Role of Magnetic Fields in Molecular Clouds: Testing Ambipolar Diffusion versus Turbulence Driven Star Formation Theory

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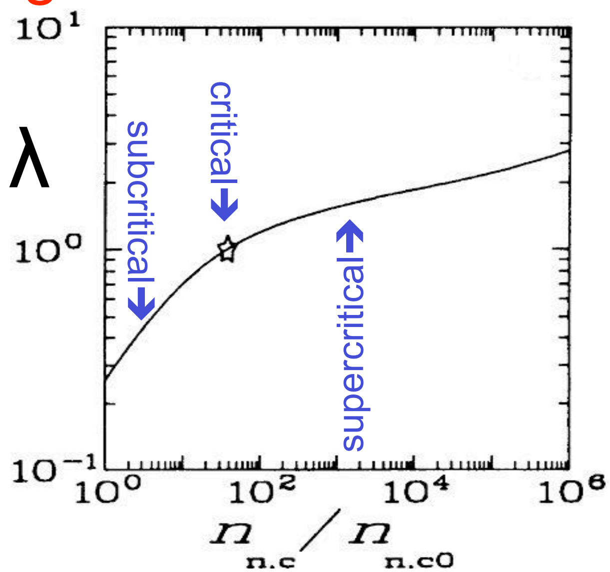
Measuring Theoretically Relevant Quantities

1) M/Φ: ratio of gravity to magnetic fields

$$\frac{M_{observed}}{\Phi_{observed}} \propto \frac{N(H_2)}{B}$$

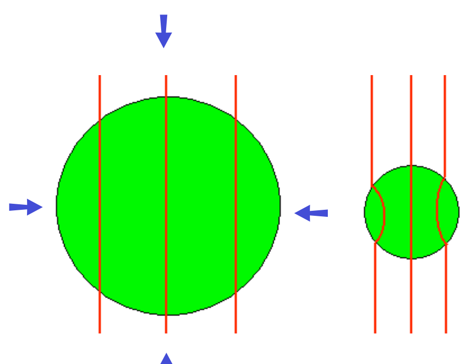
$$\lambda \equiv \frac{(M/\Phi)_{observed}}{(M/\Phi)_{critical}}$$

