Moving mesh magnetohydrodynamics: the role of magneto-turbulence in star formation

Philip Mocz

Princeton University
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How does the Universe work?  – Einstein Fellows
How did we get here?  – Hubble Fellows
Are we alone?  – Sagan Fellows
How does the Universe work?

A hierarchy of physical processes...

- initial conditions
- gravity
- fluid dynamics, turbulence
- radiation
  - microphysics
  - feedback
  - ...

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How does the Universe work?

- 0\textsuperscript{th} order: gravity often is most important
  - Sometimes gravity wins on even the smallest scales...

- 1\textsuperscript{st} order: is often fluid dynamics
  - study of fundamental physical processes
    - structure formation
    - turbulence
    - different regimes where qualitative behavior changes
magneto-gravo-turbulence in star formation

* (Mocz et al., 2017), (Hull, Mocz, Burkhart, McKee et al., 2017)
Overview

mock CARMA

Hull+(2014)

self-gravity

density pdf

\[ \log_{10}(\rho) \]

\[ t = 0.5t_{ff}, \rho^{-3/2} \]
Star formation background

- competition between turbulence, self-gravity & $B$-field
- basic theory predicts cores collapse and form **hourglass** shaped magnetic fields
- sub- or super-Alfvénic turbulence?

NGC 1333
IRAS4A
(Girart, Rao, Marrone 2006)
Origin of magnetic field structure

- **inherit** strong field from large-scale medium
- **amplify** weak field via turbulence

- **magnetic topology problem**\(^{(Mckee+1993)}\): how does the magnetic field topology evolve as the ISM forms molecular clouds and cores contract to form stars?
How does contraction of cores happen?

\[ B \propto \rho^\alpha \]

(Tritsis+2015)
Is core-formation self-similar? (Li+2015)

- self-similar scaling $100 \rightarrow 0.1$ pc (SMA)
- dynamically important $B$-fields
- anisotropic contraction
Or not! Zeeman obs. of $B$-field in clouds

- $B \propto \rho^{0.67}$, weak-field preferred
- Zeeman measurements are the gold standard for $B$-field

(Crutcher+2012)
What about smaller scales? (Hull, PM+2016)

CARMA (0.1 pc) ⇒ ALMA (0.01 pc)

- new Ser–emb 8 Type 0 protostar ALMA observation
- pinches, filaments, clumps, **chaotic!**
What can simulations teach us?: Setup

- turbulent, magnetized, self-gravitating ISM cloud ($L_0 \sim 5$ pc)
- isothermal
- $M_s = \frac{v_{\text{rms}}}{c_s} = 10$
- $\alpha_{\text{vir}} = 5v_{\text{rms}}^2(L/2)/(3GM_0) = 1/2$
- $M_A = \langle |\mathbf{v}| \rangle / \langle |\sqrt{B^2/4\pi \rho}| \rangle = 0.35, 1.2, 3.5, 35$
Simulations of star formation in turbulent ISM
$B-\rho$ scaling

**Weak-field**

$M_{A,\text{mean-field}} = 3.5$

**Strong-field**

$M_{A,\text{mean-field}} = 0.35$

(transition at $\rho_{\text{crit}} = \langle \rho \rangle M_s^2/3$)
Density-averaged radial profiles

Weak-field

$M_{A, \text{mean-field}} = 3.5$

Strong-field

$M_{A, \text{mean-field}} = 0.35$
Conclusions – I

Weak-field

- $B \propto \rho^{2/3}$
- isotropic
- turbulent morphology
- not self-similar
- $\beta = 1$ @ collapse outer-scale

Strong-field

- $B \propto \rho^{1/2}$
- anisotropic
- hourglass morphology
- self-similar
- $\beta = 1$
Conclusions – II

- $M_A \sim 1$ a good fiducial value for star formation
- Star formation may occur in both $M_A \gtrsim 1$ and $M_A \lesssim 1$ environments, very different consequences!
  - turbulent vs. hourglass morphology
  - different central magnetic field strengths
  - higher $B$ leads to more massive stars, less fragmentation
Despite core properties being similar, mean-field direction as function of length-scale strongly depends on the mean-field $M_{A,0}$.

Future ALMA observations of young proto-stellar systems can constrain $M_{A,0}$.
Turbulent reconnection diffusion

- evidence for turbulent-reconnection seen in our simulations
- Mass-to-flux ($\mu_{\Phi,0}$) in cores evolves during collapse as:
  - $\mu_{\Phi,0} = 80 \rightarrow 12.7$
  - $\mu_{\Phi,0} = 8 \rightarrow 16.5$
  - $\mu_{\Phi,0} = 2.7 \rightarrow 12.1$
  - $\mu_{\Phi,0} = 0.8 \rightarrow 5.8$

(Lazarian & Vishniac, 1999)
Density- vs Volume- averaged B-fields

- Crutcher+ (2012) Zeeman measurements recover \textit{density}-averaged $B$-fields
- $B-\rho$ scaling can be steeper with \textit{density}- as opposed to \textit{volume}-average
- Li, McKee, Klein (2015) find mass-to-flux is also affected by type of averaging
- demonstrates the importance of modeling all observational effects for interpretation of data

(Li, McKee, Klein, 2015)
Self-gravitating turbulent box properties

Histogram of Relative Orientations (Soler+2013)

- $B$–field & velocities tend to align, especially at low density
- $\nabla \cdot \mathbf{B} = 0$, shocks, prevent perfect alignment
- $B$–fields aligned with density gradient at high densities
- transition occurs at critical density $\rho_{\text{crit}}$ (Chen, King, Li, 2016)
Large-scale EE/BB modes

- *Planck* dust polarization maps of interstellar turbulence show $\text{EE/BB}=2$ (Caldwell, Hirata, Kamionkowski 2016)
- Analytic theory predicts $\text{EE/BB}=1$ for turbulence
- My simulations confirm analytic theory $\text{EE/BB}=1$ for super-Alfvenic turbulence
- $\text{EE/BB}=2$ might indicate stirring-scale or strong $B$-fields