 100 cores

This is a CN core:
$n > 2\times10^{5}$ cm^{-3} ,
$N > 1\times10^{23}$ cm^{-2}

Mass ~11 $M_{\odot}$
radius ~ 0.02 pc

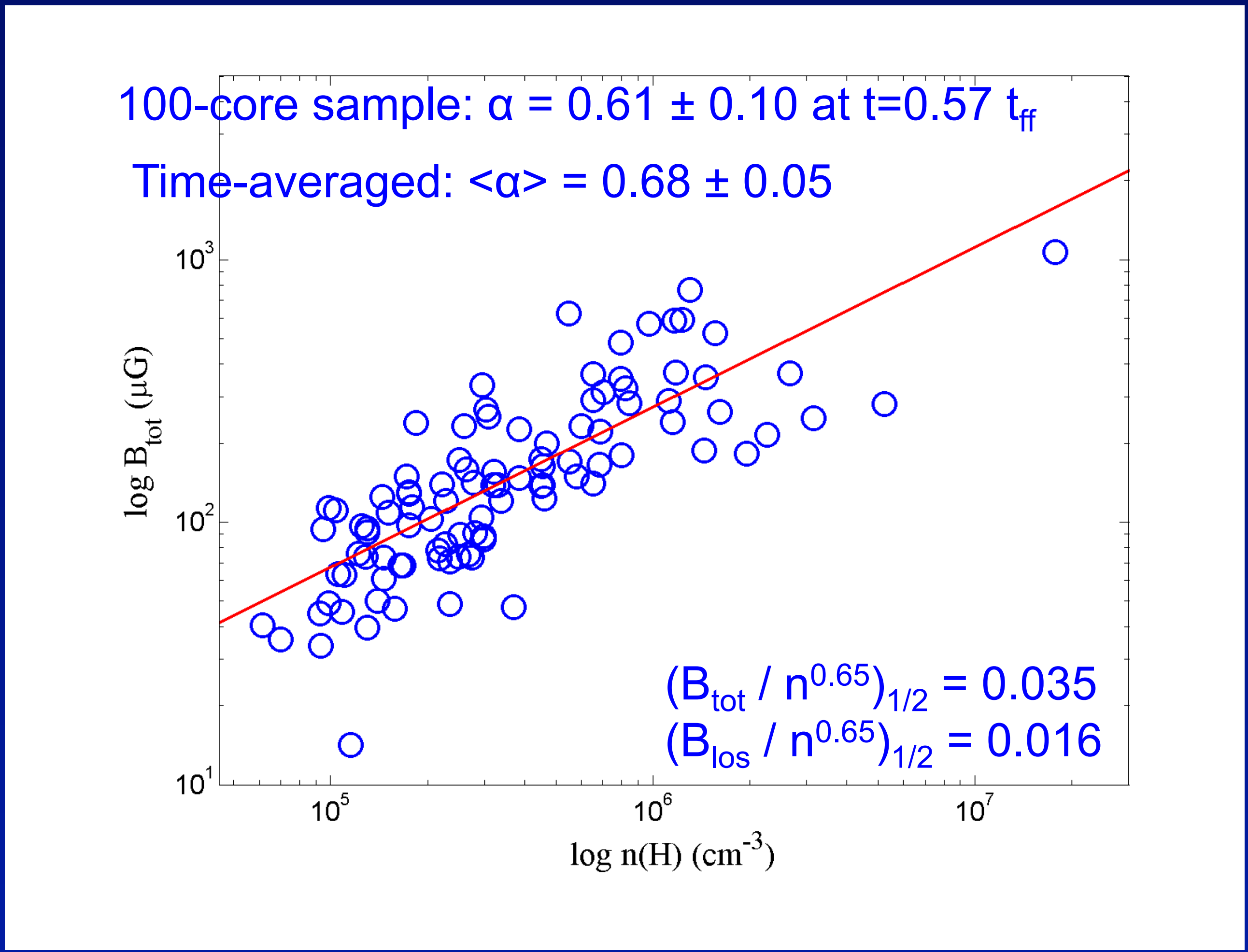
Magnetic field lines through the core. Field lines on the core mid-plane are twisted as the result of core rotation. Maximum B is 725 μG



Density Scaling of Magnetic Field: Agrees with Observation

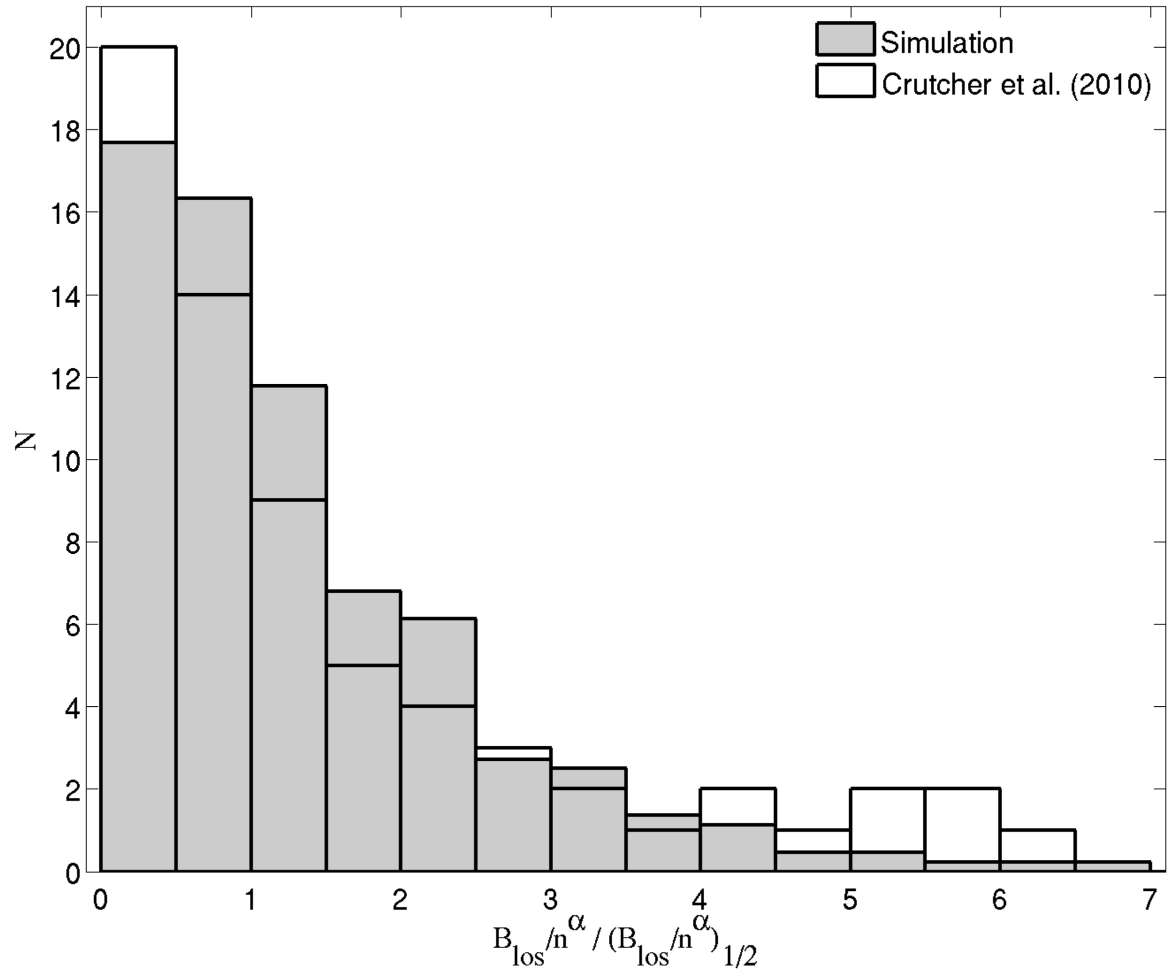
Crutcher + (2010) infer B_{tot} varies as n^{α} with $\alpha = 0.65$

