Turbulence in Molecular Clouds

A laboratory for understanding waves in partially ionized media

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ABSTRACT

Plasma in space are omnipresent, but generally found in a partially ionized state only. Thus, we need to consider the interaction between ionized and neutral gases. Since the coupling between both gases is mediated via collisions we expect, on scales shorter than their collision frequency, the gases to increasingly decouple while on larger scales the gases to move in unison. This has immediate consequences for MHD waves in the medium requiring a deviation from a single-fluid treatment, i.e. two-fluid MHD (2FMHD).

Although 2FMHD predicts a „decoupling gap“ for MHD modes in which propagation is prohibited, simulations of 2FMHD turbulence do not show such a gap. This suggests that within the framework of ideal 2FMHD an as of yet unknown process that mediates energy through this gap is present.

As Molecular Clouds (MCs) are of generally high interest in Astrophysics and Astronomy due to their role in star formation and Cosmic Ray (CR) propagation, while covering a vast variety of plasma conditions under turbulent conditions over a wide range of scales, they pose as an ideal „laboratory“ to empirically improve current understanding of MHD waves in partially ionized media.

TWO-FLUID MHD

Consider a medium consisting of an ideal ionized (ion-electron, Suffix i) and neutral gas (Suffix n), interacting via collisions. For a static equilibrium, the governing linearized equations (Soler et al. (2013)) are

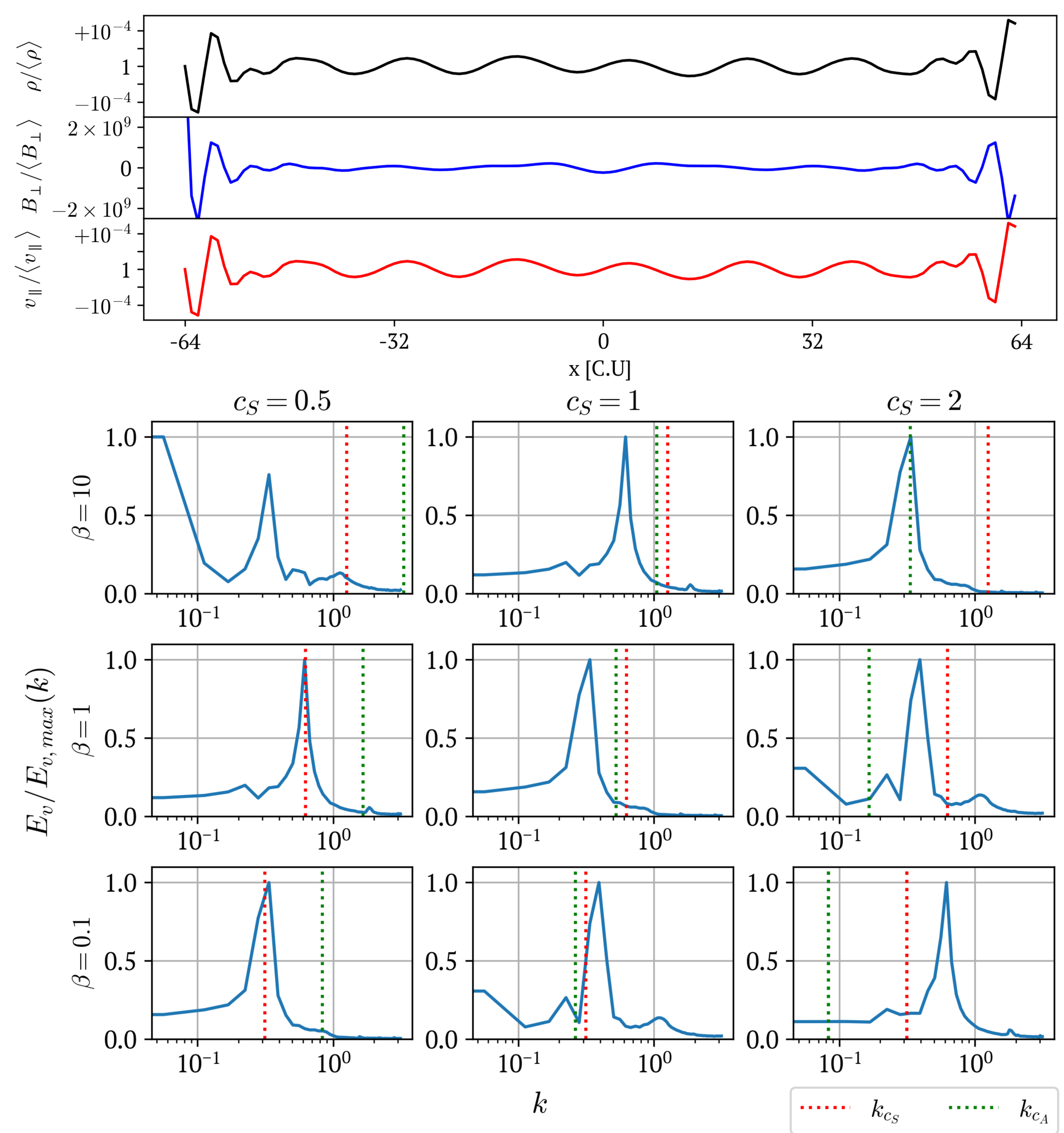
(1) $$\rho_i \frac{\partial \mathbf{v}_i}{\partial t} = -\nabla c_{S,i}^2 \rho_i + \frac{1}{\mu}(\nabla \times \mathbf{b}) \times \mathbf{B} - \gamma_D \rho_i \rho_n (\mathbf{v}_i - \mathbf{v}_n)$$

