Zeeman Measurements of Magnetic Fields in Star Forming Regions

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Magnetic Fields in Astrophysics – A Brief History

H. C. van de Hulst (1988): $\frac{B}{Ap} = \frac{S}{P_S}$

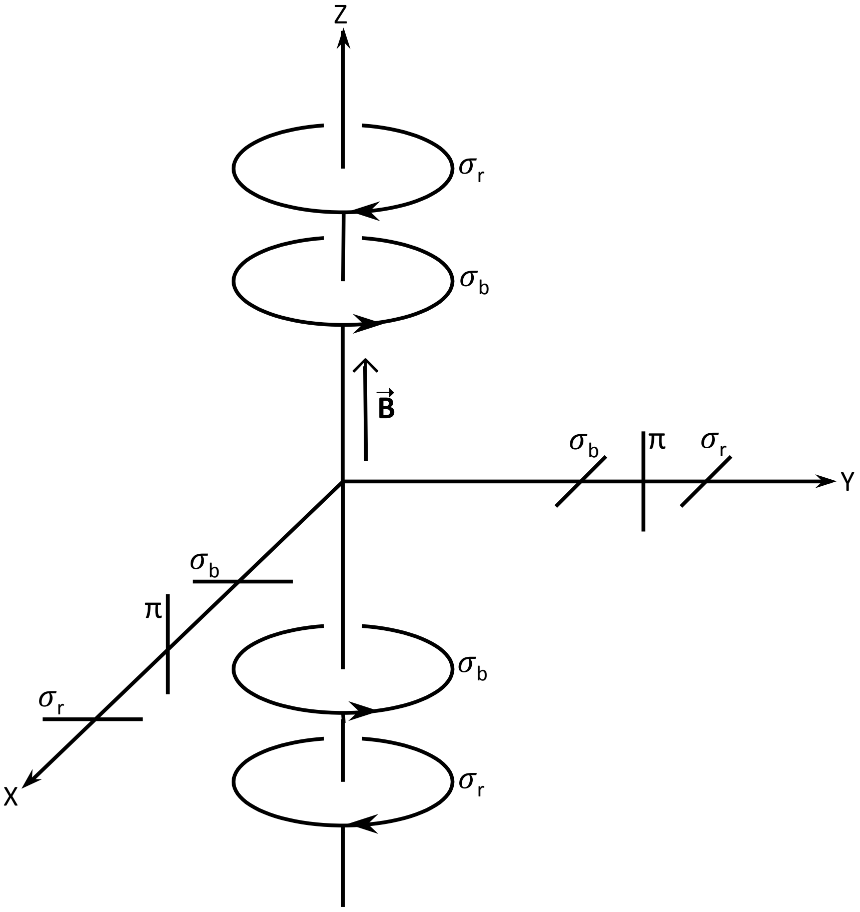
Magnetic fields are to astrophysics what sex is to psychology.

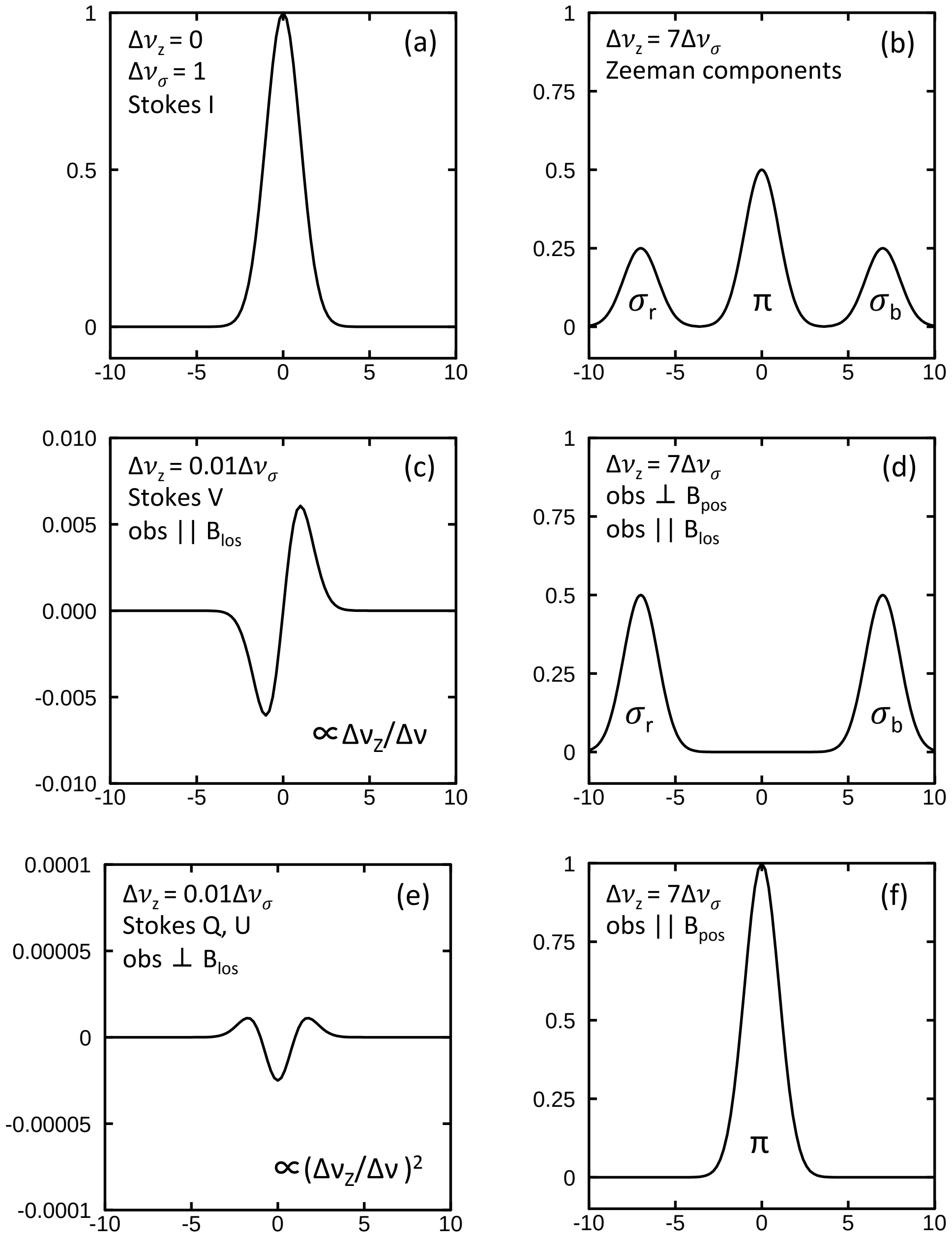
Parallels in development over the years:

1. Everyone knew it existed but good form to ignore it
2. Puzzling phenomena ascribed to it – although beyond explanation
3. It is just a form of energy, although exact understanding may still take a long time

Perhaps, as we are seeing at this conference, our understanding of magnetic fields in astrophysics, while still not exact, has advanced significantly in the past 27 years!

