Ambipolar Diffusion Effects on the Weakly Ionized Turbulence Molecular Clouds

UC-HIPACC: The Future of AstroComputing Conference
San Diego Supercomputer Center
December 16 - 17, 2010

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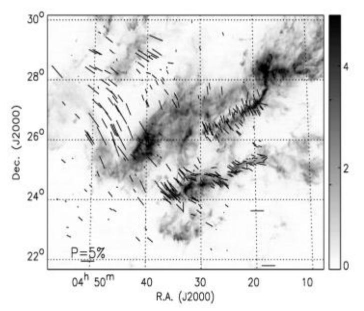
Molecular Clouds

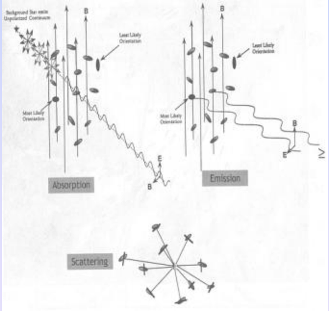
Magnetic field in MCs

- $\leq 21\ \mu\mathrm{G}$ in MCs, magnetically supercritical ($M/M_c=1.4\sim2.1$) Troland & Crutcher (2008)
- $\sim 6\ \mu\mathrm{G}$ in CNM, magnetically subcritical Heiles & Troland (2005)
- Approximate equipartition: $1.3 < E_{turb}/E_{mag} < 1.9$

Carina Nebula



Goldsmith et al. (2008)



Weintraub et al. (2000)

Supersonic turbulent MCs

- Broad molecular line widths in MCs: 1 ~ 10 km/s Zuckerman & Palmer (1974)
- Line width - size relation: $v \propto \ell^{0.5} \Leftrightarrow P(k) \propto k^{-2}$ Larson (1981), Passot et al. (1988)
- Hierarchical filamentary and clump structures Low et al. (1984), Scalo (1984), Stenholm (1984), Elmegreen & Scalo (2004)

→ **MHD turbulence**

Ideal or Non-Ideal?

Ideal MHD: ionized gas frozen with magnetic field

Weakly Ionized MCs (ions + neutrals):

$$x_i = \frac{n_i}{n_n} \le 10^{-7}$$

Caselli (1998), Bergin et al. (1999)

- ions are frozen with B-field

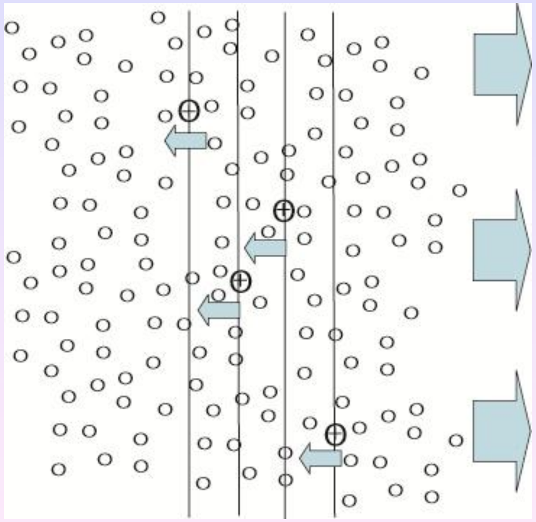
$$\omega_{ci} = \frac{eB}{m_i c} = 9.58\times 10^{-3} Z \mu^{-1} B(\mu\mathrm{G})\ \mathrm{rad\,s^{-1}}$$

$$t_{in} = \frac{1}{\gamma \rho_n} \approx 10^6\ \mathrm{s} \quad \Rightarrow \quad t_{in}\omega_{ci} >> 1$$

- neutrals depend on coupling:

Ambipolar Diffusion

Mestel & Spitzer (1956)



Slow AD-driven Quasi-Static Star Formation Process:

$$t_{AD} \sim 10\ t_{ff}$$

Spitzer (1968), Nakano & Tademaru (1972), Mouschovias (1976, 1977, 1979), Nakano & Nakamura (1978), Shu (1983), Lizano & Shu (1989), Fiedler & Mouschovias (1992,1993), …