(2) $$\rho_n \frac{\partial \mathbf{v}_n}{\partial t} = -\nabla c_{S,n}^2 \rho_n - \gamma_D \rho_i \rho_n (\mathbf{v}_n - \mathbf{v}_i)$$

(3) $$\frac{\partial \mathbf{b}}{\partial t} = \nabla \times (\mathbf{v}_i \times \mathbf{B})$$

(4) $$\nabla \cdot \mathbf{B} = 0$$

Here ρ_a, P_a, $\mathbf{v}_a$, $\mathbf{p}_a$ and $c_{S,a}$ are the equilibrium density and pressure, the perturbed velocity and momentum and the sound speed of fluid a, respectively. $\mathbf{B}$ is the equilibrium and $\mathbf{b}$ the perturbed magnetic field, γ_D the drag coefficient and μ the

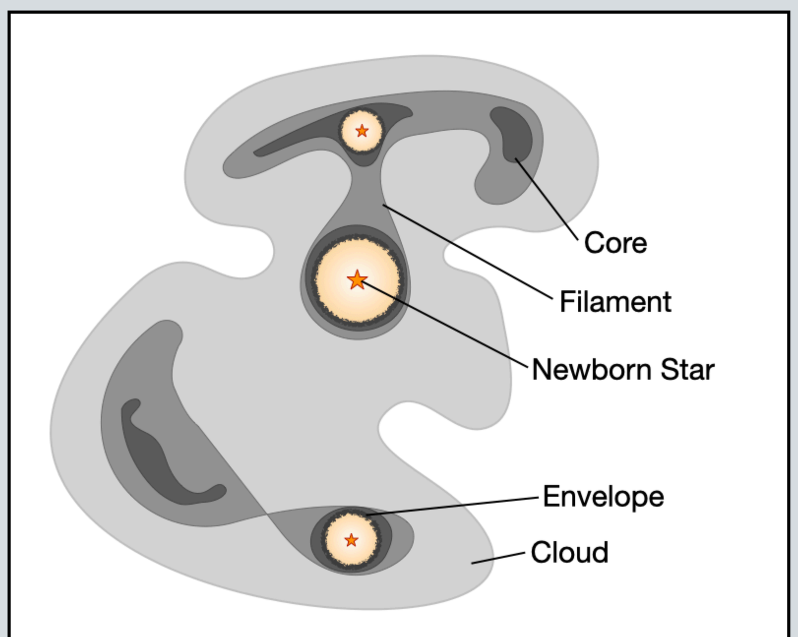


SIMULATIONS

- Meassurement of Plasma Response to periodic perturbation of velocity-field at boundaries, along single axis in a periodic box deploying modified AthenaK (Stone et al. 2020)
- Scanning various relevant (MC-like conditions) plasma parameters: γ_D, $c_{S,i}$, $c_{S,n}$, ρ_i, ρ_n and $\beta = 2(c_S/v_A)^2$
- **Currently:** Calibration of Plasma Response Frequency Spectra, **Next**: Frequency-scan for various systems
- **Further Goal:** Identify possible signature of the decoupling gap in turbulent power spectra
- **Ultimately:** Investigate energy transfer through the gap & identify physical process responsible for bridging the gap

MOLECULAR CLOUDS

- Clouds of gas and dust with conditions for molecule formation, primarily molecular Hydrogen (H_2)
- Nurseries of stars and integral part in CR propagation within the galaxy
- Densest, coldest and darkest regions in the ISM
- Hierarchical filamentary structure dominated by turbulent motion
- Ionization in innermost regions solely governed by CR ionization
- Large scale disruptions drive turbulence (e.g. Supernovae)



Environment	T [K]	ρ [cm^{-3}]	ρ_i/ρ_n	r [pc]	gas state
