Multiphase interstellar medium: a physical approach and identifying the mean field

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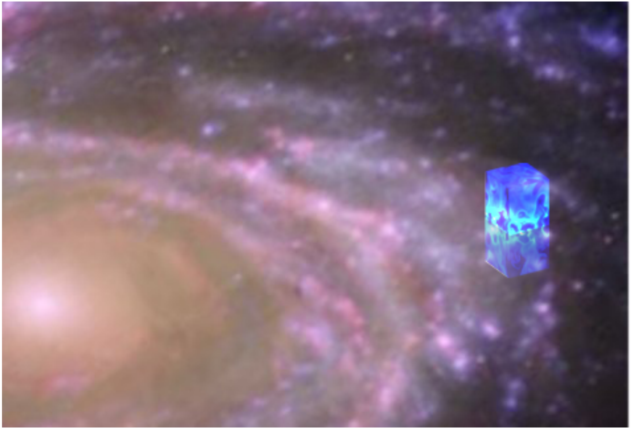
Outline of presentation

- HD and MHD model
- Problems identifying phases
- Physical features of phases
- Fitting a PDF model
- Identifying a galactic dynamo
- Defining the mean **B**
- A work in progress



2 million cpu hours
280 processors

box: $1 \times 1 \times 2\,\mathrm{kpc}^3$
$256 \times 256 \times 560$ resolution

ISM SN dynamics 3D simulation

Figure: SNe light flashes

Figure: SNe dark bubbles

Composition of the ISM a multi-phase environment
(Cox & Smith 1974, McKee & Ostriker 1977)

What is meant by 'multi-phase'? (Differential cooling – compressions)

Composition of the ISM

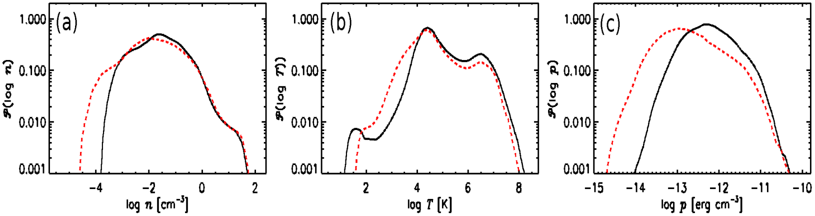
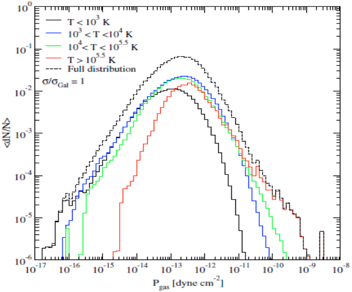


Figure: Probabilty Density Functions for log number density n (left), log temperature T (centre) and thermal pressure p (right).

(de Avillez & Breitschwerdt 2004)
suggest no real phases
$\mathcal{P}(\log p) = 0.01$ spans $10^{-14} - 10^{-11}$
not in pressure equilibrium



Looking for phase differences

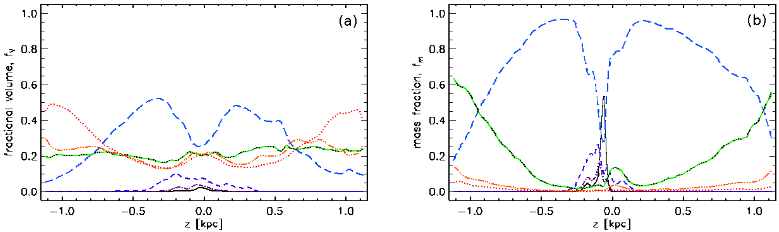


Figure: Fractional volume (left) and mass fraction (right) by z of each band of temperature, time averaged over the steady state.

$$f_{V,i}(z) = \frac{V_i(z)}{V(z)} = \frac{N_i(z)}{N(z)}, \qquad f_{M,i}(z) = \frac{M_i(z)}{M(z)},$$

