Turbulent transport of astrophysical magnetic fields

Reinaldo Santos-Lima
Collaborators

Gustavo Guerrero (UFMG, Belo Horizonte)
Elisabete de Gouveia Dal Pino (IAG-USP, São Paulo)
Alex Lazarian (UW-Madison)
Camila Koshikumo (IAG-USP, São Paulo)

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Matthias Rheinhardt (Aalto Un., Finland)
Siyao Xu (UW-Madison)

S. Andrews, L. Cieza, A. Isella, A. Kataoka, B. Saxton (NRAO/AUI/NSF), and ALMA (ESO/NAOJ/NRAO)
Motivation: star formation

- Giant molecular cloud
  ~10pc
- Clumps < 1pc
- Dense cores (sub/super-critical)
- Protostar + Keplerian disk
  ~100 AU
- Young planetary system
Star formation phases

Giant molecular cloud
~10pc

Clumps
< 1pc

Dense cores
(sub/super-critical)

Protostar + Keplerian disk
~100 AU

Young planetary system
Magnetic flux problem

Star-forming environment: relatively low electrical resistivity

⇒ magnetic diffusion required by observations ~ $10^3$ times the Ohmic diffusion \((Shu \ et \ al. \ 2006)\)

Efficiency has been challenged by observations \((Lazarian, \ Esquivel \ & \ Crutcher \ 2012)\) and theory \((Shu \ et \ al. \ 2006)\)

Ambipolar Diffusion (AD)

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \nabla \times \left\{ \frac{(\mathbf{J} \times \mathbf{B}) \times \mathbf{B}}{c \gamma_{\text{in}} \rho \rho_i} \right\}
\]
Diffusion by turbulent reconnection

• Turbulence boosts magnetic field reconnection rate [see talk by G. Kowal]
  ⇒ efficient the transport of tube fluxes

• Violation of the frozen-in condition: magnetic field diffusion independent of the medium resistivity

Theoretical prediction for the Reconnection Diffusion (RD) coefficient:

\[ D_B = \ell v_\ell \times \min \left\{ 1, \left( \frac{v_\ell}{v_A} \right)^3 \right\} \]  

(Lazarian 2005)
Can RD solve the magnetic flux problem?

- **Yes! demonstrated in:** Santos-Lima et al. (2010), Leão et al. (2013)
- RD can turn **sub-critical** cores into **supercritical** ones (Leão et al. 2013)
- RD can explain the observed mass-flux ratio relation between cloud core and envelope (Crutcher et al. 2011; Leão et al. 2013)
Why do we need turbulence?

The **big power-law in the Sky**

- ISM turbulence is MHD turbulence
- Scales ranging from AUs to kpc
- Sources: Supernova, galactic arms, outflows, etc.
- Phases of the ISM: different MHD turbulence regime.

Chepurnov & Lazarian (2010)

Burkhart et al. 2009
Why does turbulence appear?

\[
\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{\nabla P}{\rho} + \nu \nabla^2 \mathbf{v}
\]

**Turbulent flows:** \( \text{Re} \sim \frac{\text{advection}}{\text{viscosity}} \sim \frac{\ell \nu}{\nu} \gg 1 \)

- Sun’s convection zone: \( \text{Re} \sim 10^{13} \)
- Protostellar disks: \( \text{Re} \sim 10^{9} \)
- Interstellar medium: \( \text{Re} \sim 10^{7} \)
- Intracluster medium of galaxies: \( \text{Re} \sim 10^{2} \)
MHD turbulence presence during star formation

Protostellar source Ser-emb 8

Data consistent with trans- or super-Alfvénic turbulence in the host cloud

*Hull et al. (2017)*
Star formation phases

Giant molecular cloud
~10pc

Clumps < 1pc

Dense cores (sub/super-critical)

Protostar + Keplerian disk
~100 AU

Young planetary system
Magnetic braking catastrophe

- **Ideal MHD theory** → formation of rotationally supported disks is suppressed

- Magnetic fields mediate extraction of angular momentum from the disk, preventing the formation of a **Keplerian disk** (Allen et al. 2003; Galli et al. 2006; Krasnopolsky 2010; Li et al. 2011; Santos-Lima et al. 2012; González-Casanova et al. 2015; Lam et al. 2019; ...)

*Santos-Lima, de Gouveia Dal Pino & Lazarian (2012)*
But we do observe protoplanetary disks!

[S. Andrews, L. Cieza, A. Isella, A. Kataoka, B. Saxton (NRAO/AUI/NSF), and ALMA (ESO/NAOJ/NRAO)]
Can RD allow the formation of Keplerian protostellar disks?

Reconnection diffusion removes MF excess

Which mechanism does allow disk formation?