Zeeman Effect





Zeeman Effect – Detected in the ISM

ONLY direct measurement of magnetic field strengths available in regions of star formation

Sensitivity limits results to component of **B** along the line of sight inability to observe directly the magnitudes of all 3 components of **B** is the source of much of the controversy on the role of magnetic fields in star formation

Species	Wavelength	n(H) traced
H I	21 cm	$10^1 – 10^2$ cm^{-3}
OH	18 cm	$10^3 – 10^4$ cm^{-3}
CN	2.6, 1.3 mm	$10^5 – 10^7$ cm^{-3}

Mass to Magnetic Flux Ratio

M/Φ ⇒ relative importance of gravity to magnetic support

$$M_{critical} = \frac{\Phi}{2\pi\sqrt{G}}$$

$$M = \left(1 + \frac{He}{H}\right) m_H \, N_H \times area$$

$$\Phi = B \times area$$

$$\left[\frac{M}{\Phi}\right] = \left[\frac{(1 + He/H) m_H}{2\pi\sqrt{G}}\right] \times \frac{N_H}{B} \quad \text{(with respect to critical)}$$

$$[M/\Phi] < 1 \;\Longrightarrow \text{subcritical,} \quad [M/\Phi] > 1 \;\Longrightarrow \text{supercritical}$$

Formation of Molecular Cores

Ambipolar Diffusion

e.g., Ciolek & Mouschovias 1994

- clouds initially supported against gravity by magnetic pressure
- n_e/n_H is lowest in more shielded centers, so mass & magnetic field coupling is weakest
- neutrals collapse through field toward center, slowed by collisions with ions
- mass in center increases until gravity dominates magnetic support in core
- collapse accelerates near center, forming a dense core

Turbulence & Reconnection

Lazarian & Vishniac (1999)
Lazarian, Esquivel, and Crutcher (2012)

- turbulent flows lead to formation of over dense regions
- magnetic reconnection is inevitable in the turbulent interstellar medium
- reconnection rate $\propto L^{0.5}$, so important on larger scales, where turbulence is strongest
- initially leads to B ~ constant, so M/Φ can become supercritical on fast time scale, leading to near free-fall collapse
- population of dense cores depends on properties of the turbulence that forms self-gravitating regions

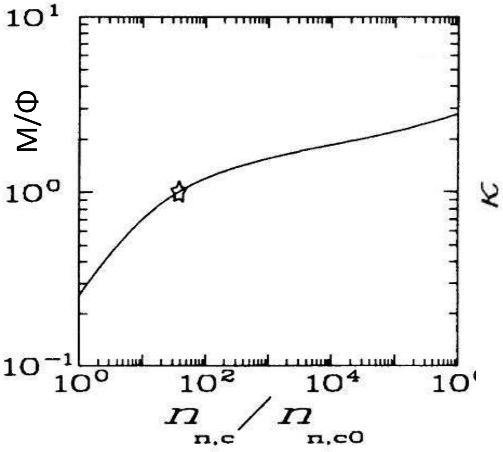
Three Observational Predictions

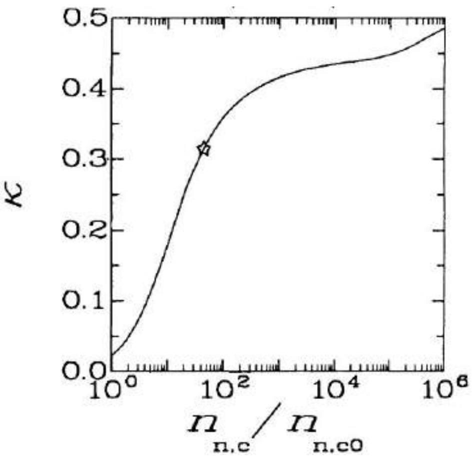
Ambipolar Diffusion

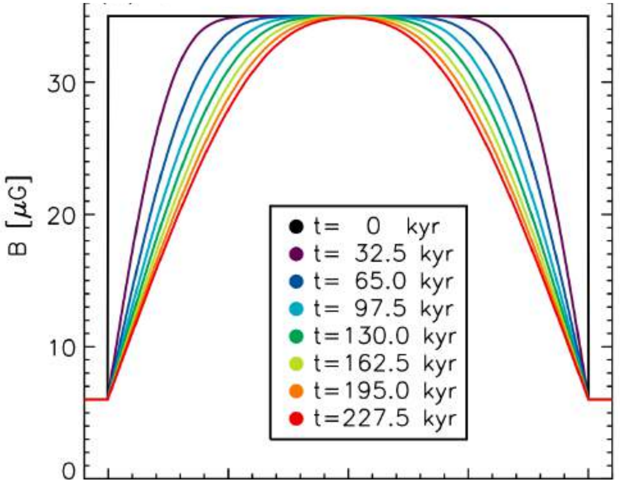
1. population of self-gravitating, subcritical clouds
2. M/Φ increases with decreasing radius
3. B scales slowly with density, $B \propto n^{\kappa}$, with $\kappa < 0.5$

Turbulence & Reconnection

1. no (or few) self-gravitating, subcritical clouds
2. M/Φ decreases with decreasing radius
3. B ~ constant until free-fall time scale is shorter than reconnection rate ($n \sim 10^4$), then $B \propto n^{2/3}$