$$(M/\Phi)_{critical} = 1/2\pi\sqrt{G}$$

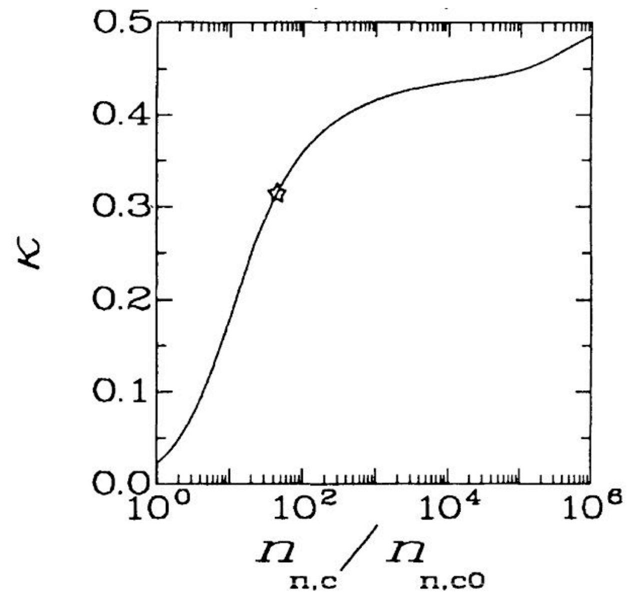


Ciolek & Mouschovias 1994

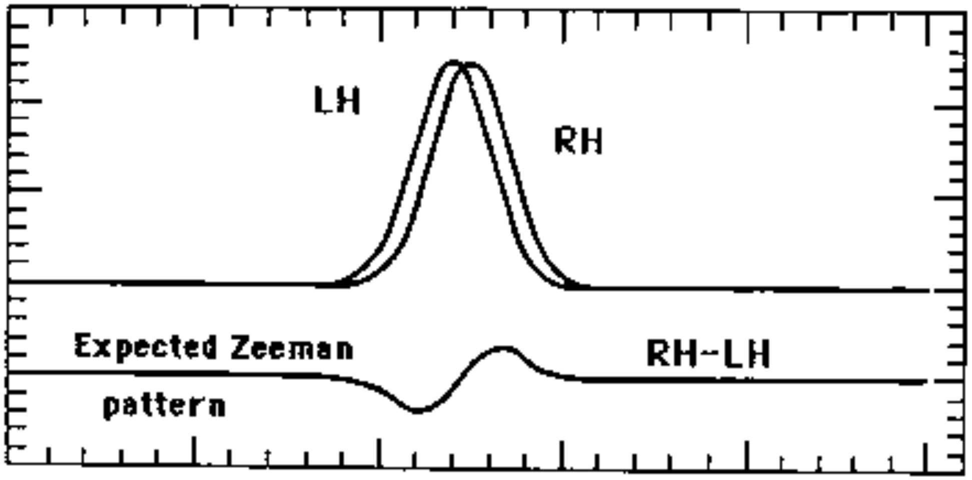
2) Scaling of B: B ∝ ρ$^{\kappa}$



$$B \propto \rho^{2/3}$$



Zeeman Effect



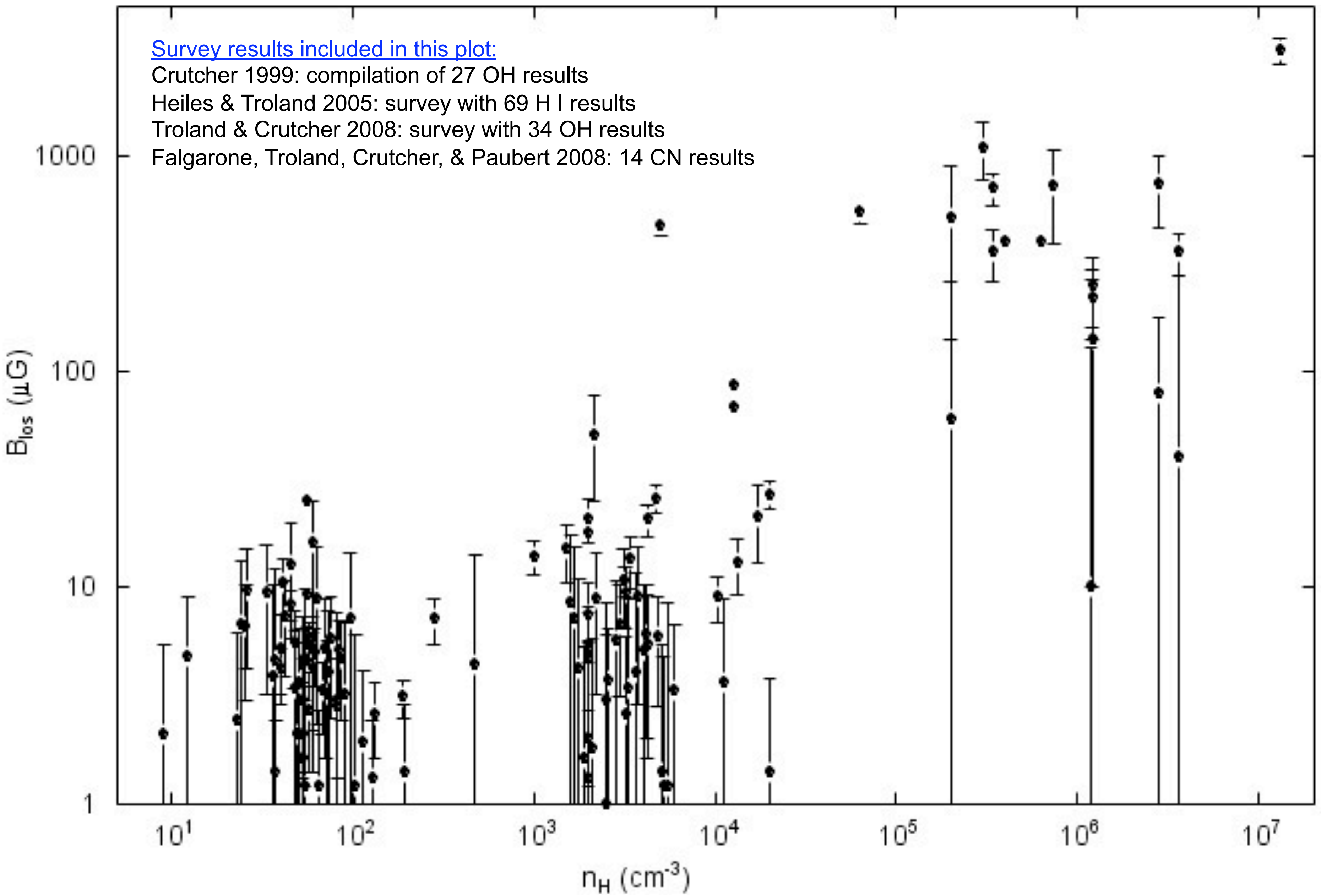
Pieter Zeeman
(1865 – 1943)

$$V = L - R \propto (dI / dv)(\Delta v_Z \cos\theta) \quad \Rightarrow \quad line\ of\ sight\ B$$