- AD, Ohmic resistivity or RD? Comparison depends on the quantitative knowledge of the transport rate due to each one.
- Quantitative tests of the RD was still missing.
- The study described in the following supports the predictions of the RD theory and allows a more careful interpretation of the RD in numerical simulations.
Disk formation at different levels of turbulence

Koshikumo et al, in prep
Back to the RD theory: missing quantitative test

- Turbulence boosts magnetic field reconnection rate [see talk by G. Kowal]
  ⇒ efficient the transport of tube fluxes

- Violation of the frozen-in condition: magnetic field diffusion independent of the medium resistivity

Theoretical prediction to be tested: $D_B = \ell v_\ell \times \min \left\{ 1, \left( \frac{v_\ell}{v_A} \right)^3 \right\}$
Direct numerical simulations: forced turbulence

- **The Pencil Code** *(Brandenburg et al.)*, 3D-MHD

\[
\begin{align*}
\frac{D\ln \rho}{Dt} &= -\nabla \cdot \mathbf{v}, \\
\frac{D\mathbf{v}}{Dt} &= -c_s^2 \nabla \ln \rho + \frac{1}{\rho} \mathbf{J} \times (\mathbf{B}_0 + \mathbf{B}) + \nu_3 \nabla^6 \mathbf{v} + \mathbf{f}, \\
\frac{\partial \mathbf{A}}{\partial t} &= \mathbf{v} \times (\mathbf{B}_0 + \mathbf{B}) + \eta_3 \nabla^6 \mathbf{A},
\end{align*}
\]

- **Test Field method** *(Schrinner et al. 2005, 2007; Brandenburg et al. 2010)*
- Non-helical forcing, subsonic, subAlfvenic, uniform \( B_0 \), \( k_{\text{INJ}} L = 3-5 \), \( \nu_3 = \eta_3 \)
First results

Theoretical prediction:

\[ D_B = \ell v_\ell \times \min \left\{ 1, \left( \frac{v_\ell}{v_A} \right)^3 \right\} \]

\[ \eta \sim L_i V_i M_A^{0-1} \]

Karak et al. (2014)
Deviations from the RD theory/LV99 hypotheses?

• Compressibility?

• Deviations of turbulence from the statistics of the weak regime?
  • Due to finite box size (Nazarenko 2007)
  • Due to the forcing used (Perez & Boldyrev 2008; Bigot & Galtier 2011; Alexakis 2011; Meyrand et al. 2015)
Direct numerical simulations of the RD:

1. Forcing effects
Forcing distribution in K-space: 2D modes

Amplitude independent of $\theta$

Amplitude $\propto (k_{||})^2$

Santos-Lima, Guerrero, de Gouveia Dal Pino, Lazarian (2021)
Turbulent diffusivity

\[ M_A^2 \propto \frac{V_{turb}}{B_0} \]

Validit of WTT

\[ M_A^3 \propto \frac{V_{turb}}{B_0} \]

2D solenoidal velocities

\[ \frac{\langle \nu_{2D,\text{sol}} \rangle}{v_{\text{turb}}} \]

Santos-Lima, Guerrero, de Gouveia Dal Pino, Lazarian (2021)
Direct numerical simulations of the RD:

1. Forcing effects
2. Finite domain size
Box length parallel to B

Turbulent diffusivity

\[ \frac{\eta_{LT}}{\frac{1}{2} \epsilon_{\text{rms}}} \]

\[ M_A \propto \frac{V_{\text{turb}}}{B_0} \]

Santos-Lima, Guerrero, de Gouveia Dal Pino, Lazarian (2021)
Turbulence Power Spectrum

$L_{\parallel} = 3L_{\text{inj}}, \text{Ma}=0.4$

$L_{\parallel} = 48L_{\text{inj}}, \text{Ma}=0.4$

Santos-Lima, Guerrero, de Gouveia Dal Pino, Lazarian (2021)
Direct numerical simulations of the RD:

1. Forcing effects
2. Finite domain size
3. Compressibility
Turbulence with finite compressibility

Turbulent diffusivity

Santos-Lima, Guerrero, de Gouveia Dal Pino, Lazarian (2021)
1. Some star forming processes seem to require the violation of the frozen in condition. The RD mechanism appears as a natural solution, and the comparison of its efficiency with other mechanisms depends on the quantitative knowledge of the RD rates.

2. Our numerical simulations seem to be consistent with the RD diffusion theory prediction for the diffusivity when approaching the incompressible limit, and show an increased efficiency when turbulence is compressible.

3. The common choices for turbulence forcing in numerical studies introduce artificial effects that cause the diffusion coefficient to deviate from the RD theory in the regime of strong magnetic fields.