Numerical Method (ZEUS-MP + AD)

2-Fluid Semi-Implicit Method:

Tóth (1995), Mac Low & Smith (1997)

$$\frac{\partial \rho_n}{\partial t} = -\nabla \cdot (\rho_n v_n); \qquad \frac{\partial \rho_i}{\partial t} = -\nabla \cdot (\rho_i v_i);$$

$$\boxed{\begin{aligned} \rho_n \frac{\partial v_n}{\partial t} &= -\rho_n (v_n \cdot \nabla) v_n - \nabla P_n - \gamma_{AD} \rho_i \rho_n (v_n - v_i) + \rho_n g; \\ \rho_i \frac{\partial v_i}{\partial t} &= -\rho_i (v_i \cdot \nabla) v_i - \nabla P_i - \gamma_{AD} \rho_i \rho_n (v_i - v_n) + \rho_i g + \frac{1}{4\pi} (\nabla \times B) \times B; \end{aligned}}$$

$$\frac{\partial B}{\partial t} = \nabla \times (v_i \times B); \qquad \nabla \cdot B = 0$$

Isothermal

$$\Delta t \le \Delta x / v_{Ai} \propto \sqrt{\chi_i} = \sqrt{\frac{\rho_i}{\rho_n}} \le 10^{-3}$$

Heavy-Ion Approximation:

Li, McKee, Klein (2006)

Li et al. (2008)

$\gamma_{AD}\, \rho_i = \text{const.}$ $\qquad \chi_i \equiv \rho_i/\rho_n$

- Criterion:

  $f_I \ll f_D \approx f_L \quad \Rightarrow \quad R_{AD}(\ell_{vi}) \gg \mathcal{M}_{Ai}^2$

- AD Reynolds number

$$R_{AD}(\ell) \equiv \frac{4\pi \gamma_{AD} \rho_i \rho_n \ell v}{B^2} = \frac{\ell}{\ell_{AD}} = \frac{t_{AD}}{t_{dyn}}$$

≤ 1 weak coupling

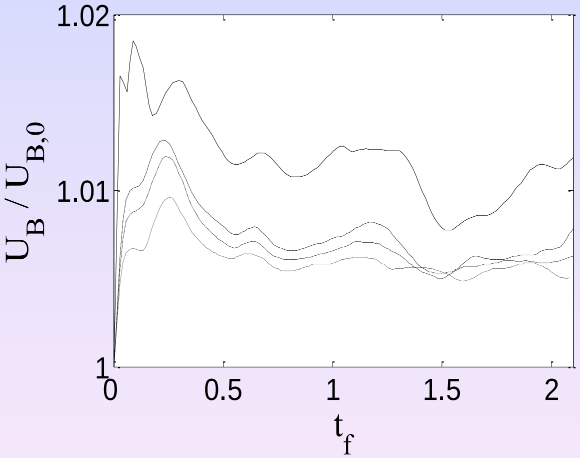
$\gg 1$ strong coupling

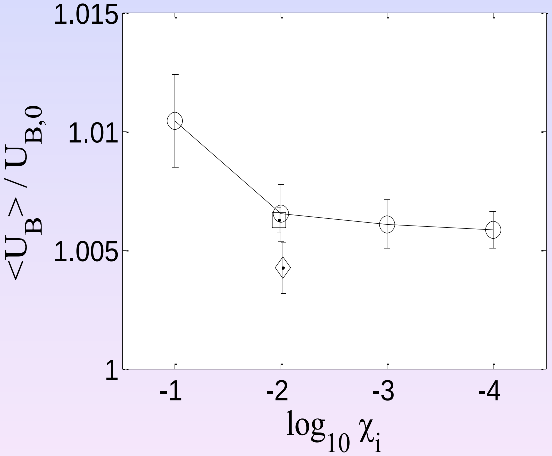
Models Parameters

Li, McKee, Klein, & Fisher (2008): 128^3, 256^3, and one 512^3

- Model parameters: $\mathcal{M}_{rms} = 3$, $\beta = 0.1$, $k = 1\sim2$, $T = 10K$, periodic boundaries
- Convergence studies in time, resolution, and ionization mass faction χ_i
- Convergence studies in power spectral indexes