For the 68 OH+CN molecular cores: median, $(B_{los} / n^{0.65})_{1/2} = 0.028$



Median $B_{tot} \approx 2\ B_{los}$ ✓ Simulated $B_{los} / n^{0.65} \approx 0.6$ x observed

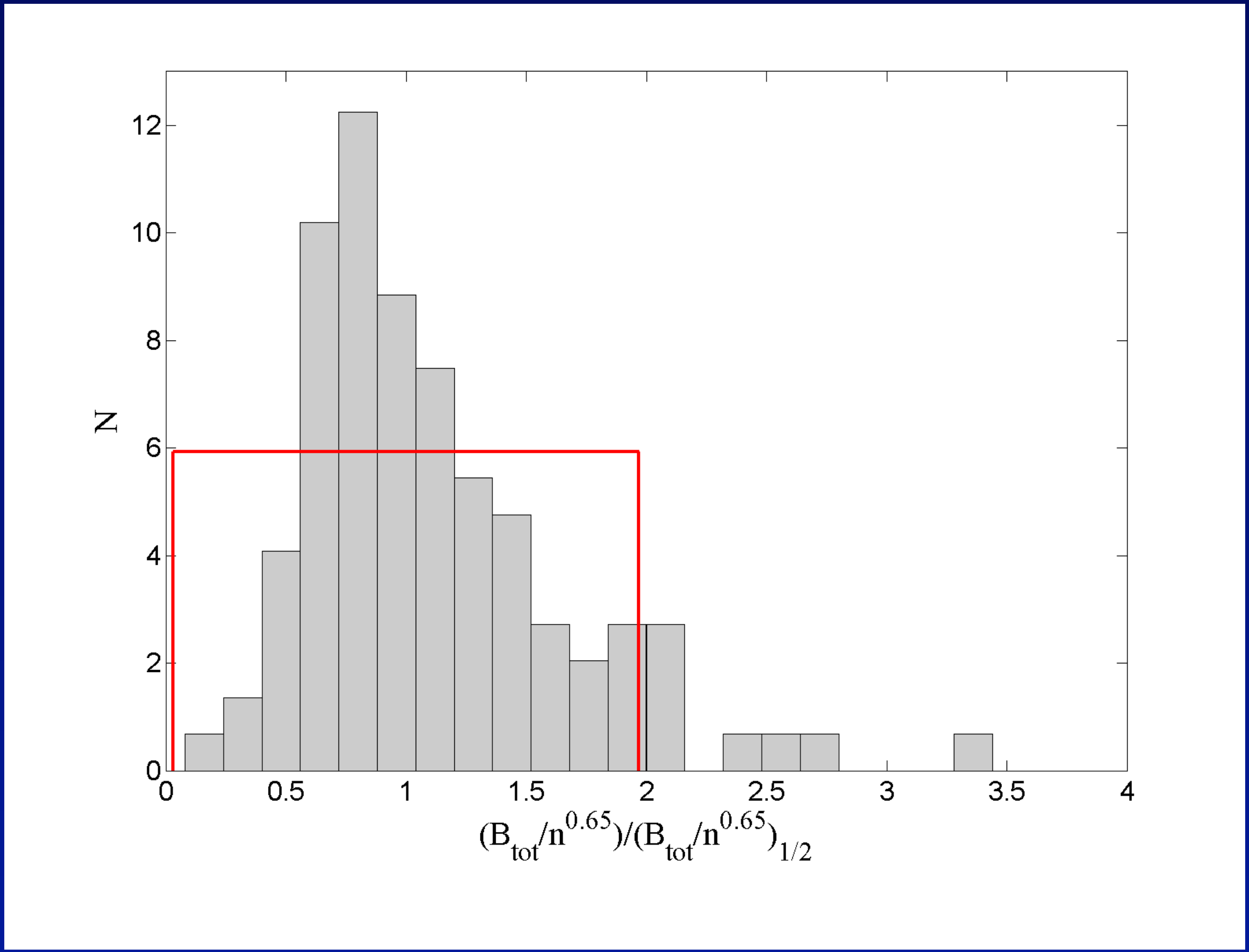
Distribution of Line-of-Sight (LOS) Field Agrees with Observation



The K-S test shows that the simulation is similar to the data (p=0.50)