$$\Delta v_Z \propto Z\ B$$

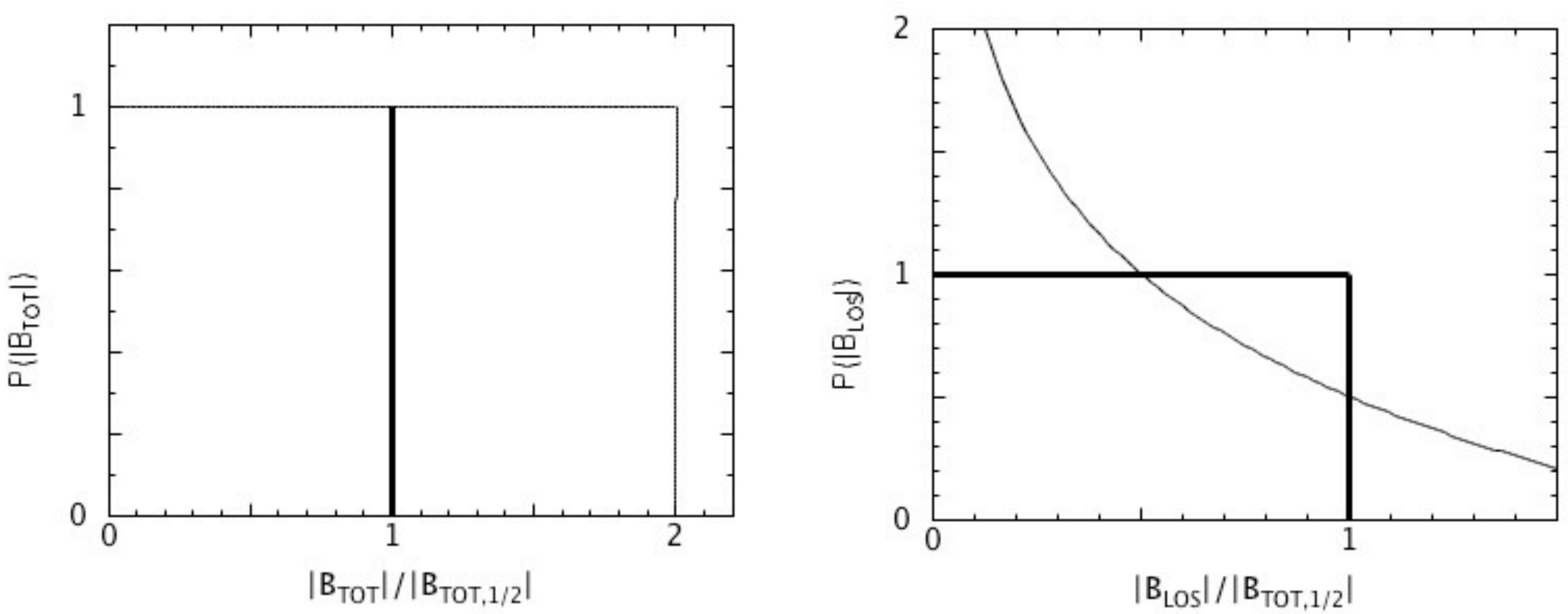
Species	Wavelength	n(H) traced
H I	21-cm	$10 - 10^3$ cm^{-3}
OH	18-cm	$10^3 - 10^4$ cm^{-3}
CN	3 mm	$10^5 - 10^6$ cm^{-3}

Results for Field Strength



What to do about measuring B_{los}, not B_{tot}?

PDFs of total B and corresponding los B



For reasonable pdf, mean or median of B_{los} ≈ ½ mean or median of B_{total}

Heiles & Crutcher 2005

Bayesian Analysis

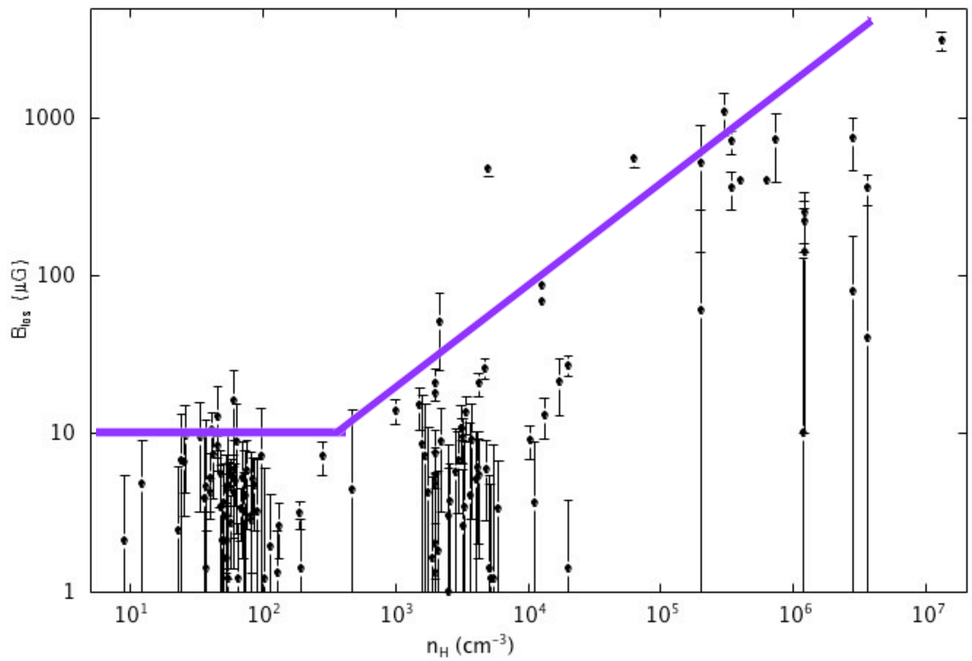
Priors (data): $B_{los} \pm \sigma_{B_{los}}$ & $(n_H)^{+2n_H}_{-0.5n_H}$