Temperature band	Line style	Phase
$T < 5 \times 10^1$ K	solid black	cold
$5 \times 10^1 \text{ K} \leq T < 5 \times 10^2$ K	purple dash-dot	cold
$5 \times 10^2 \text{ K} \leq T < 5 \times 10^3$ K	dark blue dashed	warm (transitional)
$5 \times 10^3 \text{ K} \leq T < 5 \times 10^4$ K	light blue long dashed	warm
$5 \times 10^4 \text{ K} \leq T < 5 \times 10^5$ K	green/black dash-dot	warm (transitional)
$5 \times 10^5 \text{ K} \leq T < 5 \times 10^6$ K	orange dash-dot	hot
$T \geq 5 \times 10^6$ K	red dotted	hot

Density PDFs by phase

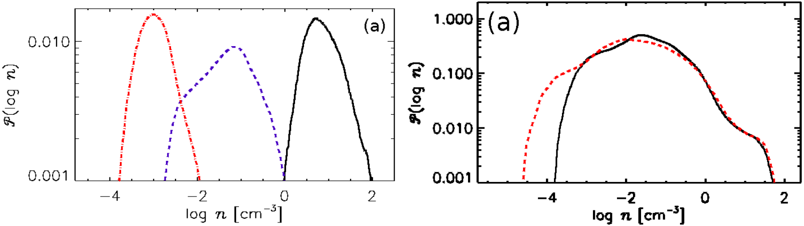


Figure: Density PDFs (left) for cold (black), warm (blue,dashed) and hot gas (red,dash-dotted) and right the whole ISM (black).

Cold $T < 500\,\mathrm{K}$, warm $500 \geq T < 5 \times 10^5\,\mathrm{K}$, hot $T \geq 5 \times 10^5\,\mathrm{K}$

Velocity PDFs by phase

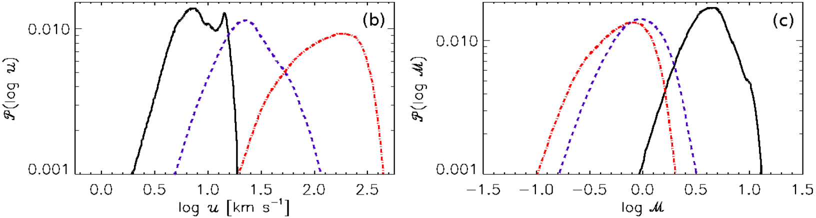


Figure: Velocity (left) and Mach number (right) PDFs for cold (black), warm (blue,dashed) and hot gas (red,dash-dotted).

$$\mathcal{M} = \frac{u}{c_s},$$

where u is the local speed,

and c_s the local adiabatic sound speed.

Systemic velocity(z) by phase

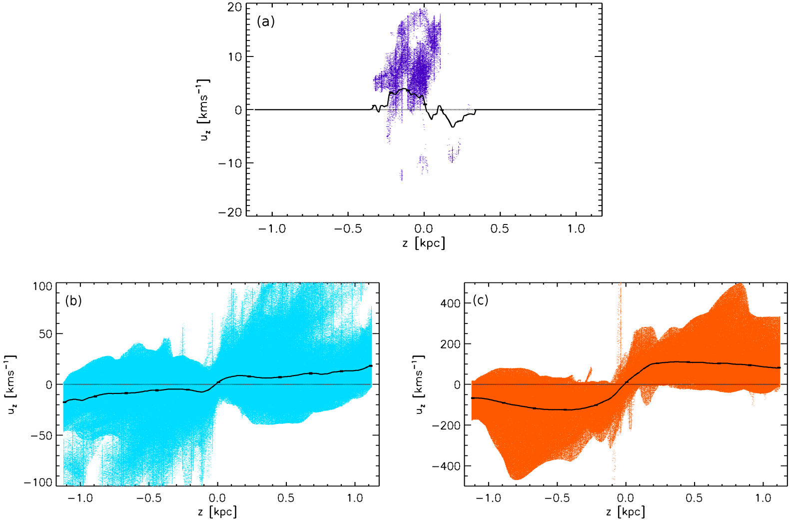


Figure: Velocity u_z scatter plots for for cold (black), warm (blue) and hot gas (orange), with $\langle u_z(z) \rangle$ by phase overplotted.