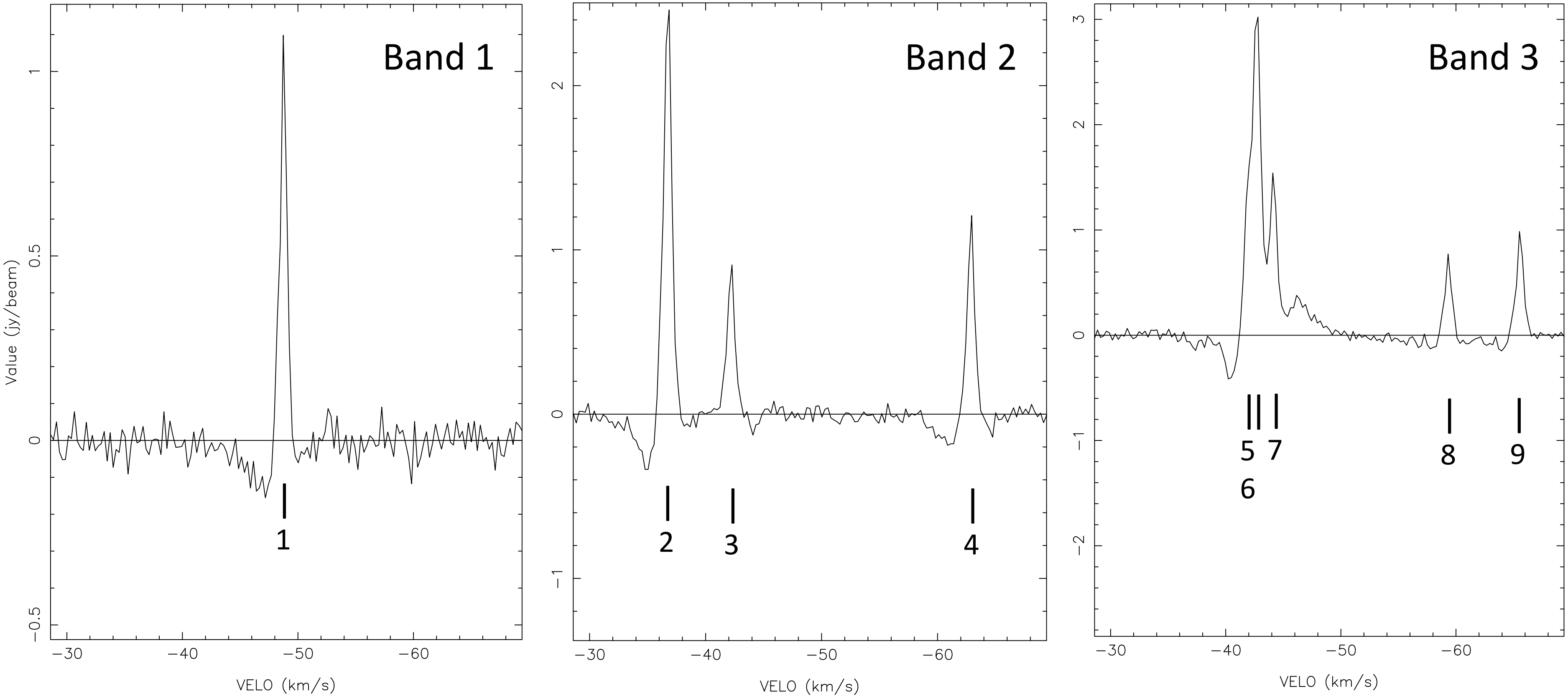




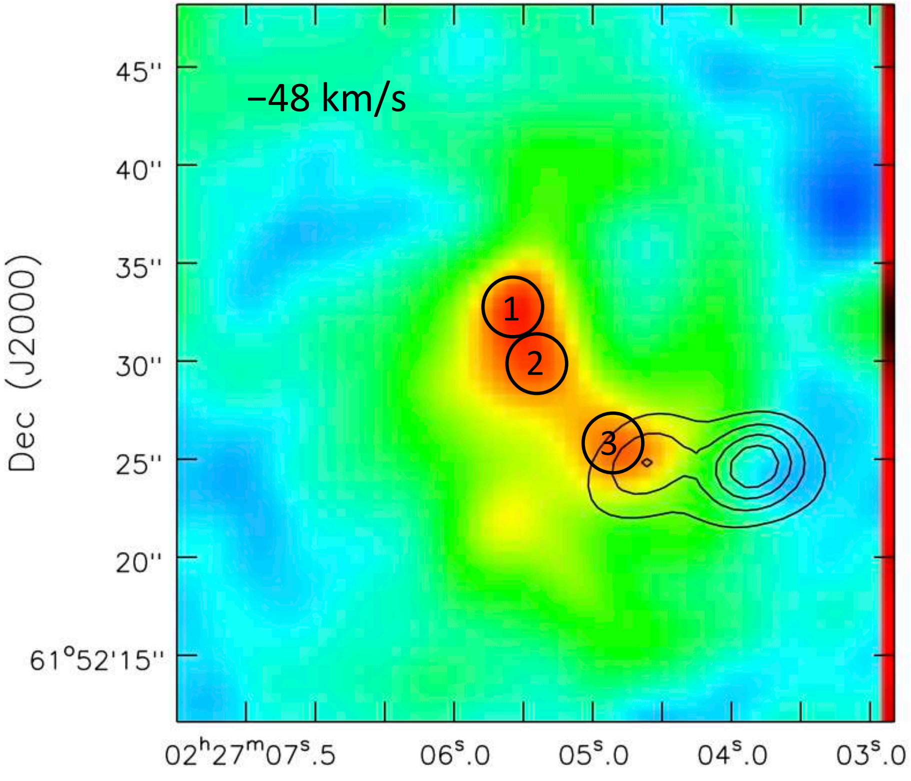
CARMA & IRAM CN 2-1 Zeeman Observing

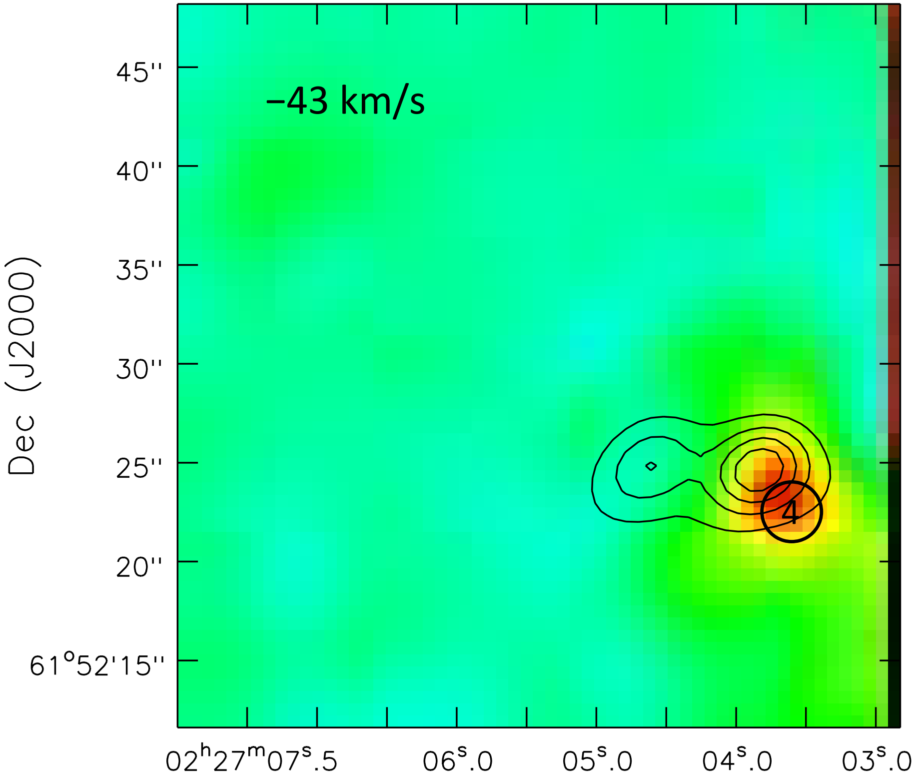
Edith Falgarone, Nick Hakobian, Pierre Hily-Blant, Chat Hull, Leslie Looney, Manuel Fernández López, Dick Plambeck, Ian Stephens, Tom Troland