Warm neutral medium (WNM)	8700	$\sim 10^{-1}$	0.017	-	ionized
Cold neutral medium (CNM)	60	$\sim 10^{1}$	1.6×10^{-4}	-	atomic
Cloud envelope	25	$\sim 10^{3}$	3.2×10^{-4}	$\lesssim 200$	molecular
Filaments	~ 10	10^4	10^{-7}	0.5 – 100	molecular
Cores	$\lesssim 10$	$\gtrsim 10^5$	10^{-8}	0.1	molecular

DECOUPLING GAP

The characteristic timescales of collisional coupling are the neutral-ion ($\nu_{ni} = \gamma_D \rho_i$) and ion-neutral ($\nu_{in} = \gamma_D \rho_n$) collision frequency. Alfvén waves may only propagate in both gases as long as collisions occur faster than the wave's frequency. With these considerations we can approximate the decoupling gap:

In MCs: **Low ionization limit:**

$$\rho_n \gg \rho_i \implies \chi \equiv \rho_n/\rho_i = \nu_{in}/\nu_{ni} \gg 1,$$

Lower limit: On large scales both species are expected to move together, i.e. we consider their combined Alfvén velocity and assume $\omega \ll \nu_{ni}$

$$v_A = B/\sqrt{4\pi(\rho_i + \rho_n)} \implies k^-_{dec} v_A \sim \nu_{ni}$$

Upper limit: On small scales we expect the ions to move separate from the neutrals, i.e. we only consider the ions Alfvén velocity and assume $\omega \gg \nu_{in}$

$$v_A \to v_{A,i} = B/\sqrt{4\pi\rho_i} \implies k^+_{dec} v_{A,i} \sim \nu_{in}$$

Additionally we can estimate the decoupling gap width in the low ionization limit as

$$\frac{k^+_{dec}}{k^-_{dec}} \sim \frac{\nu_{in}}{\nu_{ni}} \frac{v_A}{v_{A,i}} = \sqrt{\chi}.$$

Solving for the general dispersion relation Soler et al. (2013) were able to indentify a cutoff interval $(k_\parallel^-, k_\parallel^+)$ for Alfvén waves propagating along the background magn. field, the decoupling gap more accurately as our simple approximation above