Pressure PDFs by phase

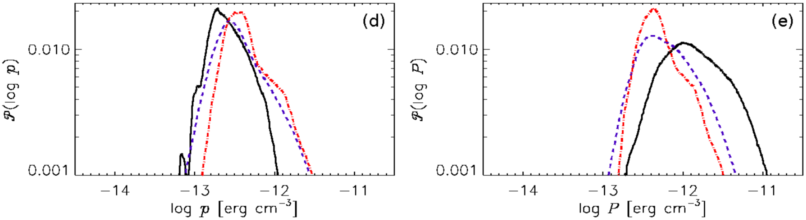


Figure: Thermal (left) and total (right) pressure PDFs for cold (black), warm (blue,dashed) and hot gas (red,dash-dotted).

$$P = p_{\rm therm} + p_{\rm turb}; \qquad p_{\rm turb} = \frac{1}{3}\rho u_{\rm turb}^2,$$

where $\mathbf{u}_{\rm turb}(z) = \mathbf{u}(z) - \langle u_z(z)\rangle\hat{\mathbf{z}}$ are the random motions of the ISM.

Lognormal fitting the density PDFs

$$\mathcal{P}(n) = \Lambda(\mu_n, s_n) \equiv \frac{1}{n s_n \sqrt{2\pi}} e^{-\frac{(\ln n - \mu_n)^2}{2 s_n^2}}$$

Phase	μ_n [ln cm^{-3}]	s_n [ln cm^{-3}]	$\overline{n}$ [cm^{-3}]	σ [cm^{-3}]	ϕ_n
Gas density from the simulation, $\lvert z\rvert < 1\,\mathrm{kpc}$					
Cold			12.4	3.57	0.38
Warm			0.14	0.11	0.080
Hot			0.0019	0.0017	0.085
The lognormal approximation, $\lvert z\rvert < 1\,\mathrm{kpc}$					
Cold	1.88	0.95	10.3	14.7	0.41
Warm	−3.03	1.59	0.17	1.96	0.08
Hot	−6.91	0.85	0.0014	0.0015	0.49

$$\phi_{n,i} = \frac{\overline{n_i}^2}{\overline{n_i^2}} = e^{-s_n^2}$$

2D PDF of ρ vs T

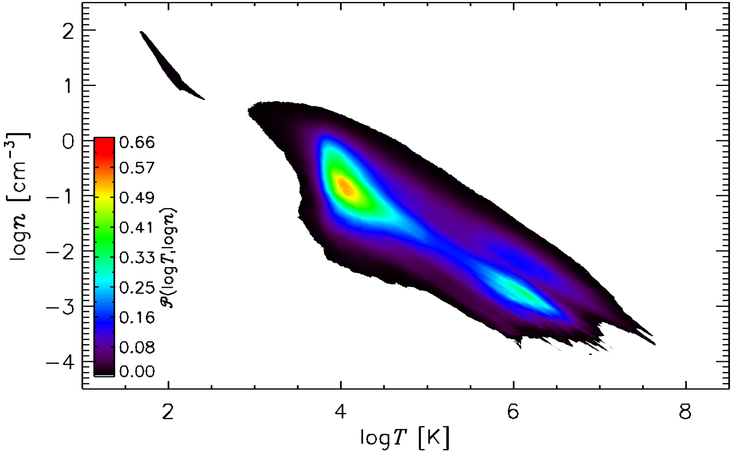


Figure: Probability density contour plot of $\log \rho$ vs $\log T$.