Remarkable, since data drawn from many clouds with different conditions

Simulated Distribution of B_{tot}, the Density-Weighted Magnetic Field

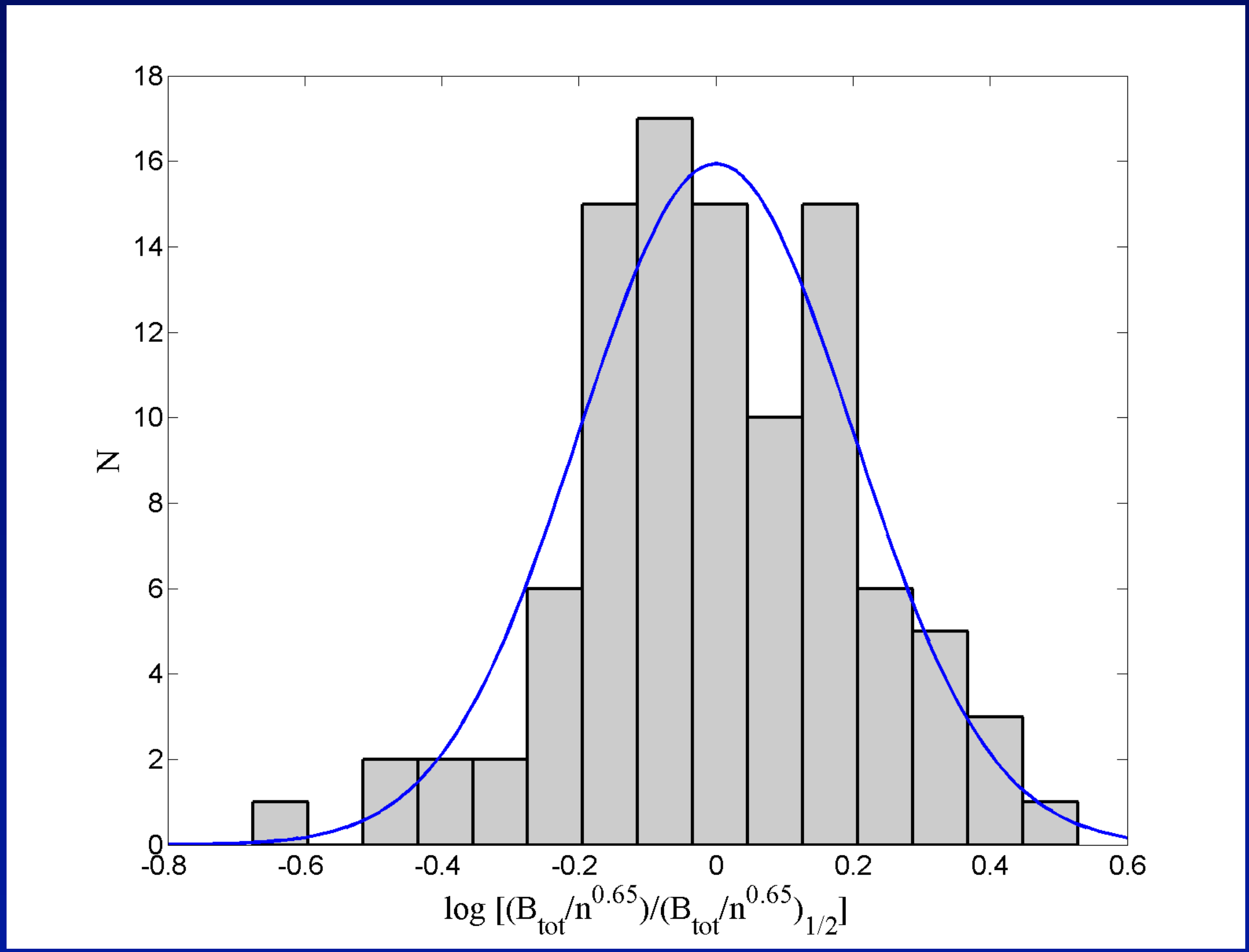


Crutcher + (2010) infer that a uniform distribution from f B_{max} to B_{max} , with f = 0.03 provides a better fit than a delta function. (Recall B_{tot} is not measured.)

We measure B_{tot} and find a non-uniform distribution with f = 0.1

Log-Normal Fit for the Distribution of Simulated B_{tot}

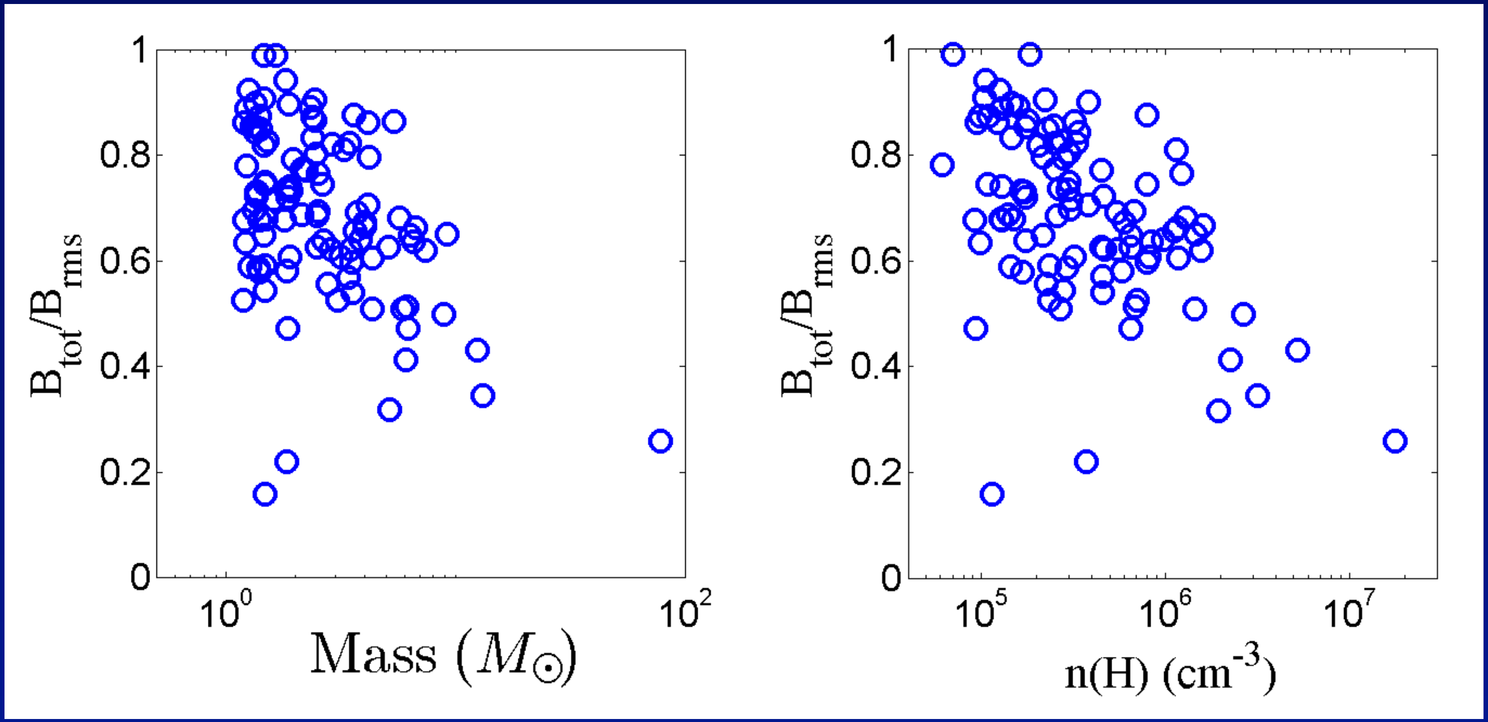
Not a uniform distribution as inferred by Crutcher et al