W3OH Position 1 CN N=2-1 Stokes I Lines



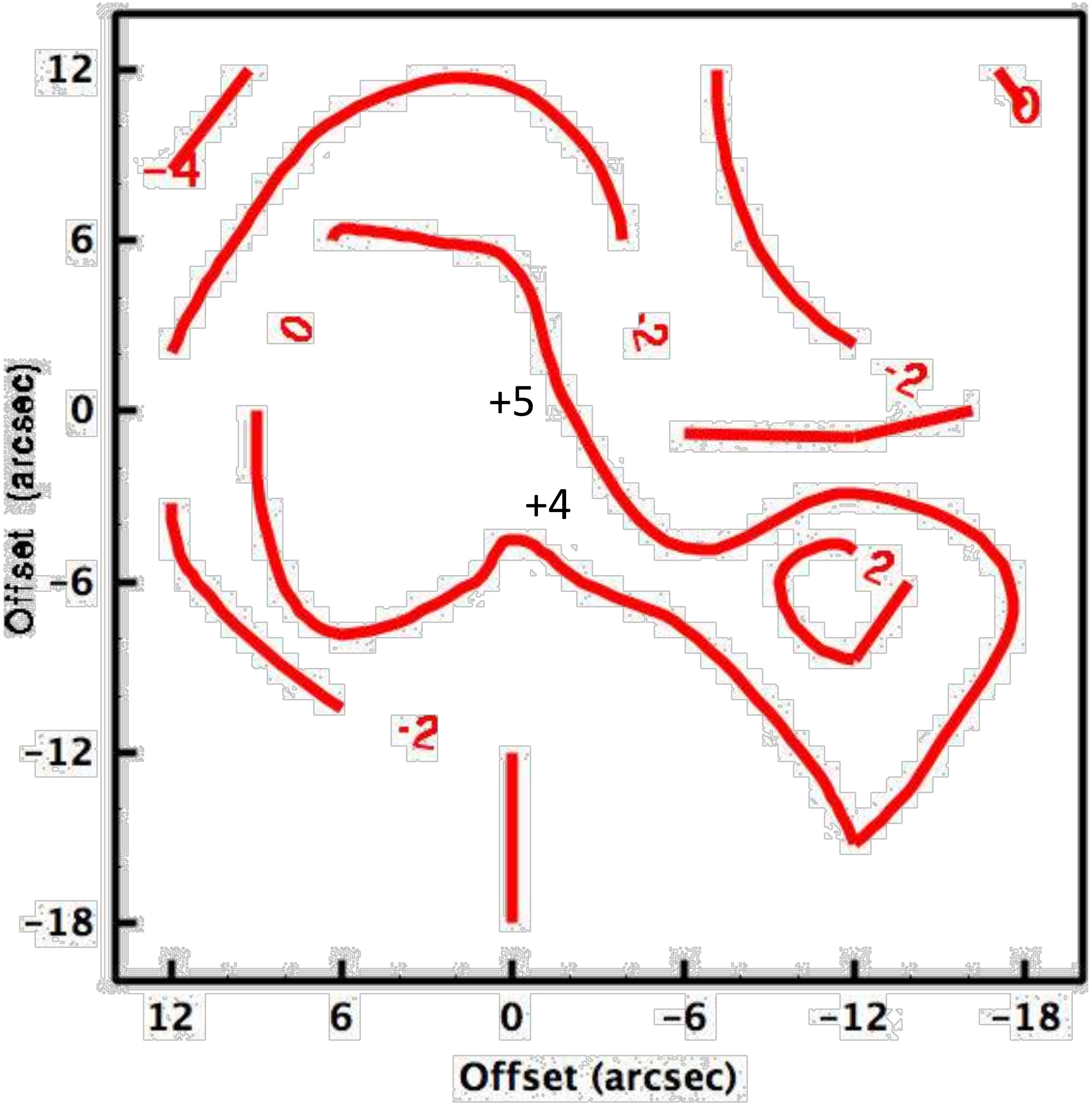
W3OH CARMA CN N=2-1 Zeeman Results



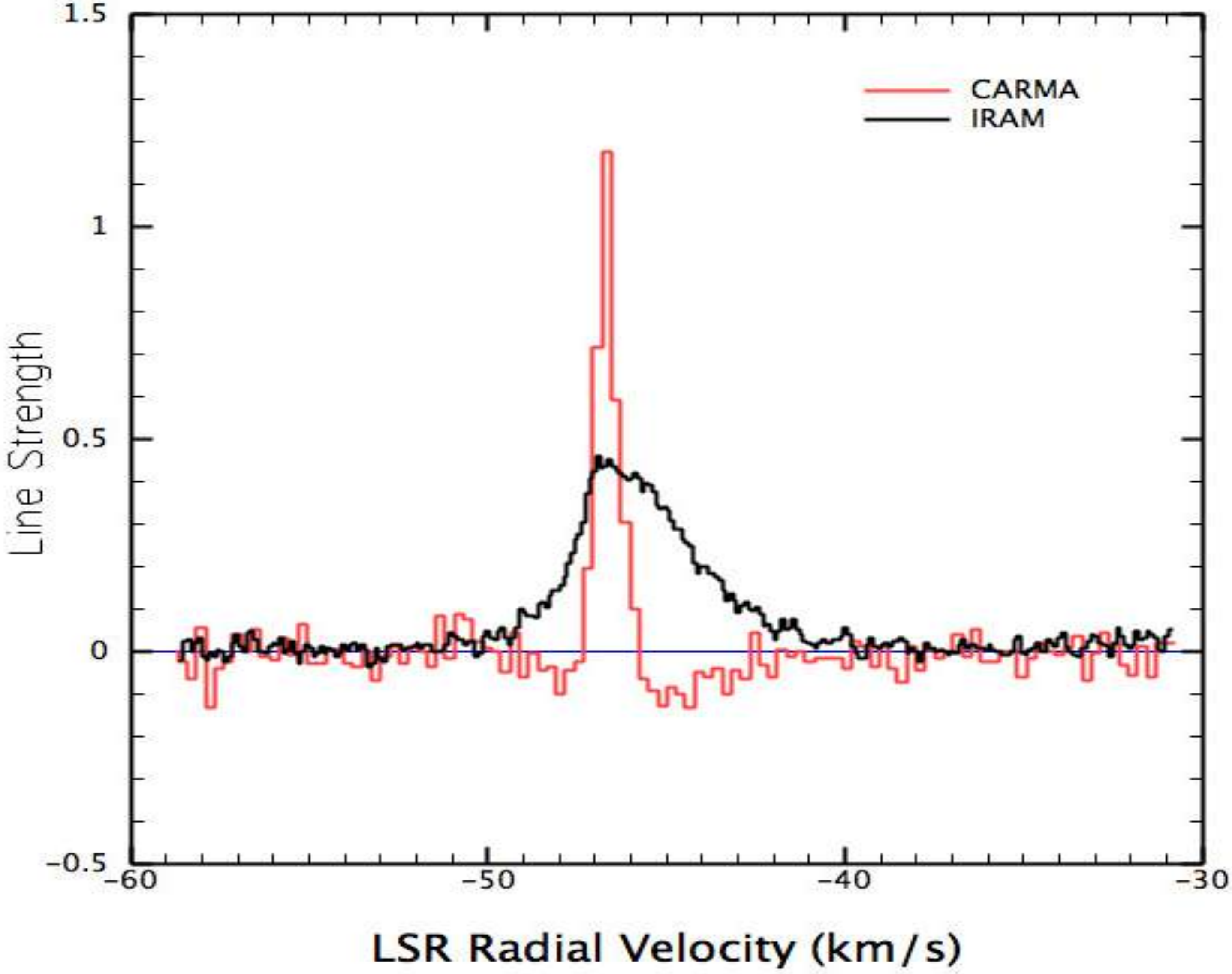


Position	B_{los}
1	+5 ± 1 mG
2	+4 ± 1 mG