2D PDF of ρ vs T

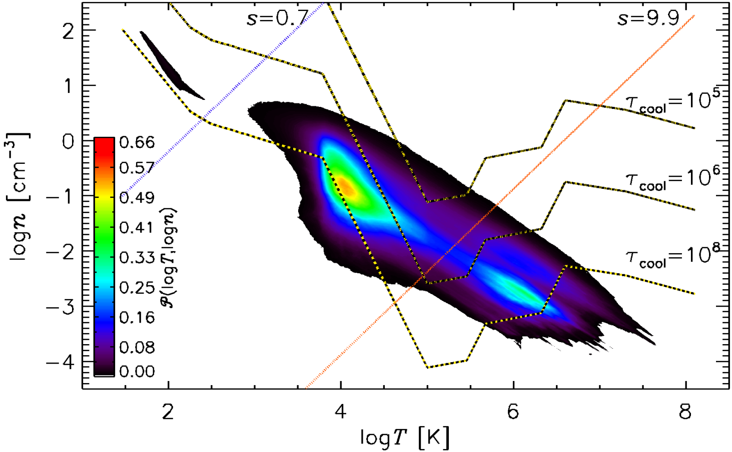


Figure: Probability density contour plot of $\log\rho$ vs $\log T$. The red and blue lines contours of constant specific entropy s $[\mathrm{km}^2\,\mathrm{s}^{-2}\,\mathrm{K}^{-1}]$.

$$s = \frac{\gamma}{c_p}(\ln T - \ln T_0) + \left(\frac{\gamma - 1}{\gamma}\right)(\ln\rho - \ln\rho_0), \qquad p = nk_\mathrm{B}T$$

4-phase PDFs of density

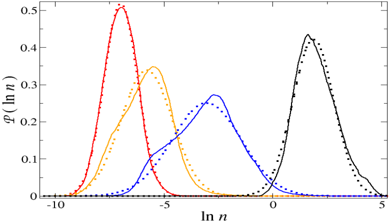


Figure: Left: lognormal fits of density PDFs for cold (black), warm (blue), hot $|z| \leq 200\,\mathrm{pc}$ (orange) and hot $|z| > 200\,\mathrm{pc}$ (red).

Phase Hot	μ_n [ln cm^{-3}]	s_n [ln cm^{-3}]	$\overline{n}$ [cm^{-3}]	σ [cm^{-3}]	ϕ_n
Gas density from the simulation, $\lvert z\rvert < 1\,\mathrm{kpc}$					
≤ 200			0.0062	0.0042	0.129
> 200			0.0013	0.00045	0.404
The lognormal approximation, $\lvert z\rvert < 1\,\mathrm{kpc}$					
≤ 200	-5.78	1.17	0.0031	0.00531	0.25
> 200	-6.97	0.77	0.0013	0.00117	0.55

Redefining temperature phases

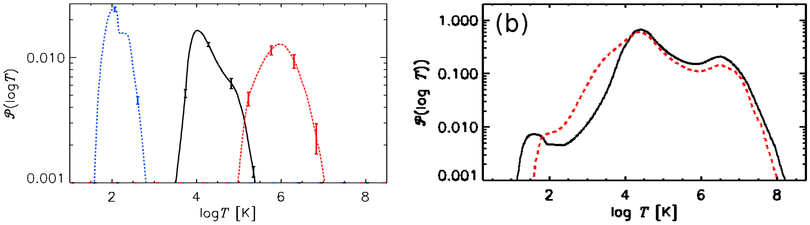


Figure: Left: temperature PDFs for 3-phases defined by s. Right: temperature PDF for full ISM (black) – cut at 500 K and 5×10^5 K for 3-phases defined by temperature.

- Counting – categorising – Not of interest
- Do we define dynamically useful descriptions?

Finding a galactic dynamo

MHD ingredients

- Differential rotation
- SN - source of vorticity?
  - collisions
  - bubbles
  - density gradient
  - turbulence
- Azimuthal seed **B**
  - $\overline{B}_y \simeq 0.4\,\text{nG}$
- Magnetic diffusivity