The model:

$$B_{tot} = B_0, \quad n < n_0$$

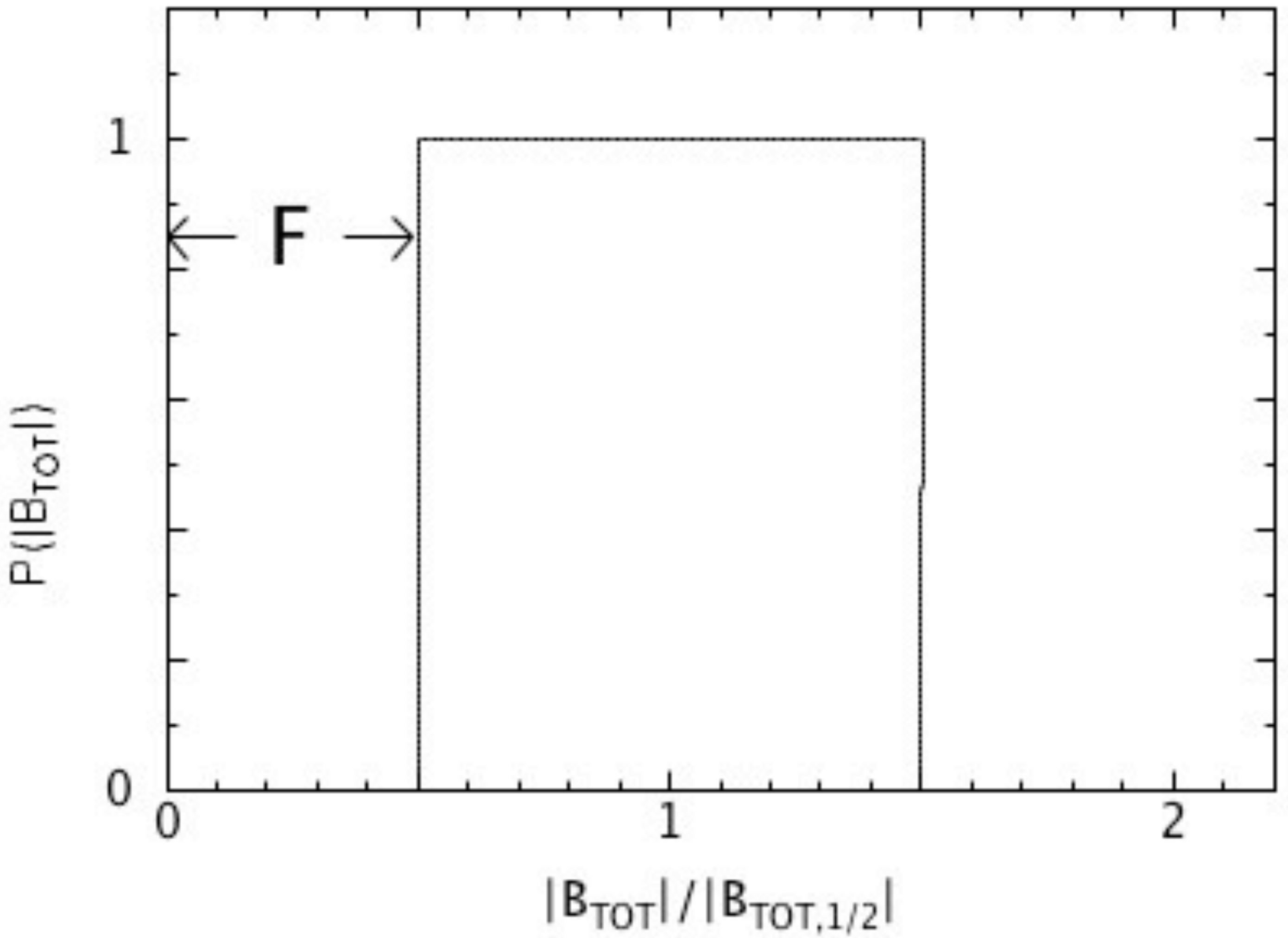
$$B_{tot} = B_0\, n^{\kappa}, \quad n > n_0$$