$\chi_i = 0.01$
speedup = 100
$R_{AD}(\ell_{vi})$ » $\mathcal{M}_{Ai}^2$



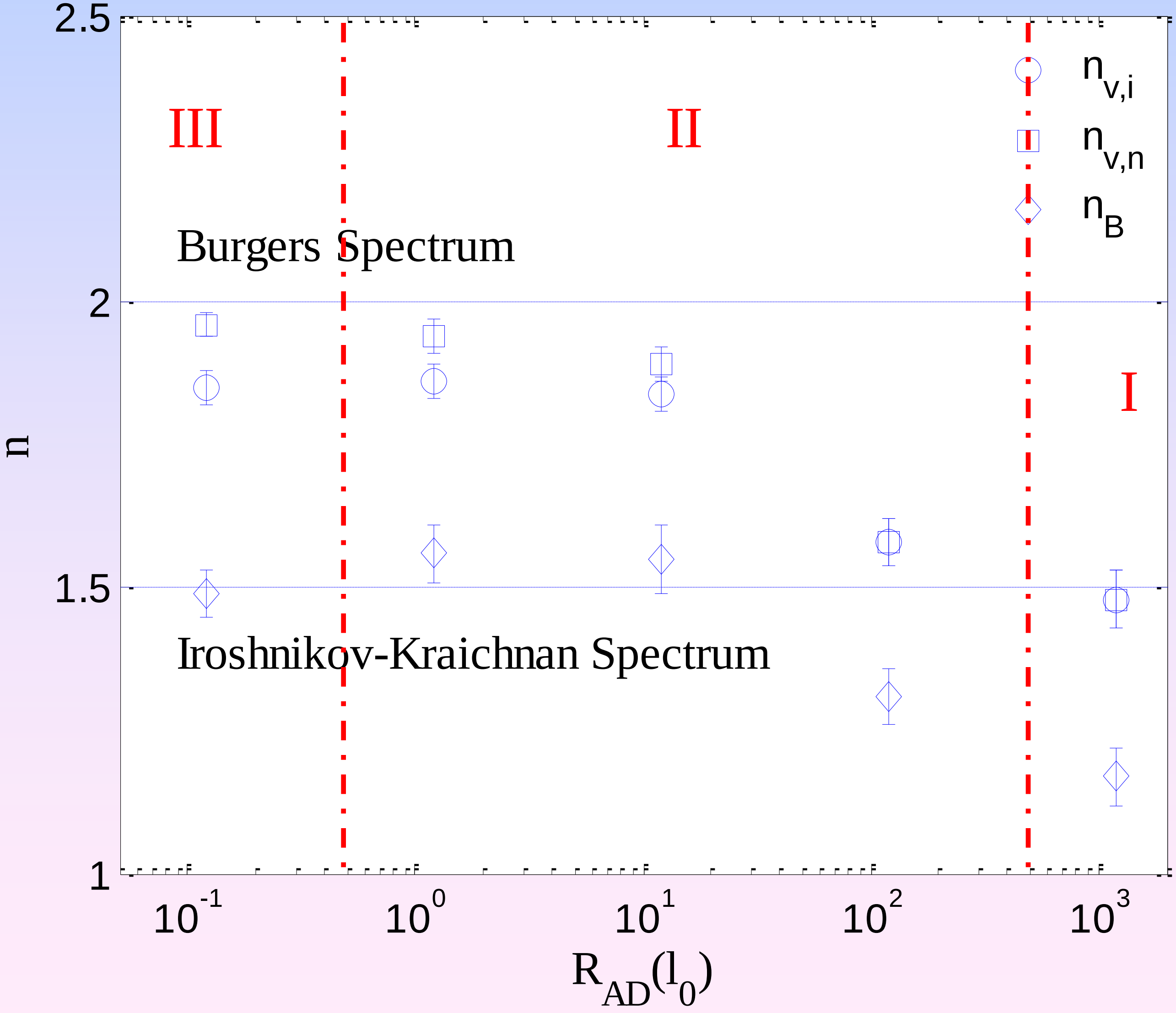


Five 512^3, no gravity, 600,000 CPU hours
R_{AD} (ℓ_0) : 0.12, 1.2, 12, 120, 1200