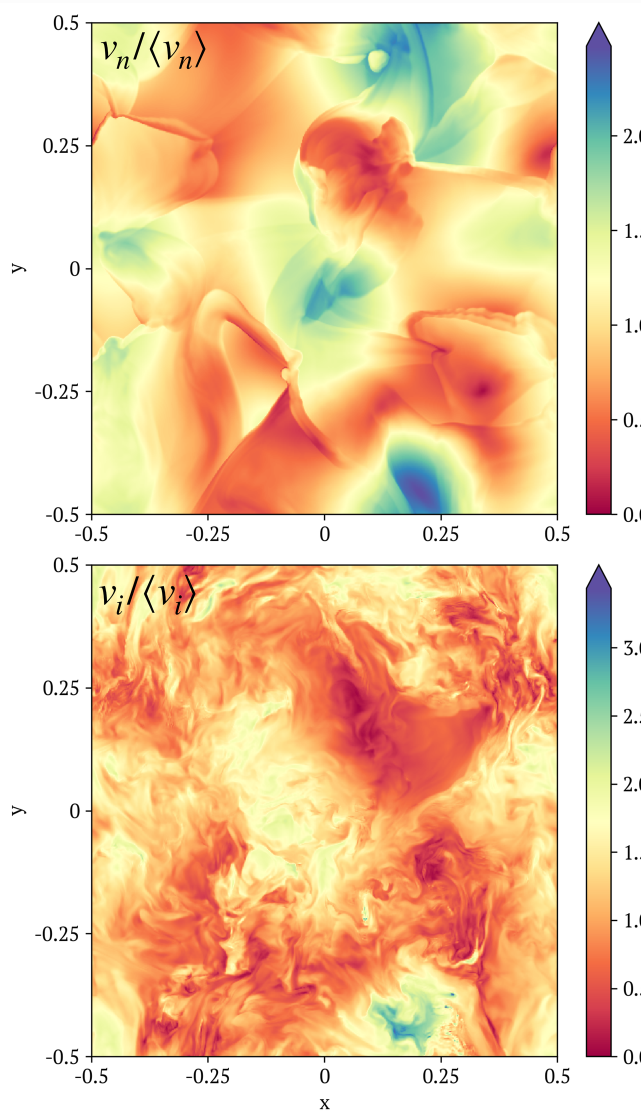
$$k_\parallel^\pm = \frac{\nu_{ni}}{v_{A,i}} \left[\frac{\chi^2 + 20\chi - 8}{8(1+\chi)^3} \mp \frac{\chi^{1/2}(\chi - 8)^{3/2}}{8(1+\chi)^3} \right]^{-1/2}$$