$$F B_{\max} < B_{tot} < B_{\max}$$



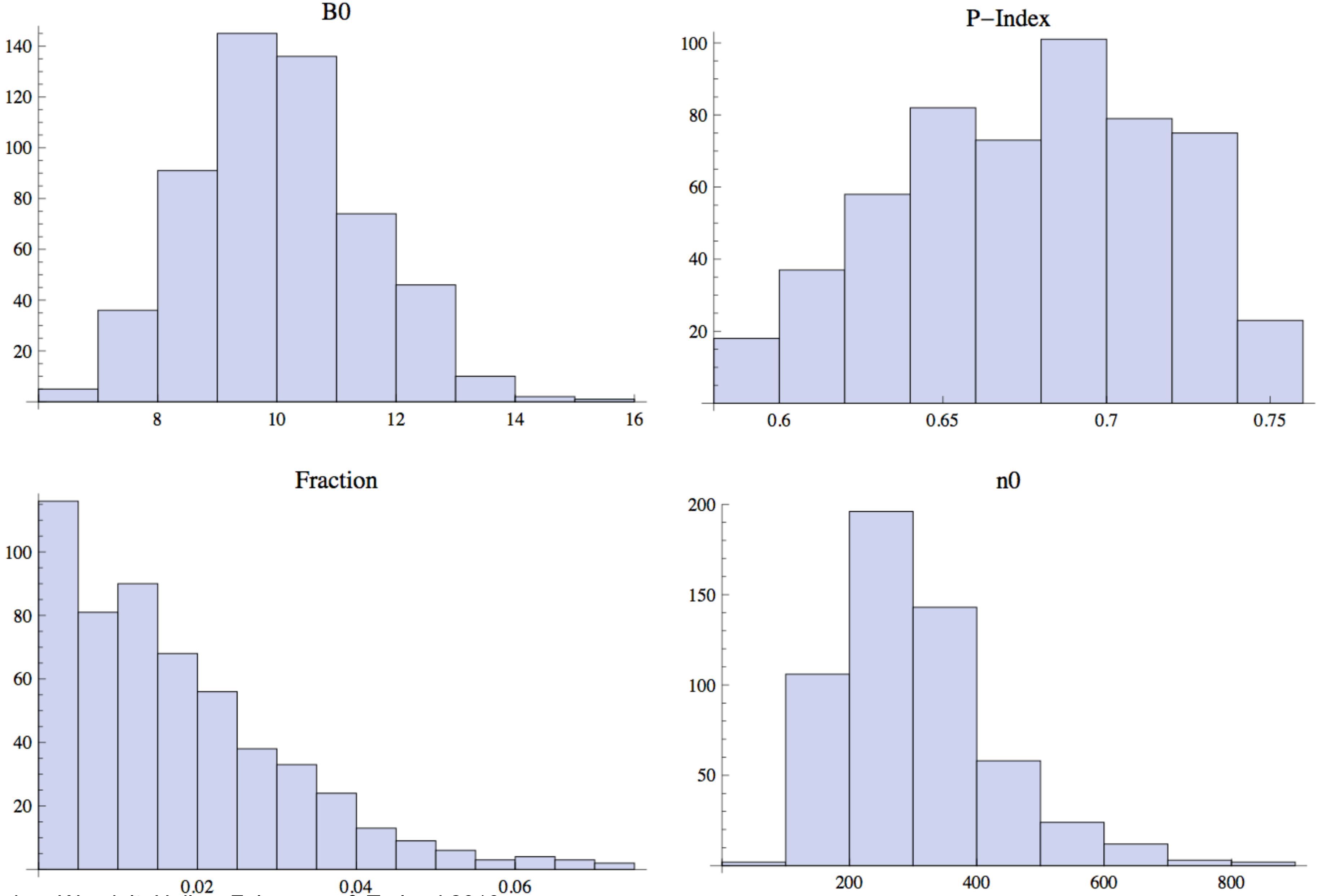
Crutcher, Wandelt, Heiles, Falgarone, & Troland 2010