Velocity Power Spectral Index

← Pure HD

Ideal MHD →



McKee, Li, & Klein (2010)

I: ideal MHD

$R_{AD} \to \infty$

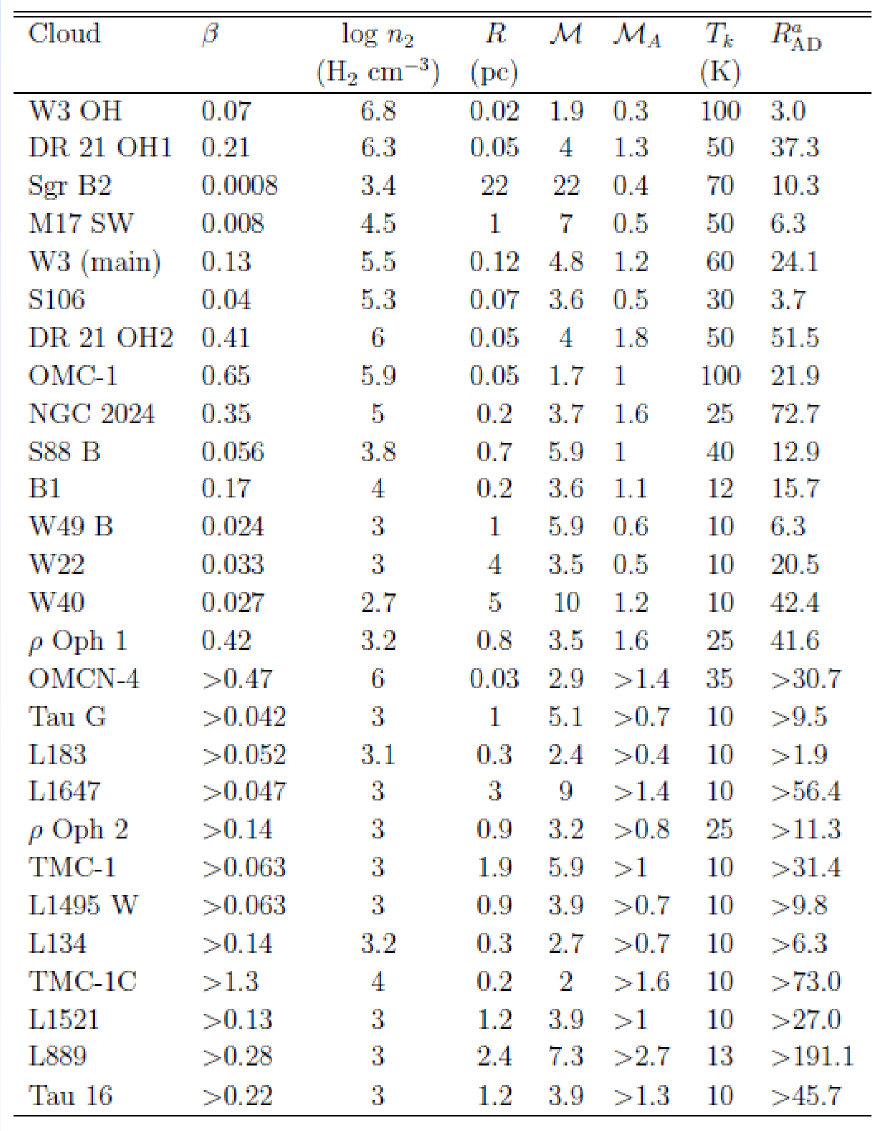
II: standard AD

$R_{AD} > \mathcal{M}_A^2$

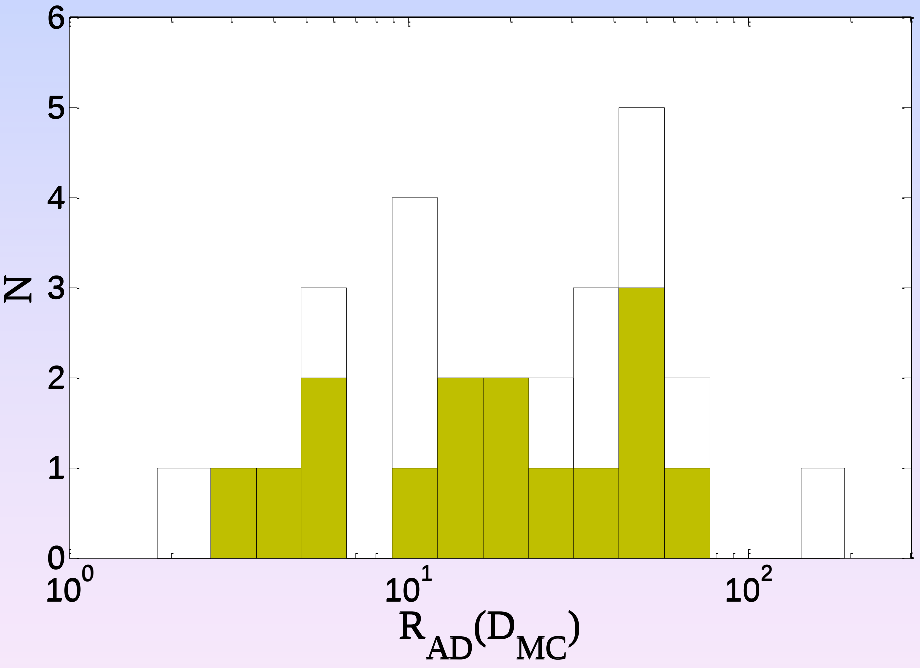
III: strong AD

$\mathcal{M}_A^2 > R_{AD} > \mathcal{M}_{Ai}^2$

R_{AD} of 27 Observed Molecular Clouds



Cloud	β	$\log n_2$ (H_2 cm^{-3})	R (pc)	$\mathcal{M}$	$\mathcal{M}_A$	T_k (K)	R^a_{AD}
W3 OH	0.07	6.8	0.02	1.9	0.3	100	3.0
DR 21 OH1	0.21	6.3	0.05	4	1.3	50	37.3
Sgr B2	0.0008	3.4	22	22	0.4	70	10.3
M17 SW	0.008	4.5	1	7	0.5	50	6.3
W3 (main)	0.13	5.5	0.12	4.8	1.2	60	24.1
S106	0.04	5.3	0.07	3.6	0.5	30	3.7
DR 21 OH2	0.41	6	0.05	4	1.8	50	51.5
