Designing mesoscopic-box PIC-based subgrid prescriptions for kinetic microphysics and embedding them into global MHD simulations

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Outline

- Introduction/Motivation
- Macro-scales and Micro-scales
- Digression: large numbers and very large numbers
- Long-Term ***Program***:
    - Subgrid models via mesoscopic boxes
    - Library of PIC-based prescriptions
    - Putting it all back together
- Concluding Remarks

Introduction

- Global fluid (e.g., MHD) models describe large-scale (macro-) dynamics: magnetic fields, fluid motions, transfer of momentum, angular momentum, (energy?)
- But many plasmas of interest are collisionless.
- MHD fails at small (micro-) scales, cannot describe kinetic aspects of the system, e.g.,
    - Nonthermal Particle Acceleration (NTPA): power-law spectra of energetic particles
    - Energy budget: electron vs. ion heating (Q_e/Q_i)
- Need kinetic description $f_s(\boldsymbol{r},\boldsymbol{p},t)$ or at least $f_s(\boldsymbol{r},E,t)$.
- Example: electron heating fraction in GRMHD sims of BH RIAFs (like M87, SgrA*) – needed for connecting with observations.

Introduction

Need kinetic description $f_s(\boldsymbol{r},\boldsymbol{p},t)$ or at least $f_s(\boldsymbol{r},E,t)$…

- MHD is valid almost everywhere, except for thin singular regions like quasi-2D layers: current sheets, vorticity sheets, shocks, etc., which require more rigorous & sophisticated physics description (e.g., 2-fluid, hybrid, kinetic).
- These intermittent regions are important, especially for powerful energy dissipation/conversion events (reconnection, shocks), driving NTPA, powering high-energy flares, etc.
- Energy dissipation & NTPA occurs in collective plasma processes, often driven by nonlinear development of plasma instabilities in these singular layers:
  - Reconnection (tearing)
  - KH instability (KH)
  - Collisionless shocks (Weibel)
- Kinetic, 3D, nonlinear, multiscale --> analytical theory difficult → numerical simulations (e.g., PIC, hybrid, Vlasov, GK, etc.)

Dissipation Processes

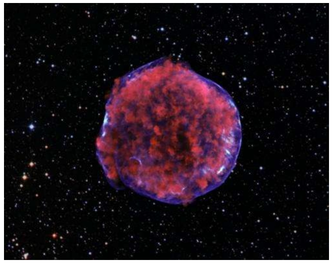
AVAILABLE FREE ENERGY

Bulk Kinetic

Magnetic (Poynting flux)

- longitudinal:

shocks

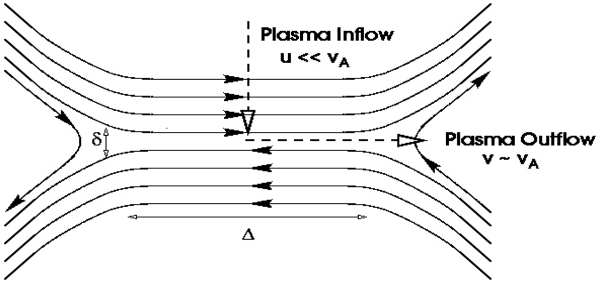


STRUCTURE

current sheets:

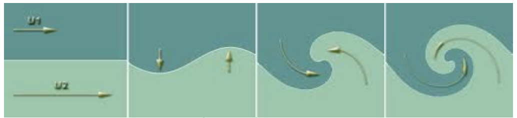
Magnetic reconnection

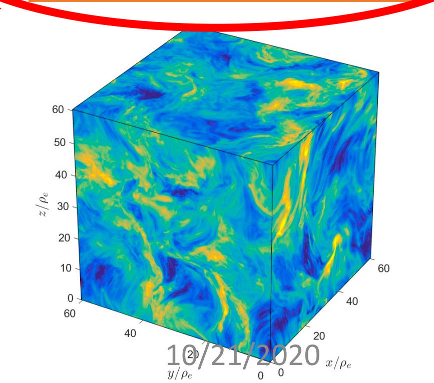
TURBULENCE



- transverse:

shear (KH) instability





Macro- and Micro-scales

- **MHD dynamics**: global system size L (macroscopic):
  - R_g for BHs, R_{NS} or R_{LC} for pulsar magnetospheres, $\mathrm{R_E}$ for Earth magnetosphere, minor radius a for tokamaks.
  - Modern 3D MHD sims (1024^3 grids) can get down to $10^{-3}L$ (except for AMR) --- formally still macroscopic!
- **Kinetic Physics**: kinetic plasma scales ℓ (microscopic):
  - λ_D, $d_{i,e}$, $\rho_{i,e}$ (have to be resolved by comp. grid)
  - Related via dimensionless parameters: β, $\theta = T/mc^2$, $\mu = m_i/m_e$, Mach number, σ, etc. (richness of kinetic plasma physics)
  - These parameters are local: determined by local plasma conditions, independent of system size.
  - Modern 3D PIC sims (1024^3 grids) have to resolve λ_D on the grid, can reach system sizes of $10^3\,\lambda_D$ --- formally still microscopic.

Digression: large and very large numbers

- Plasma processes can be considered in regimes characterized by various dimensionless plasma parameters being large ($>>1$) or small ($<<1$);
- E.g.: low-β, high-β, non-rel., large mass ratio, strong guide field, …
- All these regimes are genuinely interesting/relevant, can be found in nature, so we study them, using them for asymptotic analysis.
- Same class of "*largeness*": 10^2-10^3-10^4.
- Hence, they control scale separations reachable by modern computers.
- These are just "*large numbers*".
- In contrast: in *Astro* systems, scale separation between L and ℓ is not just large but extremely large: $L/\ell >>> 1$. A different class: "*huge*". Typically, 10^{10}.
- Can be defined vaguely as $\log(L/\ell) >> 1$, or $(L/\ell)^{\text{any reasonable power}} >> 1$.
- Or as >> than any regular large number.
- This sets system size L apart from other parameters.
- Why is this? Astronomical systems are astronomically large!