3	-2 ± 2 mG
4	-2 ± 1 mG

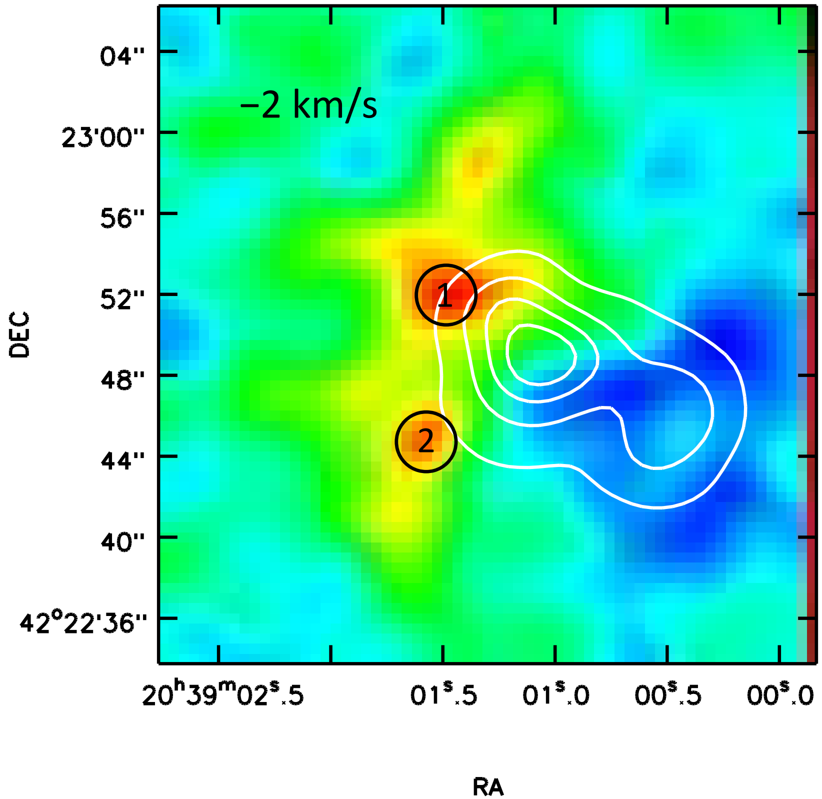
W3OH IRAM 30m CN 2-1 Zeeman Mapping

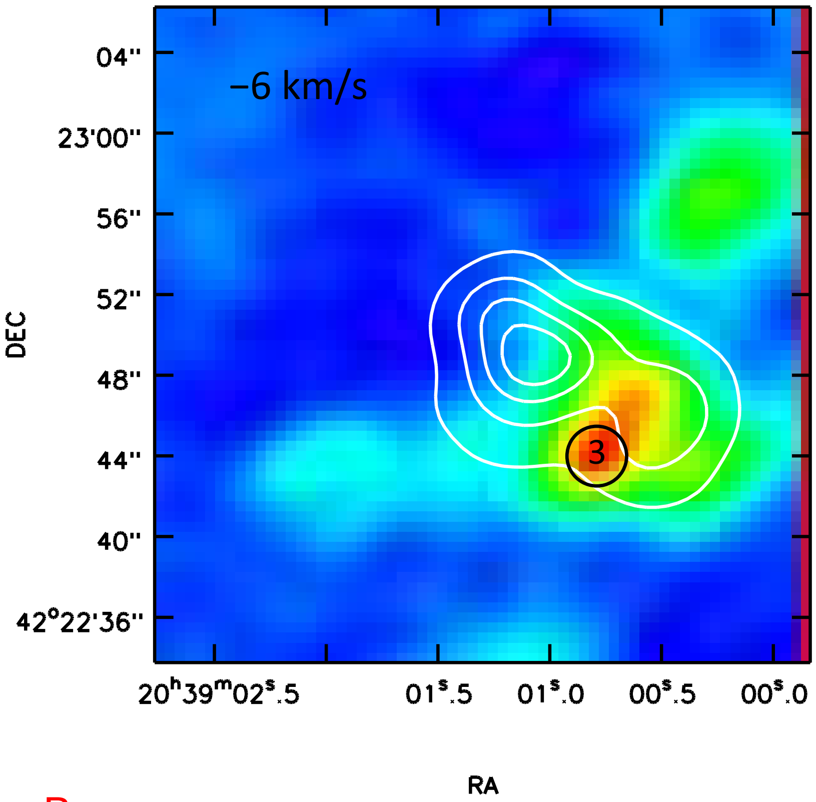


W3OH IRAM & CARMA CN 2-1 Line Profiles



