Note on MHD turbulence in the ISM

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1. GS95 (Goldreich-Sridhar 1995) theory of trans-Alfvenic turbulence (strong MHD turbulence):

   See also Lazarian & Vishniac 1999 (LV99) for super- (turbulent energy at the injection scale of turbulence > magnetic energy) and sub-Alfvenic (turbulent energy at the injection scale of turbulence < magnetic energy) turbulence.

   Critical balance: in the reference frame of local mean magnetic field (LV99), the hydrodynamic turbulent motions (turbulent mixing) in the direction perpendicular to magnetic field has the same time scale as the wave period of the wave-like motions along the magnetic field.

   Scale-dependent anisotropy: stronger anisotropy at smaller length scales, which can be derived from critical balance + perpendicular hydrodynamic motions.

   Compressible MHD turbulence can be decomposed into Alfvenic, fast & slow modes. Fast and slow modes are compressive.

   Applicability of GS95 theory in compressible MHD turbulence: Lithwick & Goldreich 01(high plasma beta); Cho & Vishniac 00; Cho, Lazarian, & Vishniac 02,03 (low plasma beta).

2. Velocity and magnetic field in MHD turbulence

   (1) small-scale turbulent dynamo: nonlinear regime, slow dynamo growth rate (dynamo timescale ~ 19/3 largest eddy-turnover time when the driving scale of turbulence is much larger than the dissipation scale of turbulence, Xu & Lazarian 2016) comes from reconnection diffusion of magnetic fields (see numerical studies by Brandenburg & Subramanian 2005; Cho et al. 2009; Beresnyak et al. 2012).

Fig.1 Turbulent dynamo and diffusion of magnetic fields.

   Small-scale turbulent dynamo in a weakly ionized medium (Xu & Lazarian 2016; two-fluid simulations: Xu, Garain, Balsara, & Lazarian 2019; Brandenburg 2019)

(2) Turbulent reconnection: reconnection diffusion of magnetic fields only depends on turbulence properties, independent of plasma parameters, e.g., resistivity (Lazarian & Vishniac 1999).

Similarity between turbulent diffusion in hydrodynamic turbulence and reconnection diffusion of magnetic fields in MHD turbulence.

(3) Astrophysical applications: uncorrelated magnetic field and density at low densities found in Zeeman measurements (Crutcher et al. 2010; Lazarian, Esquivel, Crutcher 2012), magnetic flux problem (Eyink et al. 13, Santos-Lima et al. 2010), magnetic-braking catastrophe (Santos-Lima et al. 12,13).

(4) Velocity spectrum:

Techniques for separating density and velocity contributions: e.g., velocity channel analysis (VCA), velocity coordinate spectrum (VCS) (Lazarian & Pogosyan 00,04,06; Lazarian 2009), applicable to both super- and sub-sonic turbulence, to both emission and absorption lines.

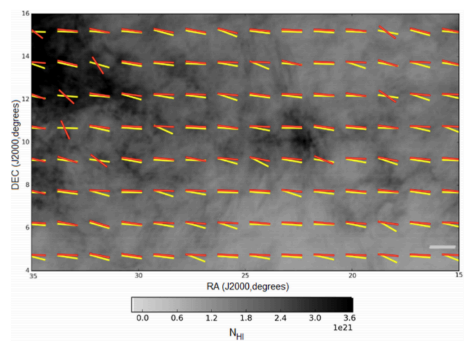

Fig. 2 Yellow---turbulent velocity gradient (GALFA-H I).
Red---magnetic field direction indicated by polarization (PLANCK).
From Yuen & Lazarian 17

(5) Velocity gradient:

Predicted by GS95 theory, tracing well magnetic fields in both diffuse and dense interstellar phases (e.g., Yuen & Lazarian 2017)

3. Density in MHD turbulence

Density spectrum: (1) Gas tracers

(2) Scattering measurements of Galactic pulsars

(3) Rotation measure (RM) fluctuations

Big power law in the sky—spectrum of electron density fluctuations in the warm ionized medium measured from Halpha emission (Chepurnov & Lazarian 2010) and interstellar scattering of nearby pulsars (Armstrong et al. 1995).

Scattering measurements of low-dispersion measure (DM) pulsars reflect Kolmogorov turbulence in the warm ionized medium. Scattering measurements of high-DM pulsars reflect shallow density spectrum in supersonic turbulence in cold interstellar phases in the Galactic disk. The transition DM is around 20 pc cm^-3 (Xu & Zhang 2017).

RM fluctuations by Minter & Spangler 1996 reflect density fluctuations as their structure function has a similar slope as emission measure (EM) fluctuations, which also shows a shallow density spectrum consistent with both pulsar measurements and cold gas tracer measurements (Xu & Zhang 2016).

Density filaments: density fluctuations are passively mixed by Alfvenic turbulence, which explains density filaments aligned with magnetic fields. Numerical testing, Xu, Ji, & Lazarian 2019

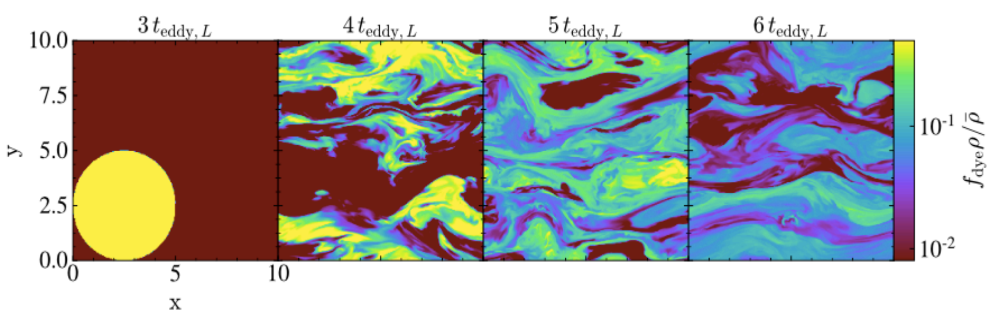

Fig. 4 Dyed density fluctuations in MHD turbulence simulation, showing formation of density filaments due to perpendicular mixing of MHD turbulence. From Xu, Ji, & Lazarian 19

4. Comic rays in MHD turbulence

Parallel diffusion: transit time damping and gyroresonance (Xu & Lazarian 2018)

Perpendicular diffusion: (1) Super-diffusion on length scales smaller than the driving scale of turbulence. Diffusion is accelerated as a function of time, as particles are separated by larger and larger turbulent eddies.

(2) Diffusion on scales larger than the driving scale of turbulence.

Perpendicular (to mean magnetic field) diffusion is suppressed by MA^4 in sub-Alfvenic turbulence (MA<1), where MA = turbulent velocity at driving scale / Alfven velocity.

Yan & Lazarian 2008; Xu & Yan 2013; Lazarian & Yan 2014.

5. Ambipolar diffusion (AD) of MHD turbulence in cold interstellar phases

AD scale of MHD turbulence was conventionally calculated by assuming isotropic scaling of MHD turbulence, which is in fact comparable to the parallel AD scale and much larger than its perpendicular counterpart due to the scale-dependent turbulence anisotropy. The perpendicular AD scale should be used for damping of MHD turbulence. Different MHD modes have different damping scales, which affects CR propagation in cold interstellar phases (Xu, Lazarian, & Yan 15, Xu, Yan, & Lazarian 16).