Multiphase structure of **B**-Field

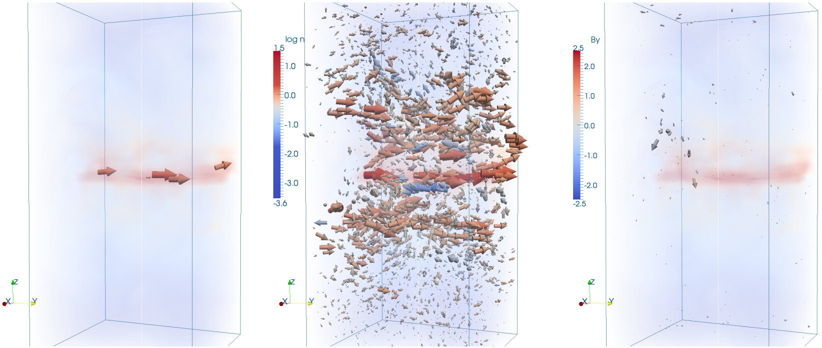


Figure: 3D snapshot of **B** filling (a) the cold gas, (b) the warm gas and (c) the hot gas. Common scaling: arrows show direction and strength, colour indicates B_y, and fill volume coloured by $\log n$.

Growth of total B

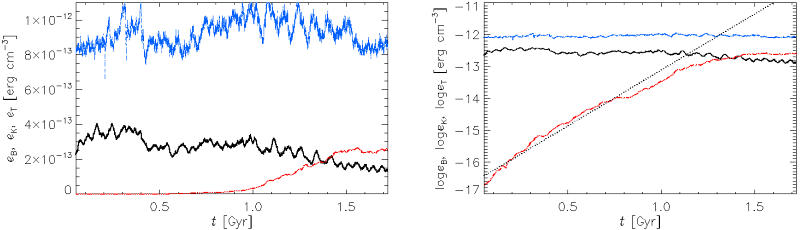


Figure: Time series of volume averages (left) and log averages (right) of thermal (blue), kinetic (black) and magnetic (red) energy densities. Dotted line estimated $6.6 \cdot 10^{-14}\,\mathrm{erg\,cm^{-3}}$ Gyr^{-1} exponent of magnetic energy growth rate.

Growth of the mean B

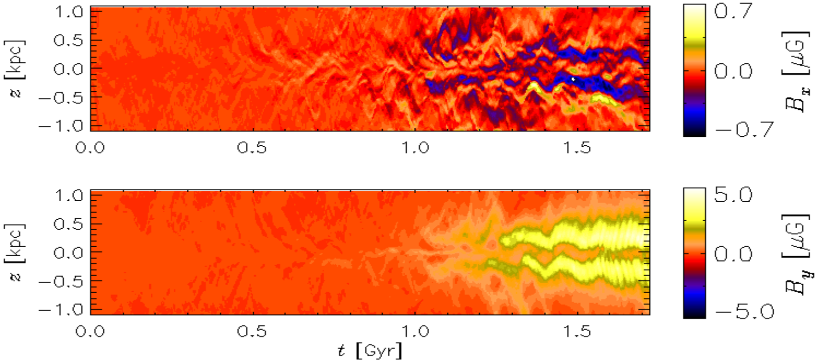


Figure: Time evolution of horizontal averages for B_x (top) and B_y (bottom). Horizontal averages for $B_z \simeq 0 \,\forall\, z$.

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{b},$$

where $\mathbf{B}_0$ is the regular or mean field, and $\mathbf{b}$ the random or fluctuating components, with $\langle \mathbf{b} \rangle = \mathbf{0}$.

How do we identify the mean field

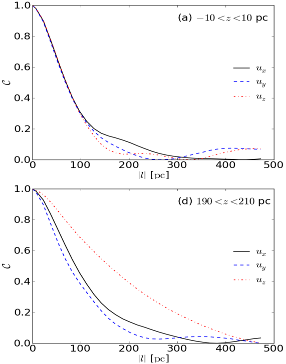


Figure: Autocorrelation: velocity u_x (black), u_y (blue) and u_z (red) for layers 20 pc thick centered; $-10 < z < 10$ pc top, $190 < z < 200$ pc bottom.