The dispersion of the log-normal is 0.2, corresponding to a factor 1.66

The K-S test for goodness of fit gives p=0.89

Field-line tangling prevents very low B_{rms} , particularly in more massive and/or denser cores



In 100-core sample:

- Smallest $B_{tot} / n^{0.65} = 0.47\ (B_{los} / n^{0.65})_{1/2}$ (~ 2 times value in Crutcher+ model)
- Smallest $B_{rms} / n^{0.65} = 1.4\ (B_{los} / n^{0.65})_{1/2}$; median $B_{rms} / B_{los} = 2.9$
  - => very small fields inferred from Zeeman obs. are due to tangling along los

What about ambipolar diffusion (AD)?

AD is the dominant non-ideal MHD effect in gas with $n < 10^{10}$ cm^{-3}

AD Reynolds number defined in terms of magnetic diffusivity λ:

$$R_{\mathrm{AD}} \equiv \frac{\ell V}{\lambda} = \frac{4\pi\gamma_{\mathrm{AD}}\rho_i\rho_n\ell V}{B^2}$$

Observed value for cores with measured B (McKee+ 10 based on Crutcher99 data)

$$R_{\mathrm{AD}} = 17 \pm 0.4 \text{ dex}$$

Consistent with theoretical expectation for $M_A \sim 1$, as observed:

$$R_{\mathrm{AD}} \sim 20\, M_A^{\,2} / \alpha_{\mathrm{vir}}^{\,1/2}$$

AD dominant on length scales ~ < L / R_{AD}(L) => important mainly on small scales

Conclusions from Simulation of Magnetized Molecular Cloud

*Excellent agreement with density dependence of B_{tot}: $\langle\alpha\rangle = 0.68$ (sim) vs. 0.65 (obs)

*Very good agreement with observed distribution of $B_{los} / n^{0.65}$

Median values differ by only a factor 1.75

*Median μ_Φ (B_{los}) is 3.4 (sim) vs. 5.2 (Troland & Crutcher 08)

Differences between simulation and observations:

Observations sample clouds with a range of physical conditions; simulation has a single set of initial conditions

Observations smoothed over scale depending on distance to source; simulations smoothed on 0.03 pc scale

Maximum mass in simulation is 74 M_{sun} vs 1400 M_{sun} (OH) and 1700 M_{sun} (CN)

Simulations do not include non-ideal effects like AD

Inferences from Simulation

*Contrary to Crutcher+ 10, we do not find very weak fields:

We find $B_{rms} / n^{\alpha} > 1.4 \, (B_{los} / n^{\alpha})_{1/2}$, $B_{tot} / n^{\alpha} > 0.47 \, (B_{los} / n^{\alpha})_{1/2}$,

whereas they infer $B_{tot} / n^{\alpha} > 0.24 \, (B_{los} / n^{\alpha})_{1/2}$

(coefficient is 0.12 in their model of a uniform distribution)

*Increase in mass to flux ratio beyond ideal MHD limit

Flux freezing implies that μ_{Φ} can decrease as matter fragments along a flux tube, but it can never increase on a flux tube.

We find that 55% of the cores have $\mu_{\Phi}(B_{tot})$ > initial value for the entire box (1.62), with a maximum of $\mu_{\Phi} = 13$ (measured in central 0.3 r).

IV. The Protostellar Accretion Disk Crisis

Earliest stage of protostellar evolution: Class 0 sources are heavily obscured (undetectable at $\lambda < 10\ \mu m$ in the 1990's) with envelope mass > mass of protostar

Class 0 protostars have accretion disks

Observations of low-mass protostars (<2.5 M_{sun}) with the Submillimeter Array at 2 arcsec resolution

Source	M_{env}[a] $[M_\odot]$	M_{disk}[b] $[M_\odot]$	M_{star}[c] $[M_\odot]$
Class 0			
L1448-mm	0.96	0.044	...
IRAS2A	1.0	0.056	...
IRAS4A1	4.5[d]	0.46	...
IRAS4A2	–[d]	0.25	...
IRAS4B	2.9[d]	0.24	...
IRAS4B′	–[d]	0.089	...
L1527	0.56	0.029	...
L483	0.82	0.0[e]	...
B335	0.93	0.017	...
L1157	0.94	0.12	...

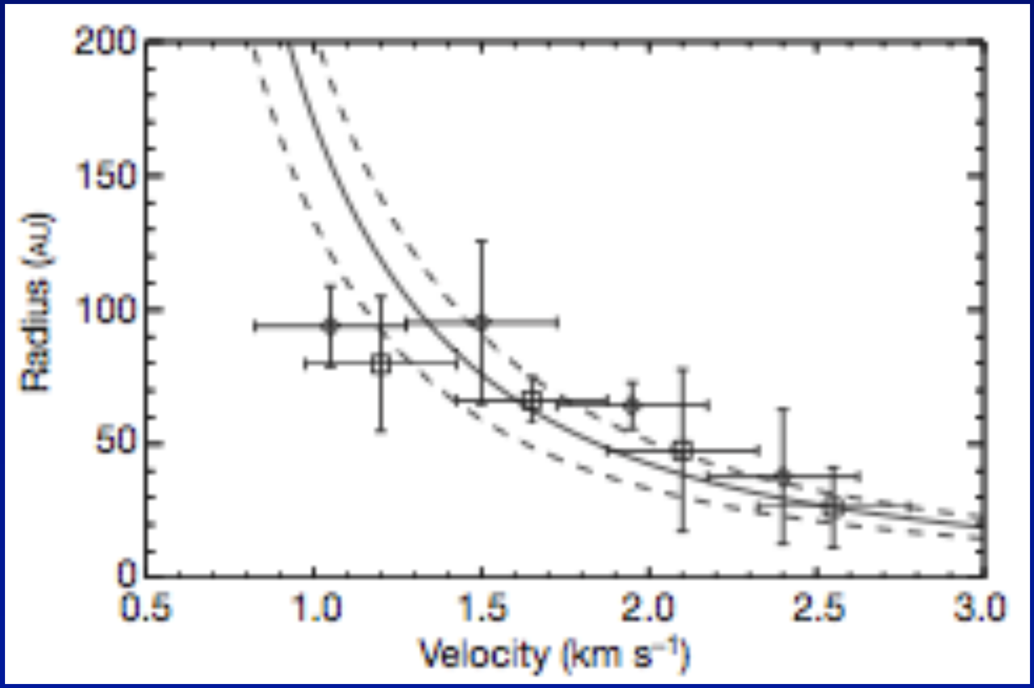
(Jorgensen+ 09)