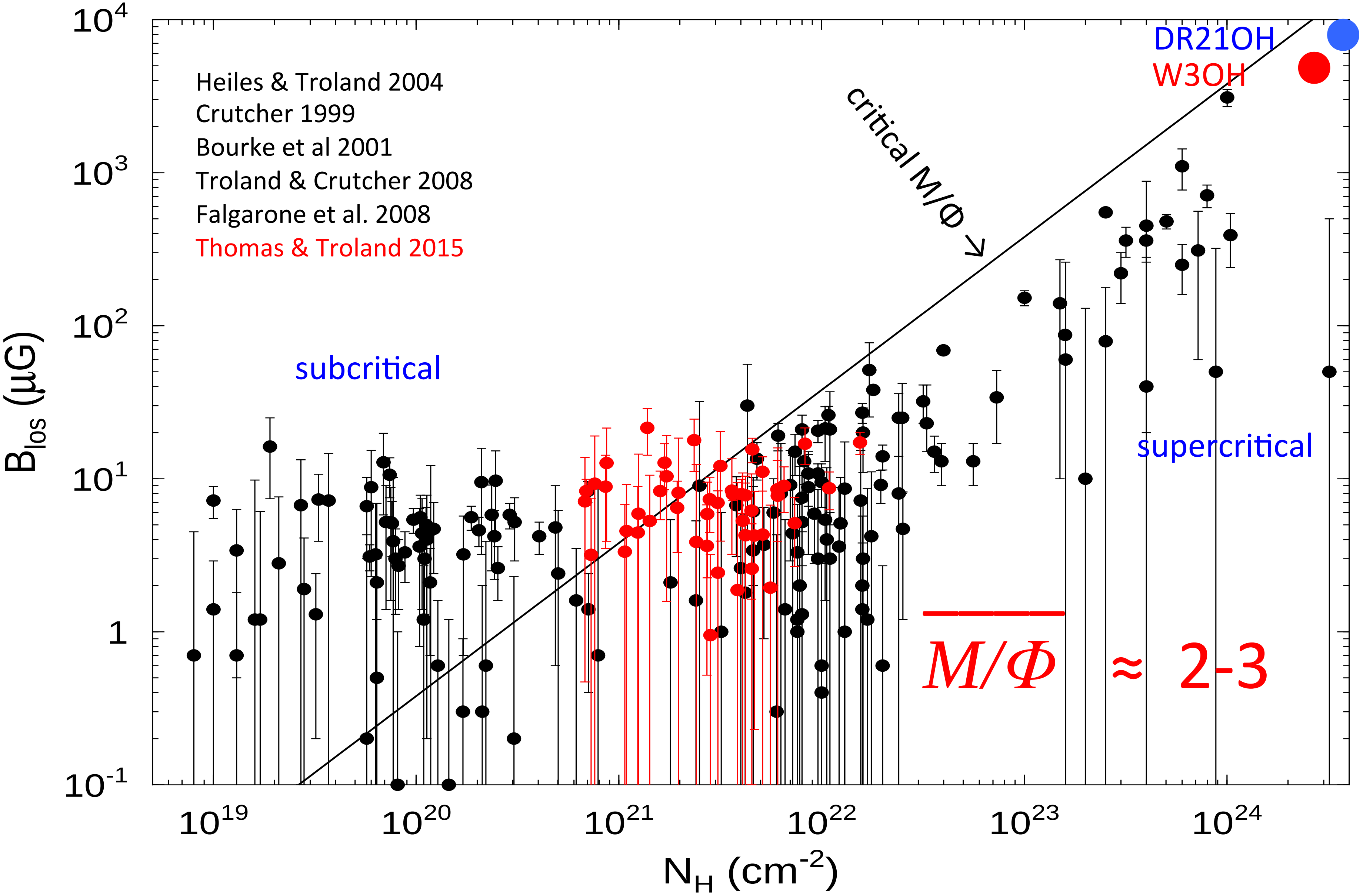
DR21OH CARMA CN N=2-1 Zeeman Results





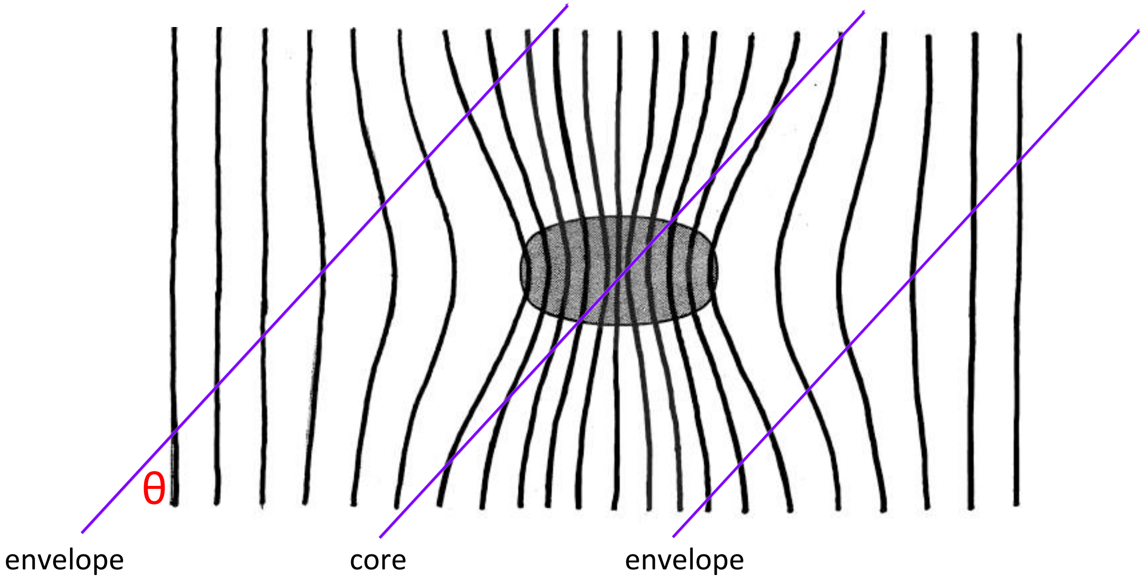
Position	B_{los}
1	-8 ± 2 mG
2	-5 ± 2 mG
3	-6 ± 2 mG

Test 1: Subcritical self-gravitating clouds?