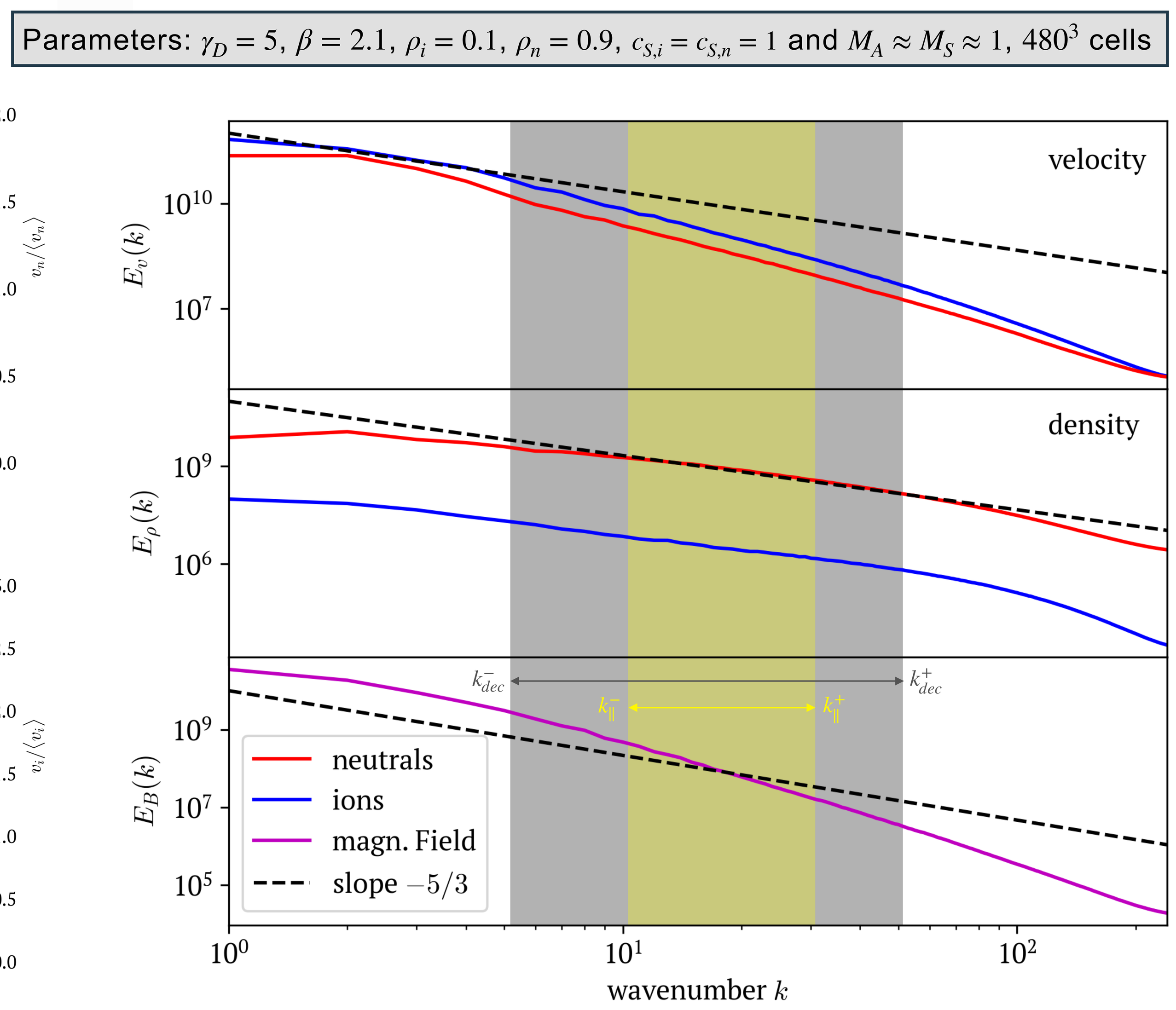
In the low ionization limit we can find approximate solutions

$$k_\parallel^- \approx 2\frac{\nu_{ni}}{v_{A,i}}\sqrt{\chi} \text{ and } k_\parallel^+ \approx 0.6\frac{\nu_{in}}{v_{A,i}}$$

With these the decoupling gap width is

$$\frac{k_\parallel^+}{k_\parallel^-} = 0.3\sqrt{\chi}$$





(1) R. Soler, M. Carbonell, J. L. Ballester & J. Terradas, 2013, ApJ 767, 171
(2) K. Silsbee, A. V. Ivlev, M.Gong, ApJ 922, 10
(3) S. Xu, A. Lazarian, H. Yan, 2015, ApJ 810, 44
(4) Y. Hu, S. Xu, L. Arzamasskiy, J. M. Stone, 2024, MNRAS 527, 3945-3961
(5) J. Ballesteros-Paredes, P. André, P. Hennebelle, R. S. Klessen, J. M. Diederik Kruijssen, M. Chevance, F. Nakamura, A. Adama & E. Vázquez-Semadeni , 2020, Space Sci. Rev. 216, 76
(6) J. M. Stone, K. Tomida, C. J. White, K. G. Felker, 2020, ApJS, 249, 4
(7) P. Goldreich & S. Sridhar, 1995, ApJ 156, 445

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