Evidence for a Keplerian disk in a Class 0 Protostar

(Tobin+ 2012)

CARMA observations of L1527 IRS: 1” resolution (140 AU)

Sub-pixel imaging: Positional accuracy of line emission = 140 AU / (signal/noise = 5) ~ 30 AU



Class 0 since $M_* = 0.2\ M_{sun}$ < Envelope mass = $1\ M_{sun}$

Disk mass = $0.007\ M_{sun}$, radius = 90 AU

Magnetic Braking Can Reduce or Eliminate Disk Rotation: The Protostellar Accretion Disk Crisis

Theory:

Magnetic braking time / free-fall time varies as μ_Φ

Suggests Keplerian disks can form for sufficiently large μ_Φ

(Mestel & Paris 1984)

Simulation leads to a crisis:

2D ideal MHD, non-turbulent simulations show disk formation requires $\mu_\Phi > 10$, significantly greater than observed (Allen, Li & Shu 2003)

2D & 3D non-ideal MHD simulations, including ambipolar diffusion, Hall conductivity, and Ohmic dissipation, confirm this result

(Mellon & Z-Y Li 2009, Z-Y Li+ 2011, Krasnopolsky+ 12)

Proposed Mechanisms for Forming Rotating Protostellar Accretion Disks - I

1. Misalignment of angular momentum and magnetic field (Hennebelle & Ciardi 09)

Misalignment observed on scales ~ 1000 AU (Hull+ 13)

Expected in turbulent media

Rotating disks form for $\mu_\Phi > 3$ for 90 degree misalignment,
for $\mu_\Phi > 4$-5 for 10-20 degree misalignment

Allowing for weak fields inferred by Crutcher+ (2010), 10-50% of cores should produce Keplerian disks (Krumholz+ 13)

2. Late formation of disk (Mellon & Li 09, Machida+ 11)

Once most of the gas in the core has accreted, there is little mass left to absorb the angular momentum of infalling gas, so disk can form

Problems: Omits effect of gas outside the core

Does not explain disks in Class 0 sources

Proposed Mechanisms for Forming Rotating Protostellar Accretion Disks - II

3. Turbulence (ideal MHD)

Santos-Lima+ 12: Toy model of rapidly rotating gas around 0.5 M_{sun} star with Mach 4 turbulence imposed on scale of 1600 AU; low resolution

In contrast to non-turbulent case, find Keplerian disk (~100 AU) and considerable loss of magnetic flux in inner regions.

Seifried+ 12: Gravitational collapse of 100 M_{sun} core with strong initial rotation (~6 x observed), weak turbulence (~0.1 x observed) and $\mu_{\Phi} = 2.6$

High resolution AMR simulation (1.2 AU)

Keplerian disks form with radii 30-100 AU

Results confirmed with wider range of initial conditions (Seifried+ 13)

No simulation without turbulence and with J || B has produced an observable Class 0 accretion disk; all well-resolved simulations with turbulence have

Simulation of Collapse of a Massive, Magnetized Core

(A. Myers, McKee, Cunningham, Klein & Krumholz 13)

Initial Conditions:

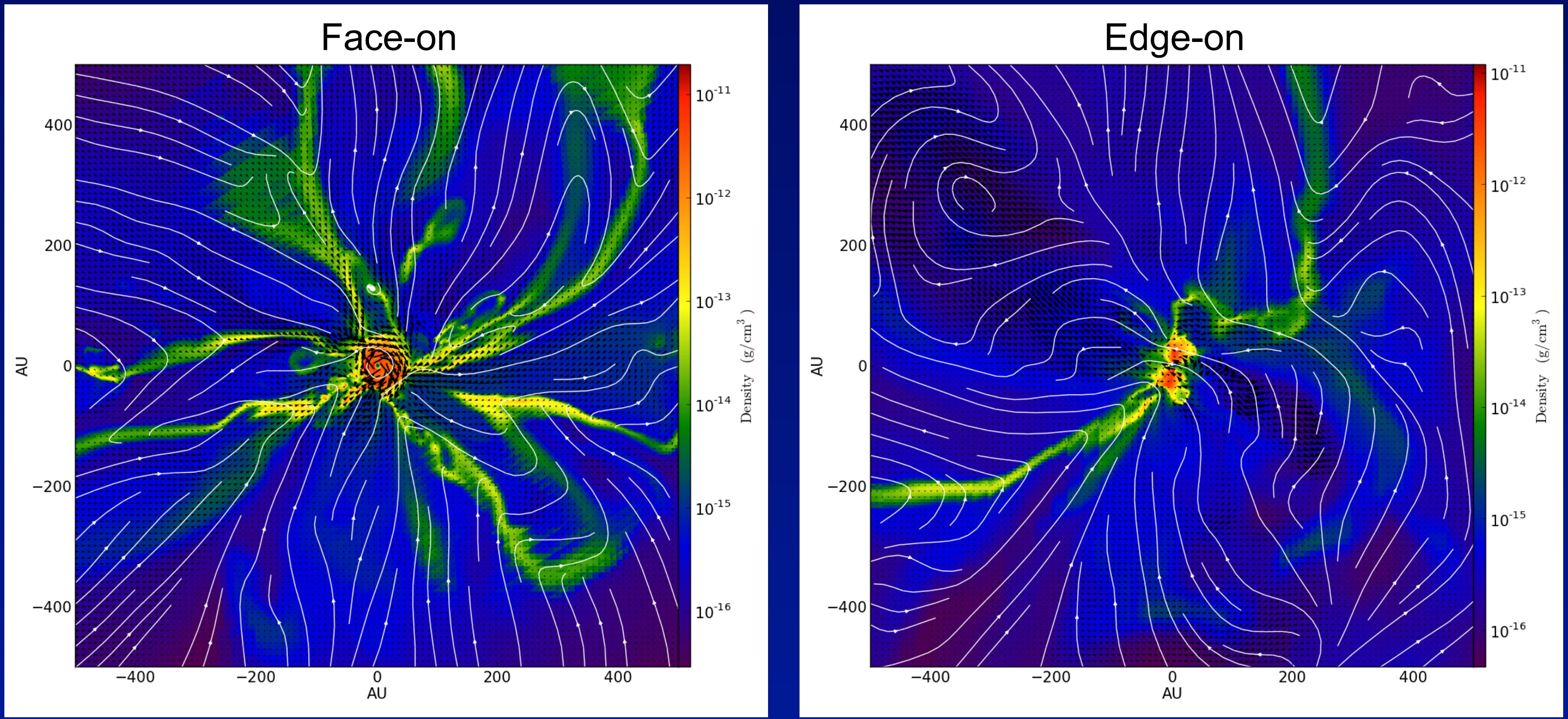
Mach 15 turbulence, no imposed rotation
M_{core} = 300 M_{sun}
R_{core} = 0.1 pc
μ_Φ = 2 for initial core (=5.6 on central flux tube)
α_{vir} = 2.5
ρ varies as $r^{-1.5}$
$\beta_{rot} \approx 0.01$ (rotation that would be inferred by an observer; ~ 0.5 x typical)
Resolution: Standard (10 AU) and high (1.25 AU)