OMC-1	0.65	5.9	0.05	1.7	1	100	21.9
NGC 2024	0.35	5	0.2	3.7	1.6	25	72.7
S88 B	0.056	3.8	0.7	5.9	1	40	12.9
B1	0.17	4	0.2	3.6	1.1	12	15.7
W49 B	0.024	3	1	5.9	0.6	10	6.3
W22	0.033	3	4	3.5	0.5	10	20.5
W40	0.027	2.7	5	10	1.2	10	42.4
ρ Oph 1	0.42	3.2	0.8	3.5	1.6	25	41.6
OMCN-4	>0.47	6	0.03	2.9	>1.4	35	>30.7
Tau G	>0.042	3	1	5.1	>0.7	10	>9.5
L183	>0.052	3.1	0.3	2.4	>0.4	10	>1.9
L1647	>0.047	3	3	9	>1.4	10	>56.4
ρ Oph 2	>0.14	3	0.9	3.2	>0.8	25	>11.3
TMC-1	>0.063	3	1.9	5.9	>1	10	>31.4
L1495 W	>0.063	3	0.9	3.9	>0.7	10	>9.8
L134	>0.14	3.2	0.3	2.7	>0.7	10	>6.3
TMC-1C	>1.3	4	0.2	2	>1.6	10	>73.0
L1521	>0.13	3	1.2	3.9	>1	10	>27.0
L889	>0.28	3	2.4	7.3	>2.7	13	>191.1
Tau 16	>0.22	3	1.2	3.9	>1.3	10	>45.7