Assumed Parameterization of PDF



Crutcher, Wandelt, Heiles, Falgarone, & Troland 2010

Results of Bayesian Analysis



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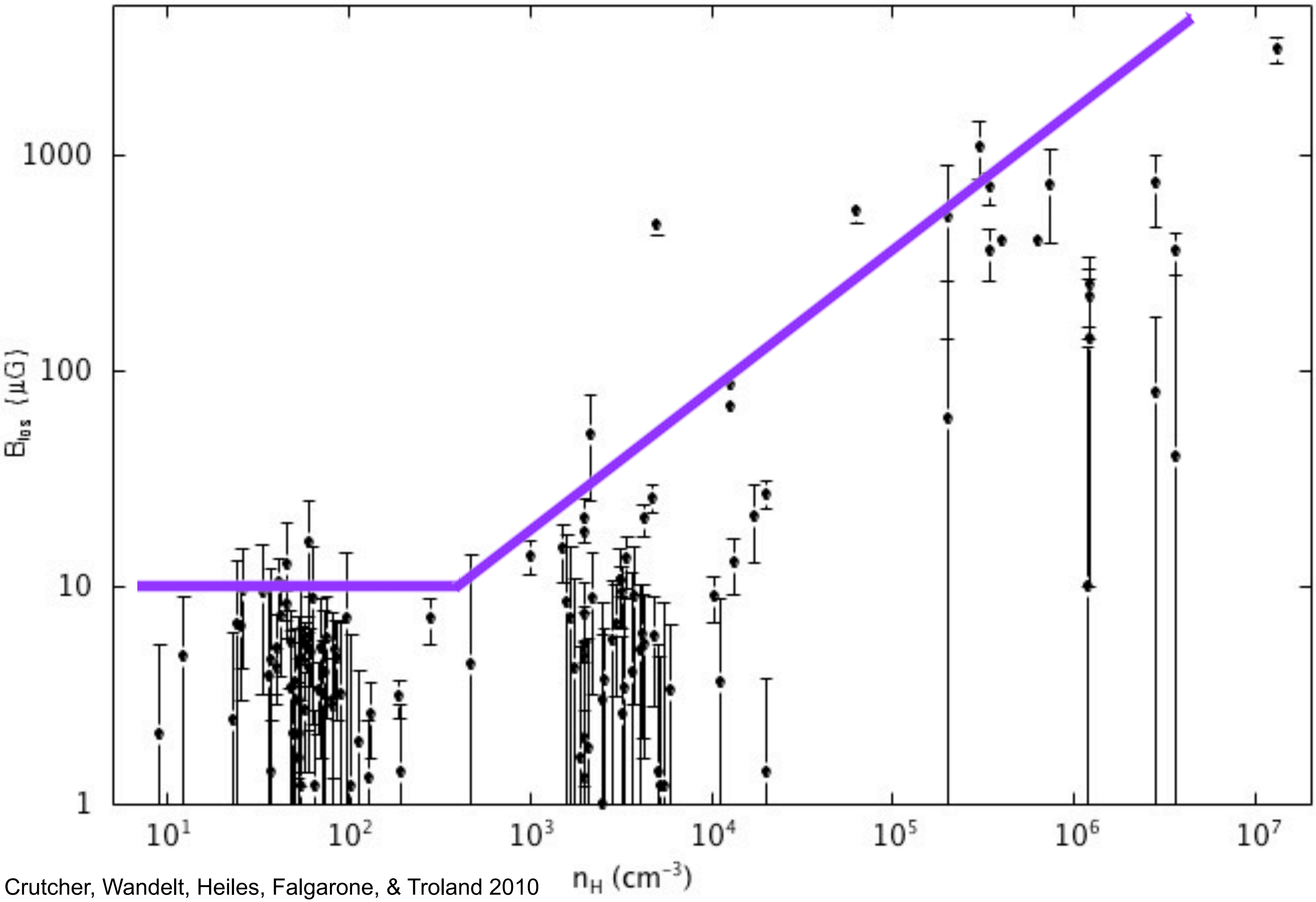
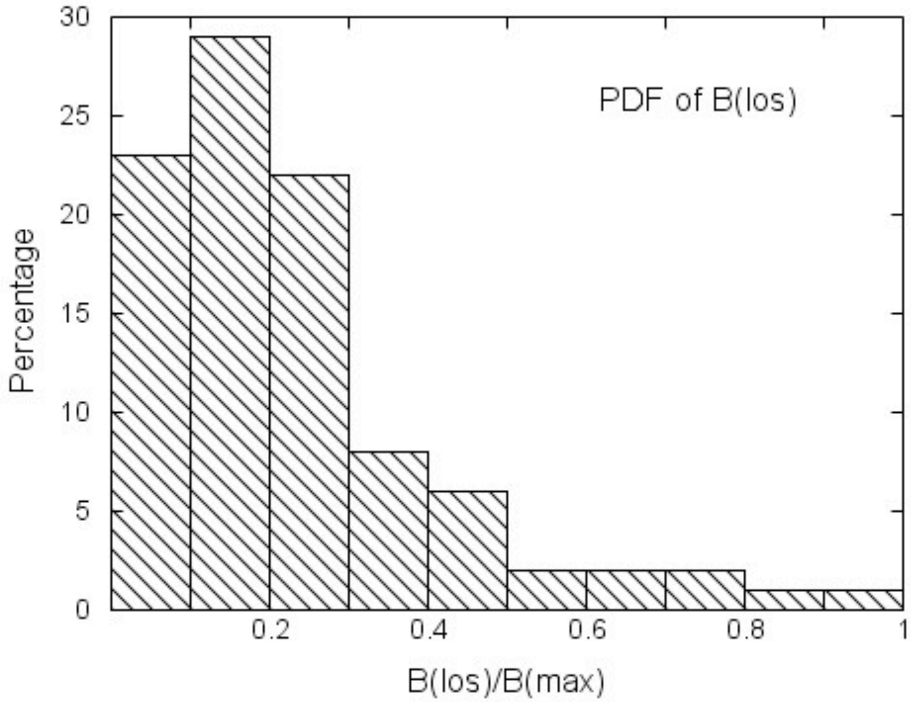
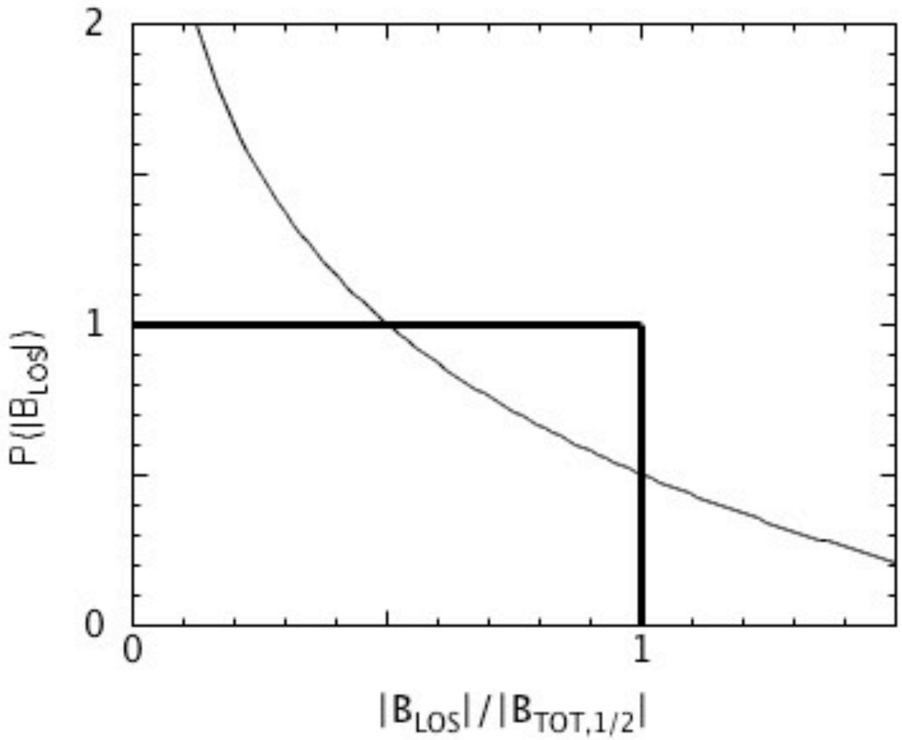
Results of Bayesian Analysis