- Volume averaging
- Horizontal averaging
  (Gressel 2008)
  (Dobbs & Price 2008)
- Averaging by phase or total ISM
- Convolve **B** with gaussian

$$\mathbf{B}_0(\mathbf{x}) =$$

$$\frac{1}{(\sqrt{2\pi} l_B)^3} \int_V \mathbf{B}(\mathbf{x}') \exp\left\{\frac{-(\mathbf{x}-\mathbf{x}')^2}{2 l_B^2}\right\} d\mathbf{x}'$$

$$\mathbf{B}_0(\mathbf{k}, l_B) = \mathbf{B}(\mathbf{k}) \exp\left\{\frac{-(l_B^2 \mathbf{k}\cdot\mathbf{k})^2}{2}\right\}$$

3D and 1D spectra

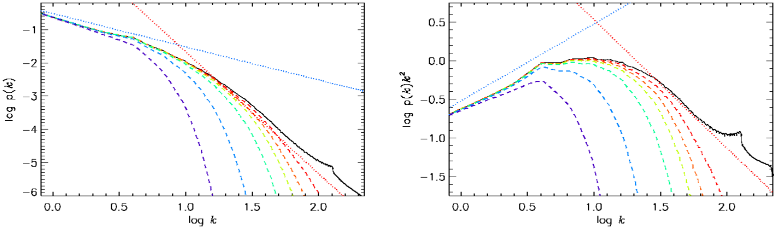


Figure: Left: Single snapshot 3D $\log|B(k)|$ averaged over spherical shells, over plotted with convolved profiles plotted for $l_c = 50, 75, 100, 150, 300\,\mathrm{pc}$. Right: rescaled by k^2 for 1D spectra.

$l_c = \mathrm{FWHM}$ (full width half maximum) and $l_c = 2\sqrt{2\ln 2}\,l_B$.

l_c	$\langle B_0^2\rangle$	$\langle b^2\rangle$
Total **B**	2.77	0.00
50	1.28	1.45
100	1.25	1.46
300	1.09	1.52

Comparing total mean field

Figure: snapshot convolved **B** field over entropy slices ($l_c = 50\,\mathrm{pc}$)

Figure: snapshot total **B** field over entropy slices

Growth of the field components

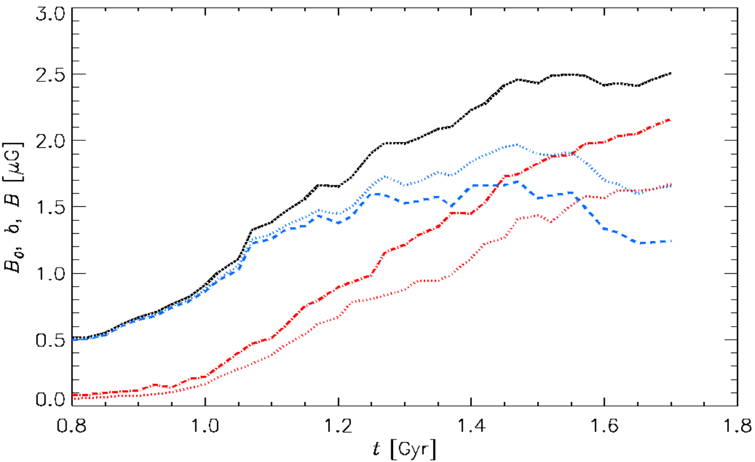


Figure: Growth of magnetic energy. Total $\langle B_{\rm rms} \rangle$ (black) $\langle B_0 \rangle$ (red) and $\langle b_{\rm rms} \rangle$ (blue). Dashed lines: $\mathbf{B}_0$ derived using horizontal averages; dotted lines: derived using convolved gaussian.

Summary and discussion

- Is the multi-phase description of the ISM accurate and useful?
- Does the composition of the ISM have lognormal properties?
  – and if so is it useful?
- Why is it important to define the mean and random properties of the velocity and magentic fields?
- What is the correct physical approach to defining the mean field?
  – and does it affect the result?
- How do we identify the correct l_c to define the mean field?
- Should we revisit p_{turb} with convolved velocity?
- Should we convolve the fields by volume or by phase volume?

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