Crutcher (1999)
McKee, Li, & Klein (2010)

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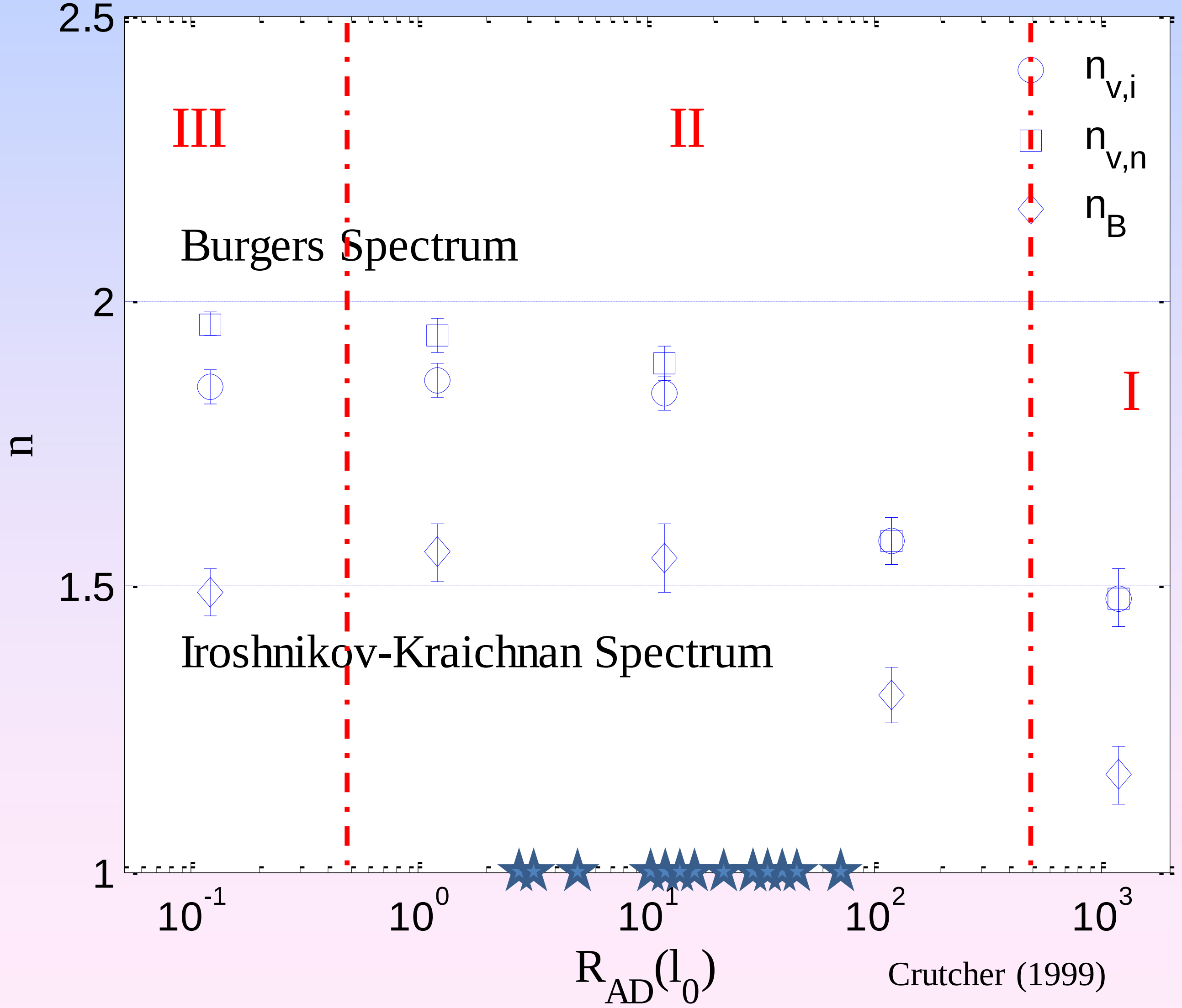