Crutcher 2012

Test 2: M/Φ Change from Envelope to Core



$$M \propto N_H \propto T_{line}\Delta V$$

$$\Phi \propto B = B_{los} / \cos\theta$$

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

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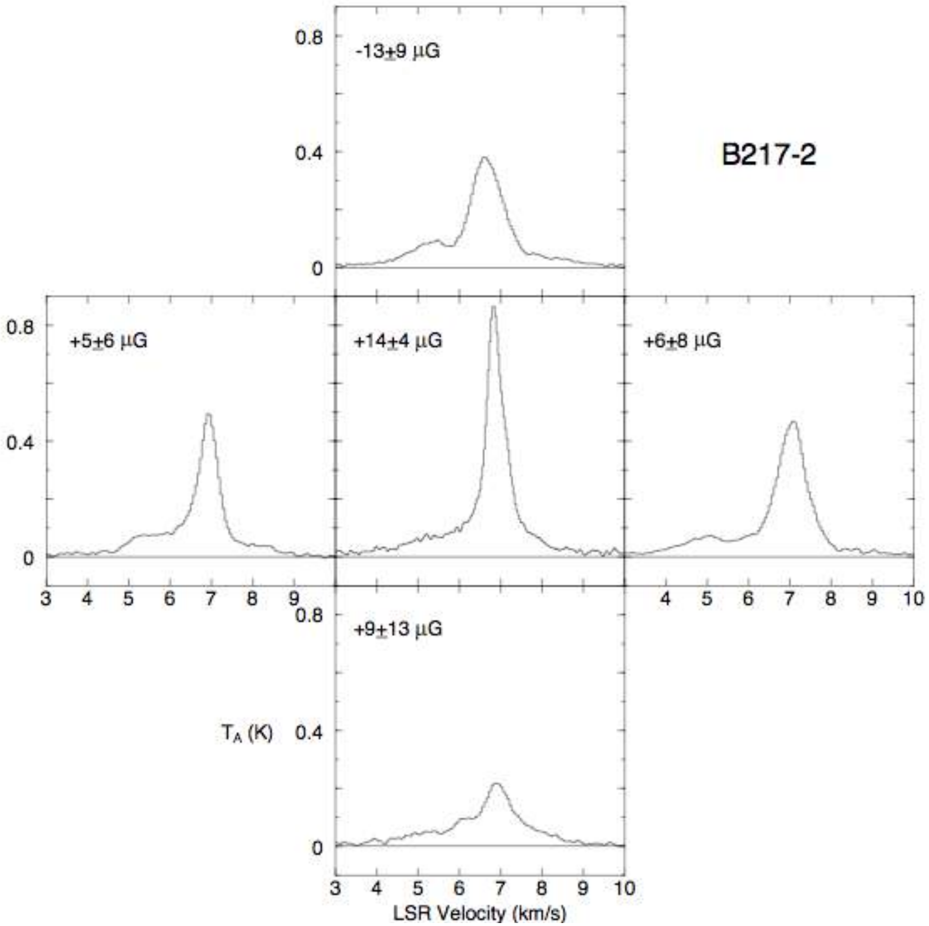
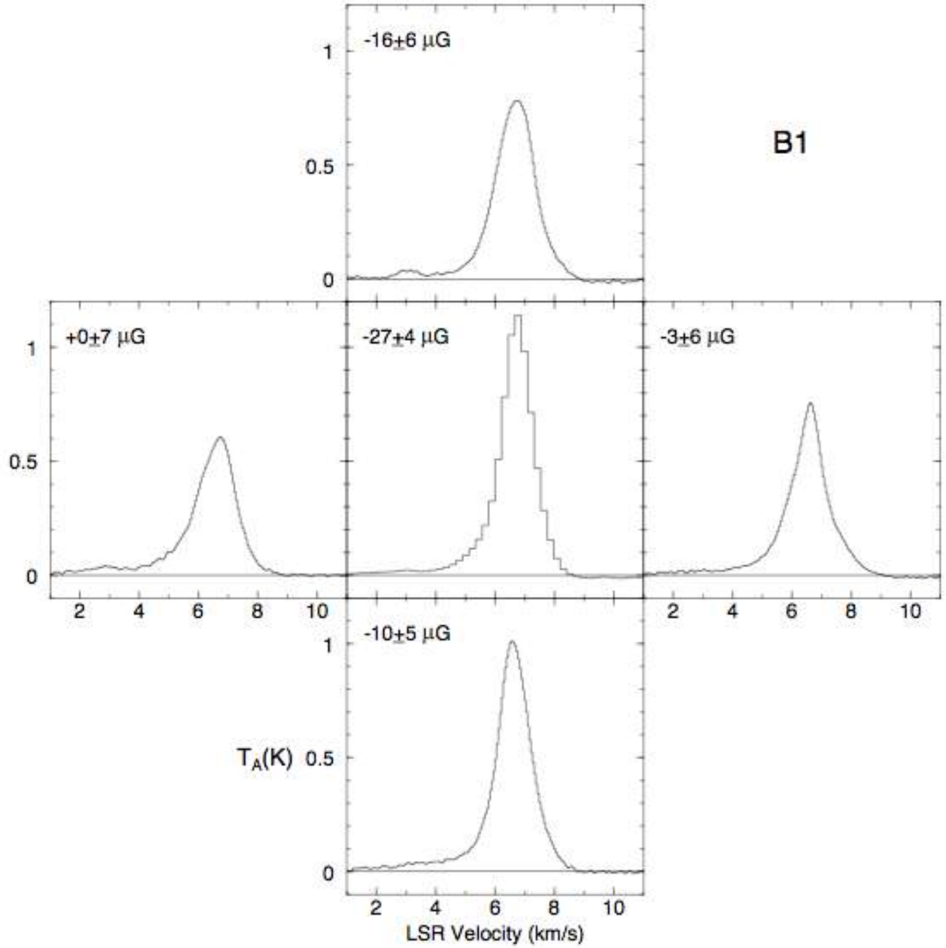




Crutcher, Hakobian, Troland 2008

Test 2: M/Φ Change from Envelope to Core

Cloud:	L1448	B217-2	L1544	B1
B_{LOS}(core):	-26 ± 4	+14 ± 4	+11 ± 2	-27 ± 4
B_{LOS}(envelope):	-0 ± 5	+2 ± 4	+2 ± 3	-8 ± 3
$\frac{M/\Phi\ (\text{core})}{M/\Phi\ (\text{envelope})}$:	0.07 ± 0.34	0.19 ± 0.41	0.46 ± 0.43	0.44 ± 0.19