Crutcher, Wandelt, Heiles, Falgarone, & Troland 2010

Observed PDF of B_{los}

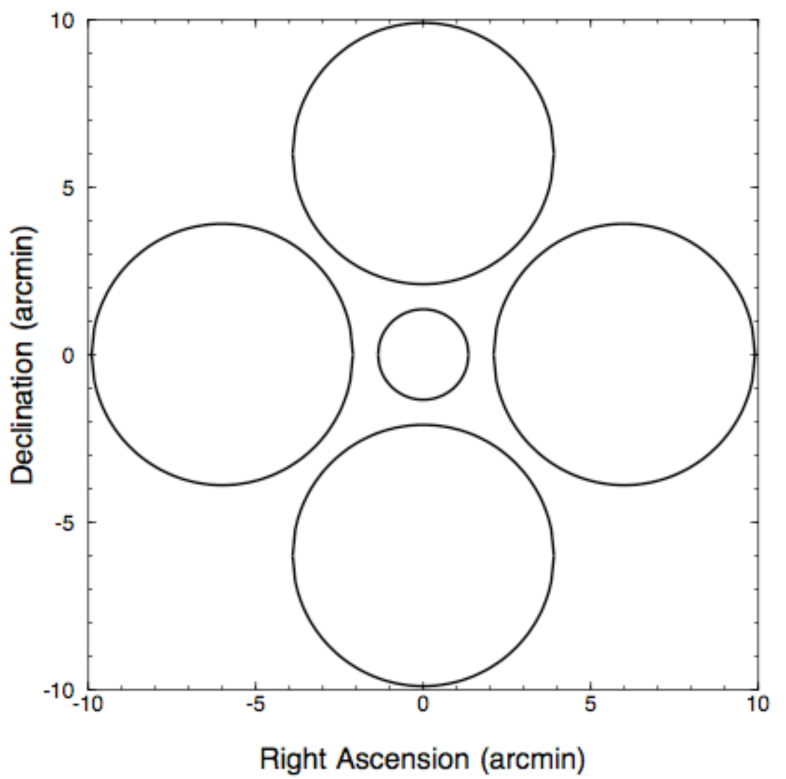




Testing M/ΦChange from Envelope to Core

Measure differential M/Φ between core and envelope:

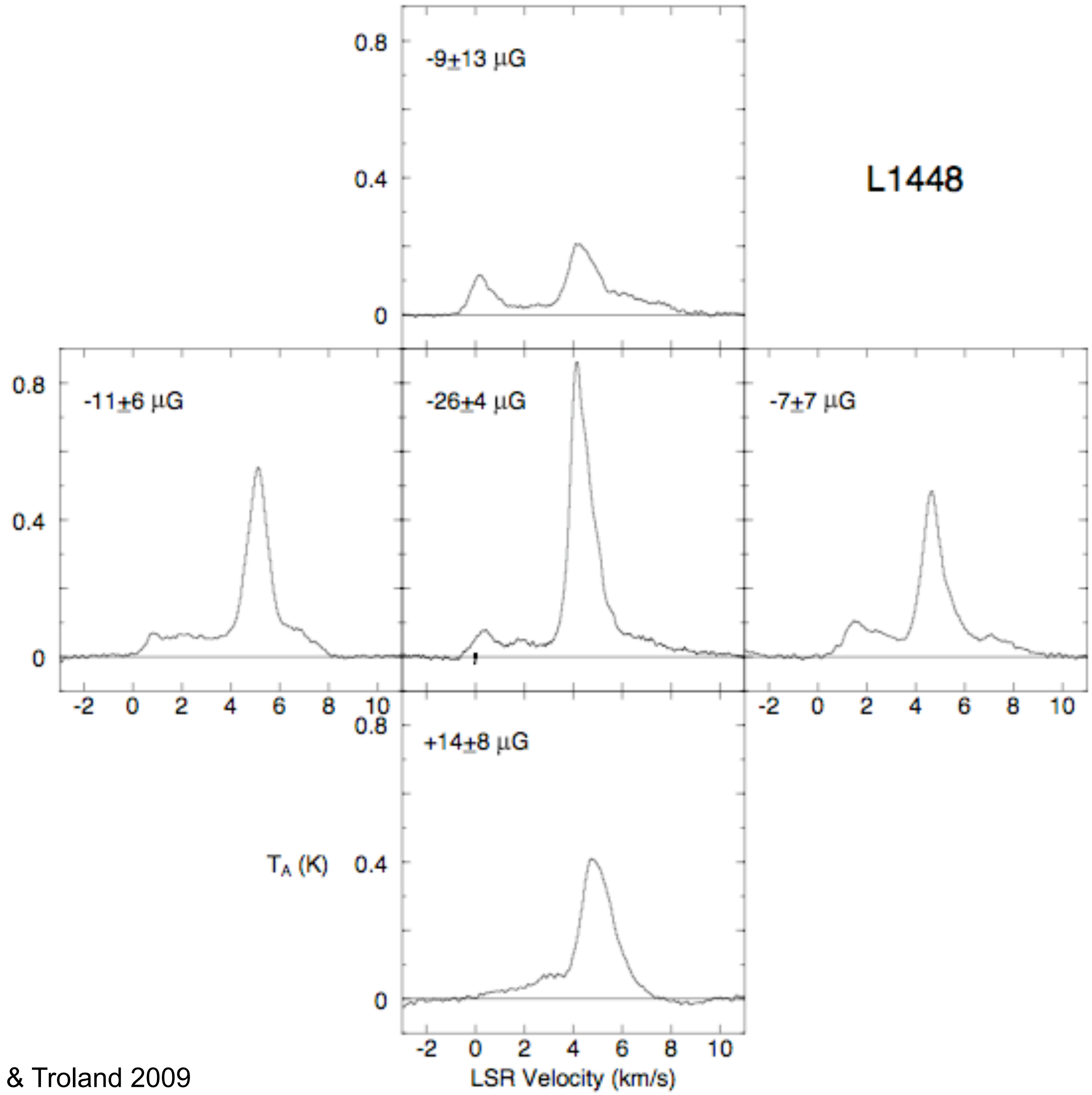
$$\frac{[M/\Phi]_{core}}{[M/\Phi]_{envelope}} = \frac{[T_{line}\,\Delta V / B_{los}]_{core}}{[T_{line}\,\Delta V / B_{los}]_{envelope}}$$