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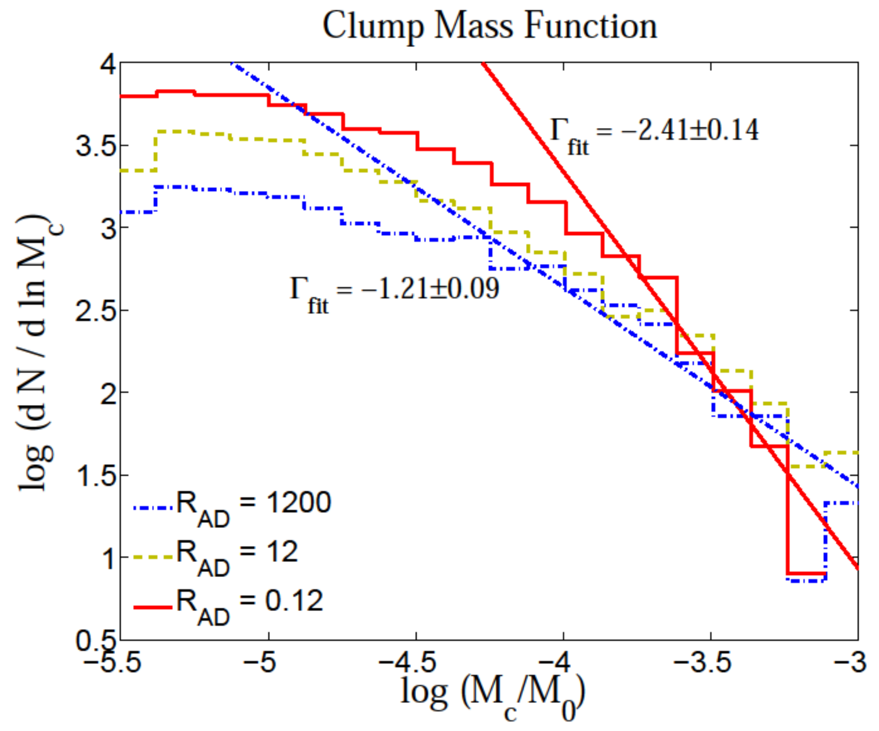
Clump Mass function and Mass/Flux Ratio

Turbulence Fragmentation:

Padoan & Nordlund (2002), Padoan et al. (2007)
Hennebelle & Chabrier (2008, 2009)