The level of turbulence imposed is much greater than in previous simulations, and is comparable to the observed level in high-mass star-forming regions.

Turbulent velocity field imposed on initially spherical core

Formation of a Keplerian disk in the high resolution simulation

High resolution (1.25 AU) simulation run to 0.2 free-fall times (6000 yr)

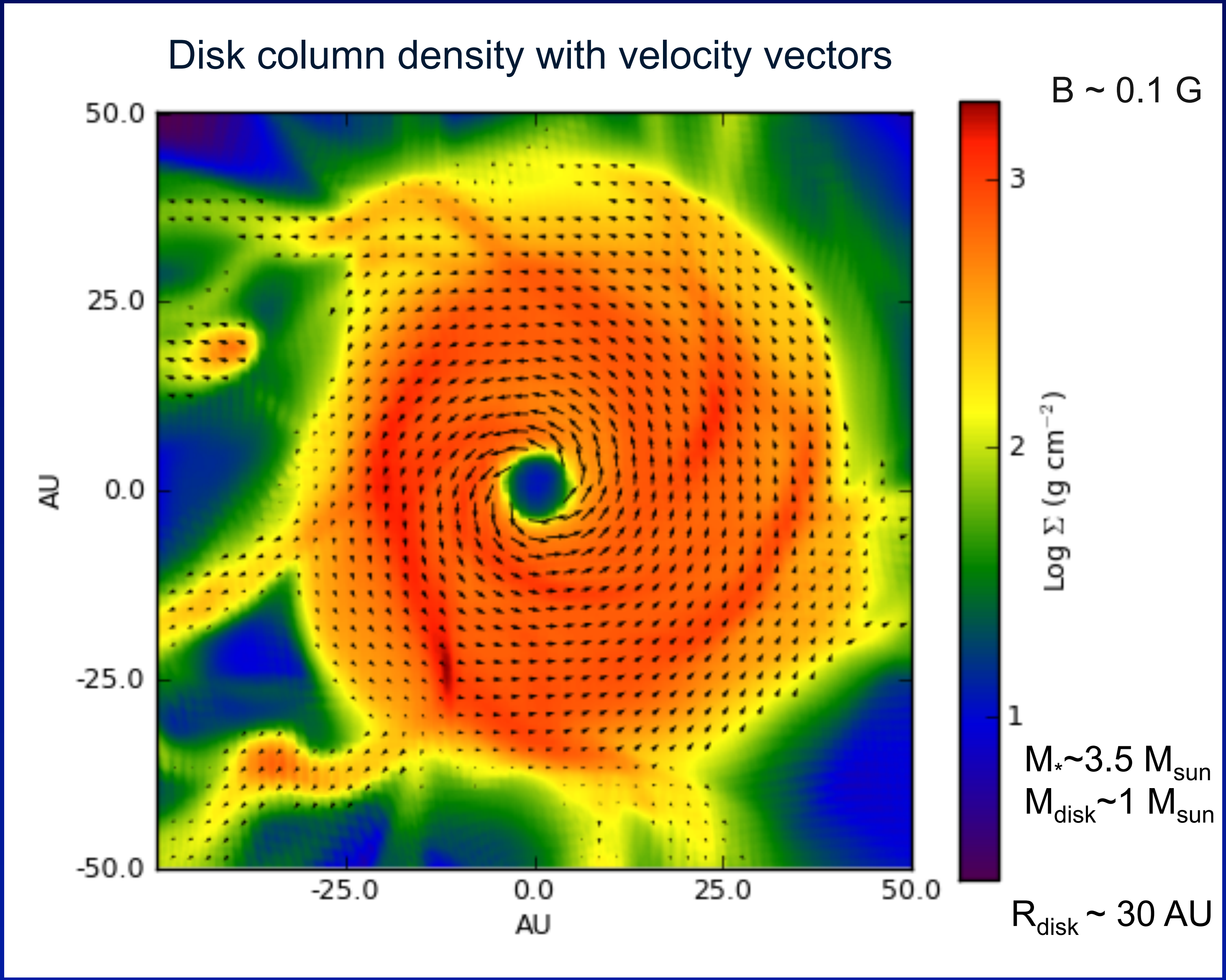


Density (color) and magnetic field (white lines) in planes perpendicular to and parallel to angular momentum of gas within 100 AU of star

Bipolar outflow normal to disk with v ~ Keplerian velocity, consistent with obs.