Crutcher, Hakobian, & Troland 2009

Telescope beam sizes were chosen to ideally sample core and envelope regions of published ambipolar diffusion models. Averaging the four large GBT beams "synthesizes" a toroidal beam, exactly what is needed to sample only the envelope region.

Testing M/Φ Change from Envelope to Core



Crutcher, Hakobian, & Troland 2009

Results

Cloud:	L1448	B217-2	L1544	B1
B(core):	-26 ± 4	+14 ± 4	+11 ± 2	-27 ± 4
B(envelope):	-3 ± 4	+2 ± 5	+5 ± 3	-7 ± 4
T_{line} ΔV (core):	1.21	0.60	1.17	2.20
T_{line} ΔV(envelope):	0.73	0.47	0.64	1.60
$\frac{M/\Phi\,(\text{core})}{M/\Phi\,(\text{envelope})}$:	0.21 ± 0.30	0.19 ± 0.46	0.89 ± 0.59	0.37 ± 0.18
Probability of > 1:	0.005	0.07	0.37	0.003

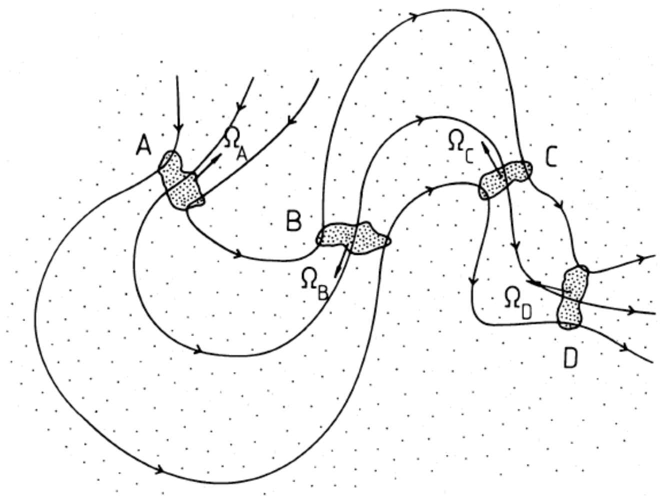
Published ambipolar diffusion models require ratio ~ $1/\lambda_{initial}$, typically ~ 2

SuperAlfvénic simulation result: mean $\frac{M/\Phi\,(\text{core})}{M/\Phi\,(\text{envelope})}$ = 0.67, range is 0.08 to 1.6
(Luntila, Padoan, Juvela, & Nordlund 2008)

Crutcher, Hakobian, & Troland 2009

Question: What about Mouschovias Criticisms?

1. He claims the data show that B_{los} varies from one envelope position to another around each core. Hence, our assumption that θ, the angle between the field and the line of sight, is approximately constant is inconsistent with our data.



L1544:	25 ± 7, or 3.5σ
L1448:	25 ± 10, or 2.5σ
B217:	18 ± 11, or 1.7σ
B1:	16 ± 9, or 1.7σ

Conclusion: The data are statistically consistent with our assumption of approximately constant θ.

Question: What about Mouschovias Criticisms?

2. He uses our expression for the ratio of M/Φ between envelope & core, in which θ divides out because it is assumed to be constant, to analyze our data including explicitly the putative variation and even reversal in direction in B_{los} from one envelope position to another around each core, to "show" that the uncertainty in the ratio M/Φ is sufficiently large that the results are consistent with ambipolar diffusion.

   Hence, his own analysis is inconsistent – assuming that θ is highly variable from position to position, then using an expression that assumes it is invariant.

CONCLUSION: Our analysis is consistent with our data, and Mouschovias' analysis is not internally consistent. (The Mouschovias paper was rejected for publication by ApJ.

Conclusions

1. Observational results on interstellar magnetic fields are increasing rapidly, so we can at least begin to understand the role of magnetic fields in star formation.

2. Total strength of **B** seems to range from near zero to a maximum value in molecular clouds; maximum values of B_{tot} imply ~ critical cores, smaller values of B_{tot} imply significantly supercritical cores.

2. Slope of B vs. n(H) is about 2/3, consistent with collapse with magnetic fields not dominate.

3. Increase in M/Φ from envelope to core required by published ambipolar diffusion models is not seen.

4. Nonetheless, magnetic fields are highly significant and probably crucial to understanding the physics of star formation. In at least some cases, M/Φ is ~ critical in molecular clouds. However, observational evidence now favors the generally weak field, turbulent model over the model in which fields are strong in all cloud cores with ambipolar diffusion always governing core formation and evolution.