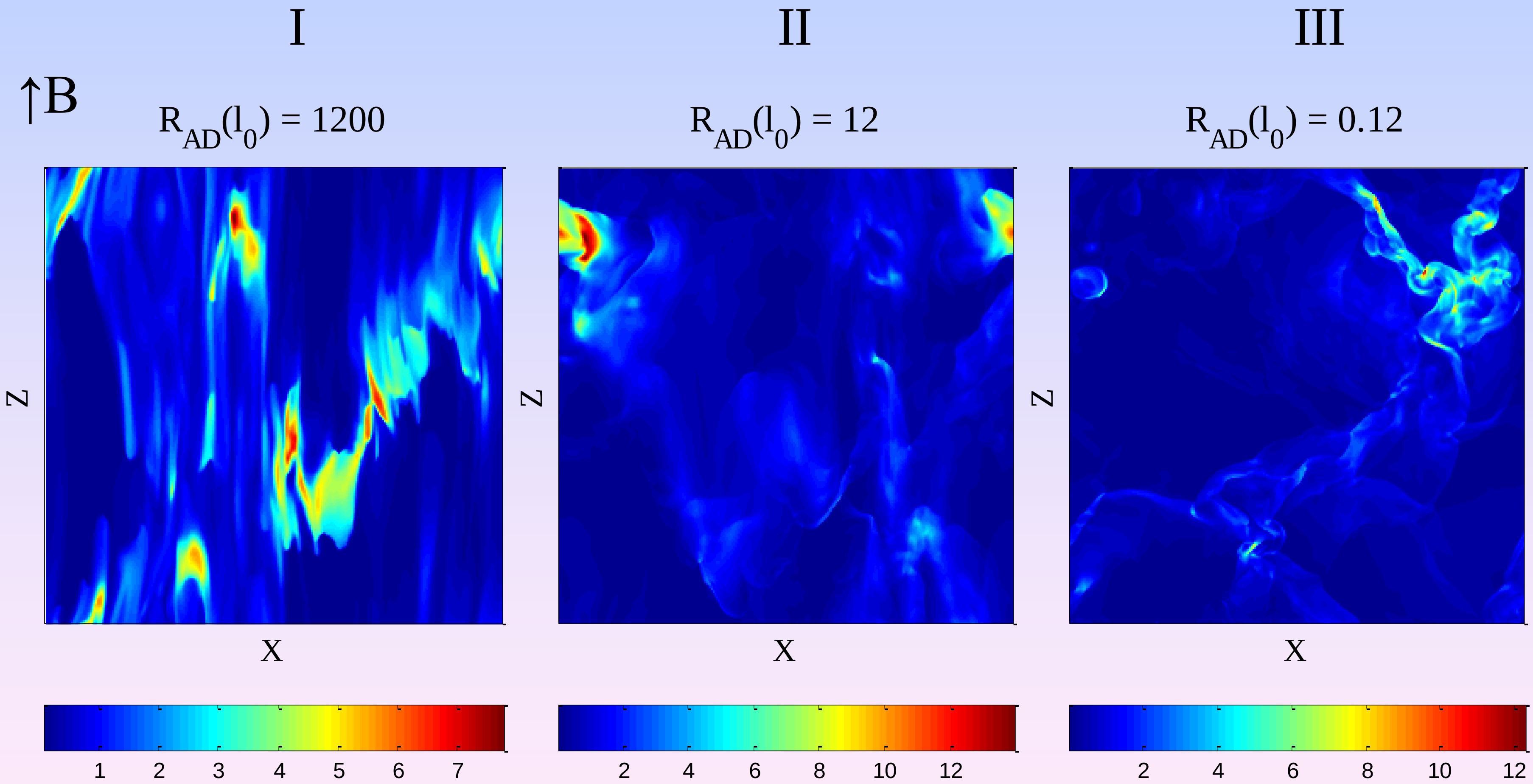
$$N(m)dm=C\left[1+\mathrm{erf}\left(\frac{4\ln m+\sigma^2}{2\sqrt{2}\sigma}\right)\right]m^{-x}dm$$

$$P_v(k)=k^{-n}$$



McKee, Li, & Klein (2010)

Morphological Change of Turbulence Gas with AD



I

$R_{AD}(l_0) = 1200$

II

$R_{AD}(l_0) = 12$

III

$R_{AD}(l_0) = 0.12$

Conclusions

- 2-fluid semi-implicit + heavy-ion approximation is fast and works well on turbulence simulations!

AD Reynolds Number $R_{AD}(\ell_{vi})$ » $\mathcal{M}_{Ai}^2$ Li, McKee, & Klein (2006), Li et al. (2008)

- Many statistical properties (e.g. velocity and density power spectra, density PDF) of the magnetized turbulence system change as a function of R_{AD}, which is a good parameter on measuring how important AD is.

Li et al. (2008)

- AD is still important in weakly ionized MCs at small length scale and that leads to important astrophysical implication on many aspects of the MCs (e.g. morphological change, clump mass function, mass/flux ratio, ions & neutrals line width ratio, correction of Chandrasekhar-Fermi method, turbulence enhancement to AD diffusion, AD heating, …) when AD is strong.

McKee, Li, & Klein (2010), Li, McKee, & Klein (2011)