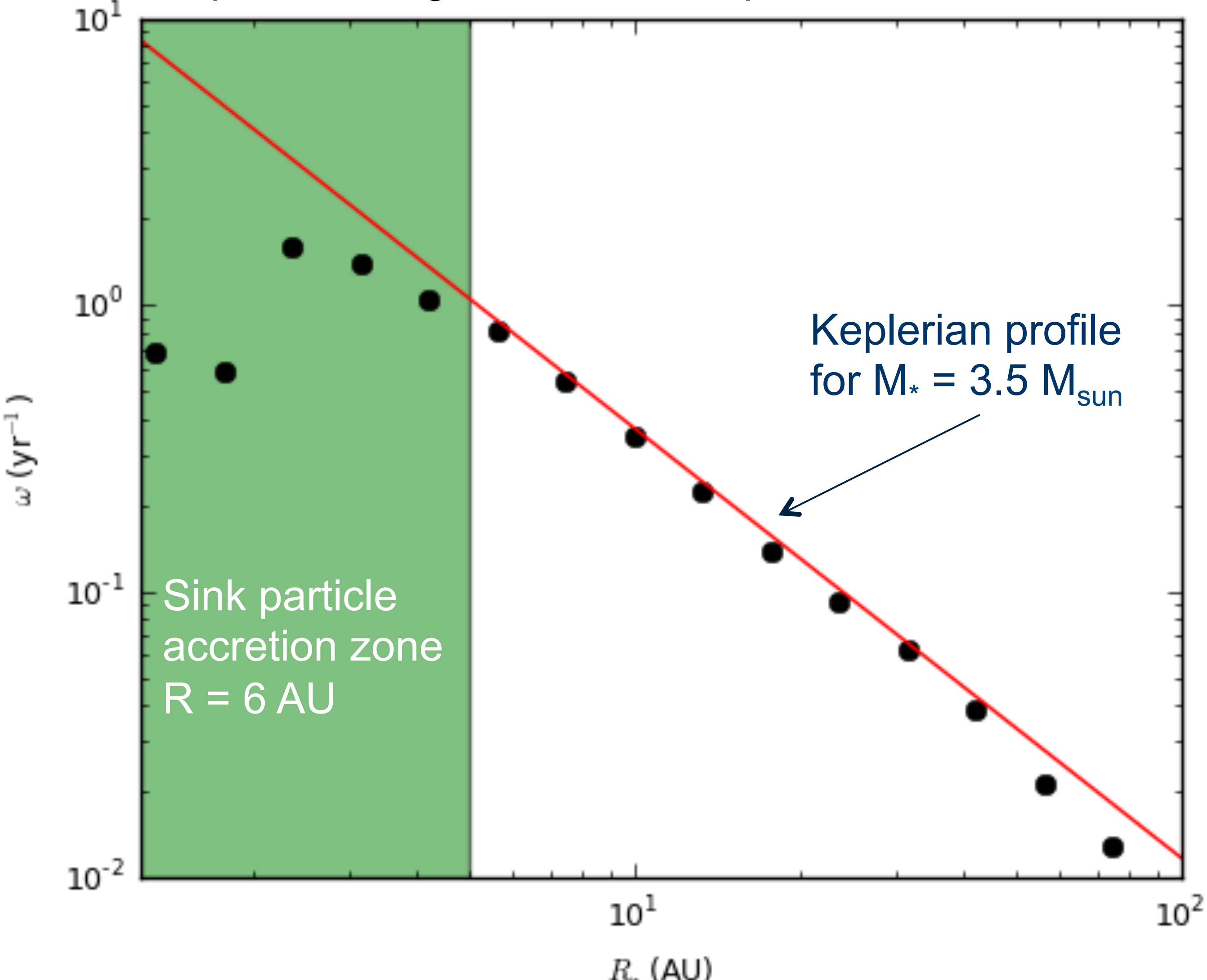
Disk forms in central regions

Central protostellar accretion disk at t = 6000 yr

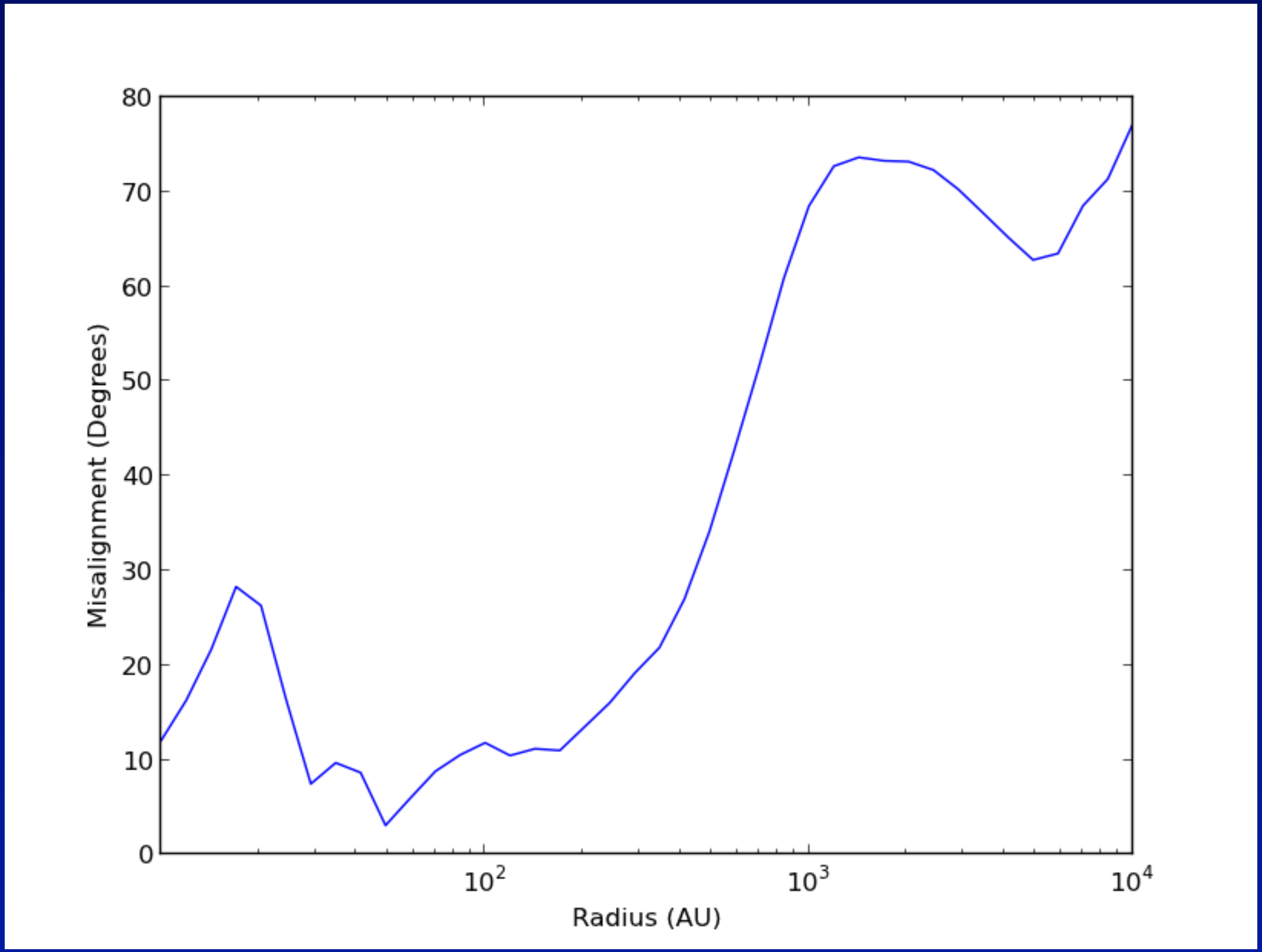


Central mass-to-flux ratio μ_Φ increased from 5.6 to 20, consistent with disk formation