  E.g., BH: $R_g/d_e \sim (R_g/r_e)^{1/2}$, $r_e = e^2/m_e c^2$
- Exceptions: Earth magnetosphere, PWN, Pulsar magnetosphere, tokamaks

Digression: Mesoscopic scales due to extra physics

- Additional “exotic” physics (beyond traditional collisionless plasma physics – radiation, QED, collisions) can break this scale dichotomy and introduce additional scales anywhere, including between L and ℓ:
  - Collisional mean free path (ICM)
  - Radiative cooling length
  - MeV photon mean free path to pair production.

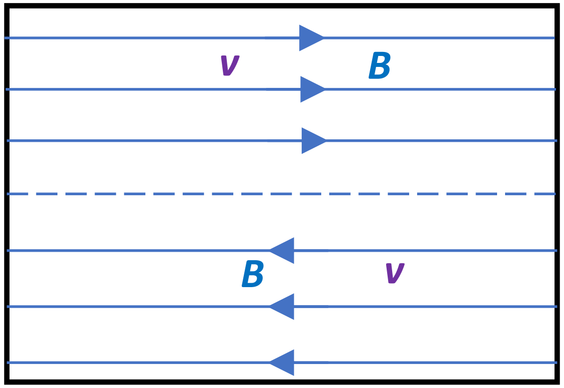
The Program

- Example: GRMHD simulations of BHs need electron heating fraction (Q_e) and NTPA prescriptions for connecting to observations.
- Existing models employ simple local prescriptions (e.g., GK-based Howes'10) for turbulent Q_e in terms of local plasma β.
- But this is too simplistic! Need more info, not just about local plasma conditions (like β), but also about dominant spatial structure (current sheets, etc.) and character of collective plasma dissipation process at play (recn, turbulence, shocks).
- This information cannot be determined at a point but requires analysis of fluid fields (***u***, ***B***, etc) in some vicinity.

The Program

1. In MHD sim: Find and classify singular dissipative structures (CSs, *a la* Zhdankin 2013-2015)
2. Draw mesoscopic boxes around these structures (for flares) and in regions of regular turbulence (for persistent dissipation).
3. Extract relevant fluid-level quantities in these boxes from MHD simulation.
4. Set up a local kinetic (e.g., PIC) problem corresponding to these fluid parameters.
5. Consult pre-existing library of PIC-based prescriptions for this problem, or motivate and run new simulations if needed.
6. Feed Q_e and NTPA results back into MHD simulation for radiation processing or compute radiative signatures directly from radiative-PIC simulation.

Meso-Boxes: Reconnection & KH

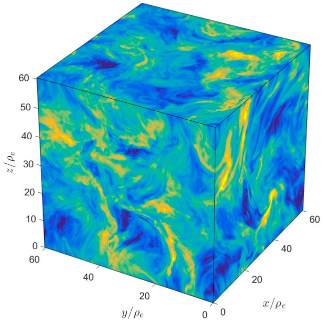


Magnetic Reconnection
Kelvin-Helmholtz Instability

- In general, reconnection is asymmetric: plasma parameters differ on two sides (1,2) of CS.
- In general, CSs may also be vorticity sheets --- reconnection happens together with KH.
- Meso-box parameters (i=1,2; *s* = i,e):
  - Upstream plasma on both sides: B_{0i}, B_{gi}, n_i, T_{si}, u_i
  - L_x, L_y, L_z
  - Frills: upstream P_{perp} and $P_{||}$, T_e, $f_s(E)$
- Construct dimensionless parameters: β, σ, b_g, etc.
- Consult library of empirical prescriptions as tables or analytical formulae (e.g., *Werner et al. 2018, Ball et al. 2019*, etc.); guide, motivate future PIC campaigns to fill the library.
- Feed resulting Qe and NTPA back into MHD sim or compute prompt radiative signals.

Meso-Box Parameters: Turbulence

- Analyze fluid-level turbulence parameters in MHD meso-box:
- Determine key parameters:
  - δBrms/B_0;
  - Turb Mach number;
  - Plasma β;
  - Character of turb. fluid motions (solenoidal, compressive, etc.);
  - Local electron and ion temperatures;
  - Turbulence imbalance;
  - Pressure anisotropy



- Apply PIC- or GK-based empirical prescriptions for Q_e (e.g., Howes 2010, Zhdankin et al. 2019-2022; Kawazura et al 2019-2020), e.g.

  $Q_e/Q_i = (\rho_e/\rho_i)^{2/3}$ or $(\rho_e/\rho_i)^{1/3}$ depending on driving type

- Feed results back into MHD simulation

Concluding Remarks

- If $L_{\text{meso}} = 10^{-2}\, L$ and $L_{\text{PIC}} = 10^{3}\, \ell$, then we need to extrapolate results only over the dynamic range of

$$L_{\text{meso}}/L_{\text{PIC}} = 10^{-5}\,(L/\ell) \sim 10^{5} \text{ (for } L/\ell = 10^{10}\text{)}$$

→Thus, we will be half-way there!

- Long-term program – needs a lot of work, time…
- Many caveats and challenges remain:
  - PIC setup parameter space is very multi-D: corresponds to 2 (somewhat reduced) sets of fluid quantities:

    $[B_g/B_0, \beta, \theta_i, \theta_e, L_z/L_x, L_y/L_x, u_x, u_z] \times 2 - 1 = 15$
  - How to port PIC data back into MHD?

THANK YOU!