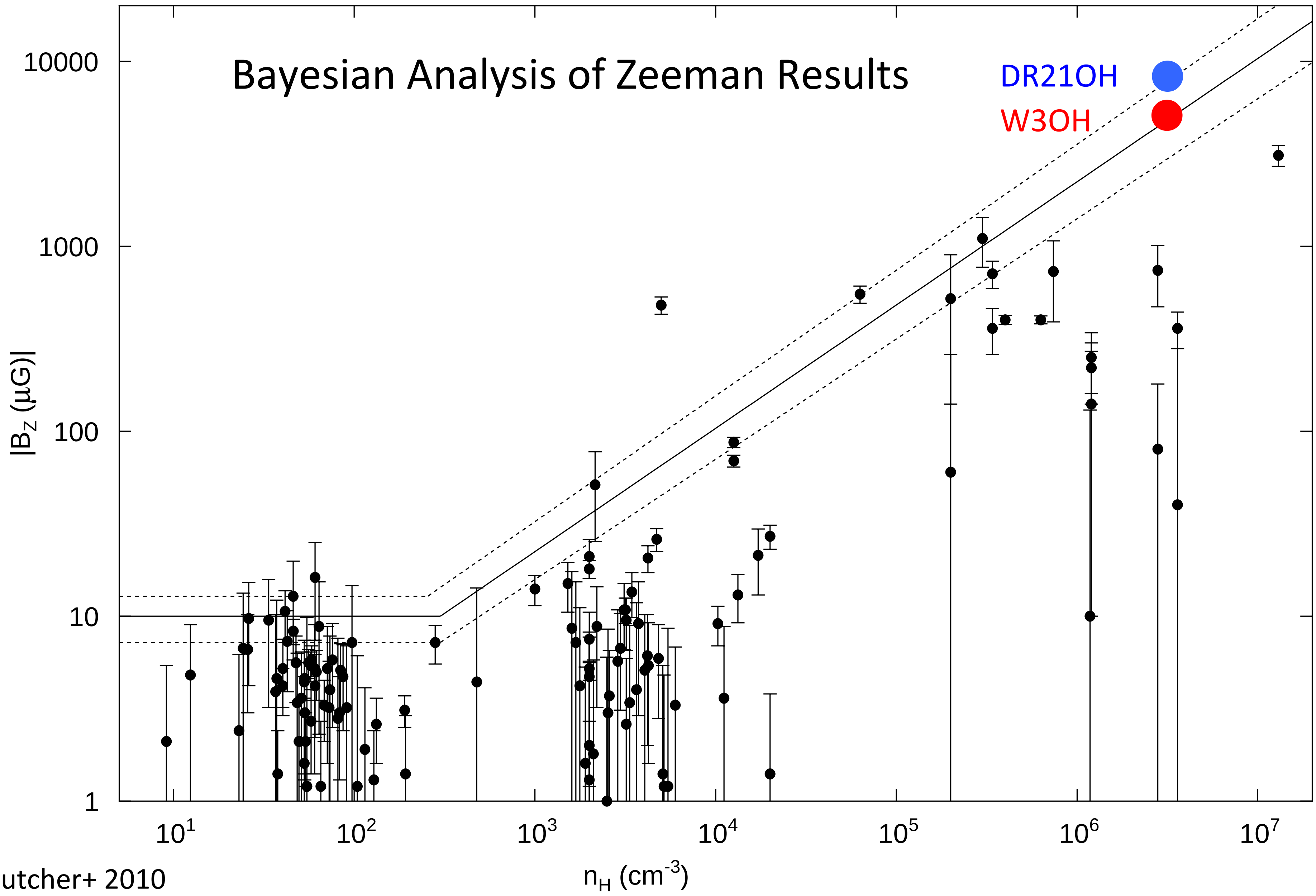
Ambipolar diffusion models require ratio >1

Difference from 1:	2.7 σ	2.0 σ	1.3 σ	2.9 σ
Probability ≥ 1:	0.005	0.05	0.11	0.01

Probability that ***all 4*** cores were formed by ambipolar diffusion: 3×10^{-7}

Crutcher+ 2009

Test 3: Scaling of B with Density



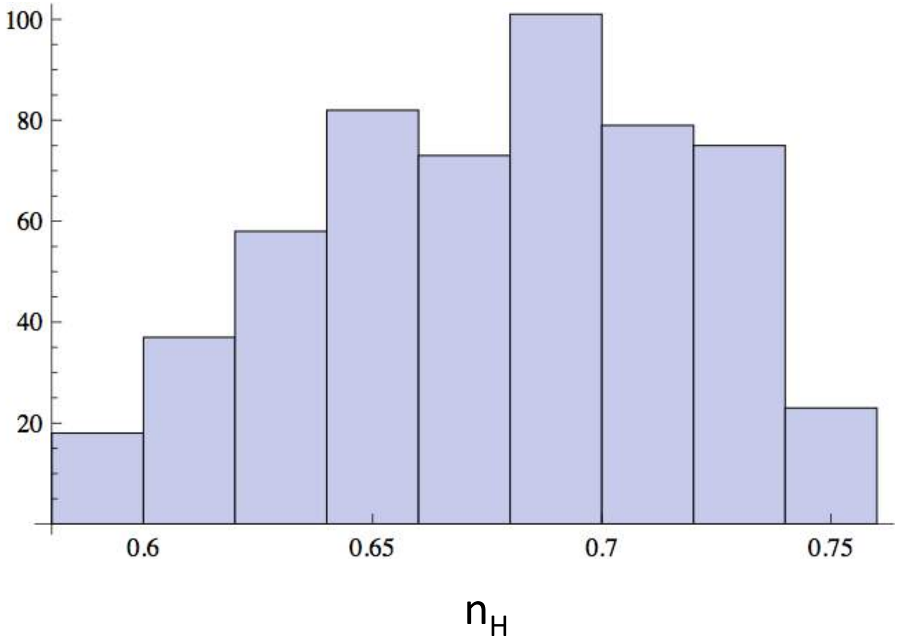
Crutcher+ 2010

Results from Bayesian Analysis

1) PDF of B(total) is flat, not delta function
(although other PDFs, such as log normal, were not tested)

2) scaling of B with density, $B \propto n^K$

PDF of K from Bayesian analysis



Crutcher+. 2010

observational tests	Ambipolar Diffusion	Turbulence with Reconnection
1) Self-gravitating subcritical clouds	✗	✓
2) $M/\Phi(r)$ decreases	✗	✓
3) $B \propto \rho^{2/3}$	✗	✓

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Is this definitive and is the issue closed?