Despite the magnetic field, a Keplerian disk has formed



Field and angular momentum are aligned on small scales, misaligned on large scales (prediction for ALMA)



Misalignment could contribute to disk formation (Hennebelle + Ciardi 09)

V. What Accounts for the Violations of Flux Freezing?

Turbulent box simulation of a magnetized molecular cloud

Ideal MHD: Fragmentation can reduce mass to flux on a flux tube, but no process can increase it

But simulated cores have μ_Φ (B_{tot}) up to 13;   55% are above the initial value for the entire simulation box (4.55 pc)

Formation of Keplerian circumstellar disk from turbulent, magnetized core

Large increase in μ_Φ on central flux tube (5.6 -> 20) at high resolution

Two possibilities:

Numerical resistivity—verified convergence to 0.37 t_{ff}

Turbulent reconnection, leading to “reconnection diffusion” (Lazarian 05; Santos-Lima+10; Lazarian+12)

Role of magnetic reconnection in removing magnetic flux

Possible role of reconnection in removing magnetic flux from collapsing clouds recognized ~ 50 yr ago (Strittmatter 1966)

Note that reconnection moves flux, but does not destroy it

Reconnection occurs at a point in a 2D slice, and is often inefficient

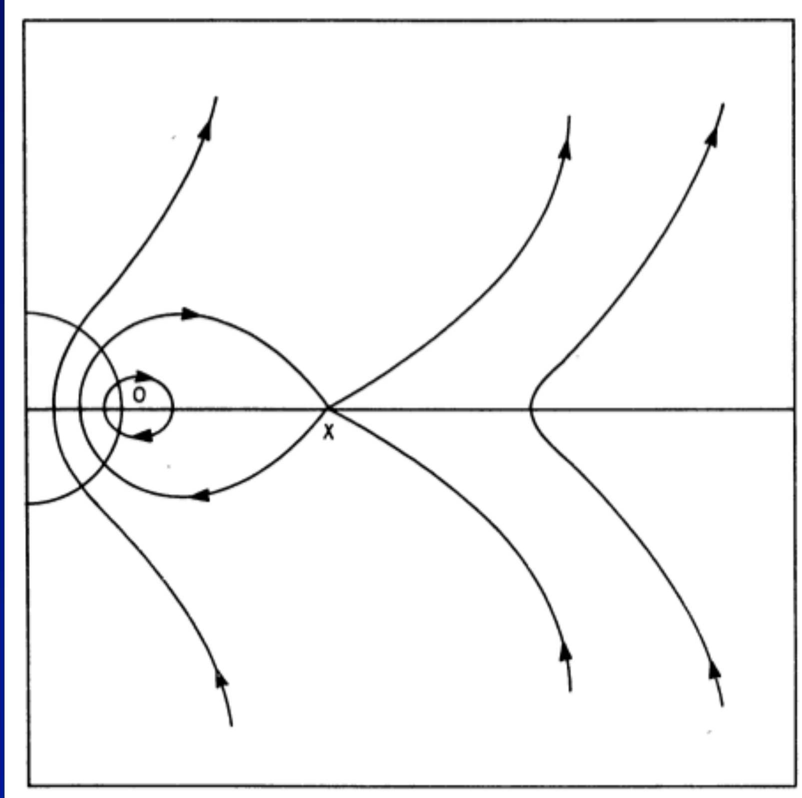


FIG. 2. *Formation of O and X-type neutral points.*

(Strittmatter 1966)

Turbulent Reconnection

In a turbulent medium, fluctuations in the magnetic field cascade down to small scales (Goldreich & Sridhar 1995), permitting reconnection throughout the volume of the turbulent medium (Lazarian & Vishniac 1999)

Reconnection in a turbulent medium leads to diffusion of matter relative to field, termed “reconnection diffusion” by Lazarian+

Since reconnection diffusion is based on a turbulent cascade, the mechanism for resistivity is not crucial, so it is automatically included in numerical simulations, which have numerical resistivity.

Effect of AD on turbulent reconnection unclear

Numerical tests underway to confirm that conclusions are independent of numerical resistivity. Future work will include AD

Ideal MHD is not ideal in a turbulent medium

Conclusions: Two Classical Problems in Star Formation

1. The magnetic flux problem:

How can the mass to flux ratio increase so that $M > M_\Phi \sim \Phi / (2\pi G^{1/2})$, allowing gravitational collapse to occur? (Mestel & Spitzer 1956, MS56)

Observation confirms that HI clouds are magnetically subcritical, as conjectured by MS56, but that molecular cloud cores are supercritical.

Giant Molecular Clouds (GMCs) are supercritical since they have column densities satisfying the MS56 criterion to overcome the interstellar field

While cloud cores can form by flows along field lines, it is difficult to see how a core can accumulate all the mass along a flux tube in a GMC, which could be ~100 pc long (similar to MS56 problem)

Our simulations show that the mass to flux in a turbulent medium increases more than expected in ideal MHD, possibly due to reconnection diffusion, and this can contribute to resolving the magnetic flux problem. Ambipolar diffusion may not be essential.

Observation by computer: Simulation in good agreement with B observed along the line of sight, but we can determine the 3D magnetic field

Conclusions: Two Classical Problems in Star Formation

2. The angular momentum problem

How can interstellar gas lose the 99% of its angular momentum required to form a star? (Mestel 1965, Spitzer 1968)

Magnetic torques can solve the angular momentum problem (Spitzer 1968)

True, as shown by many theoretical calculations and simulations

But, can be so strong that they prevent disk formation (MS56), thereby predicting

the protostellar accretion disk crisis

long before protostellar accretion disks were discovered

Santos-Lima+, Seifried+, and we (Myers+) find that simulations including turbulence lead to formation of observable disks

Reconnection diffusion (Lazarian+) is a plausible, but unproven, explanation

Ideal MHD is not ideal in a turbulent medium