Physics of Pressure-Strain Interaction in Simulations of Magnetic Reconnection

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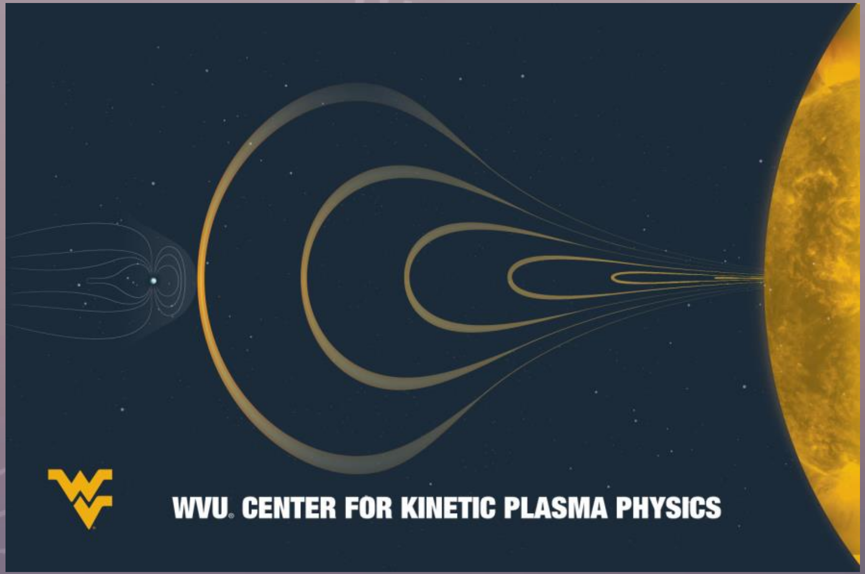


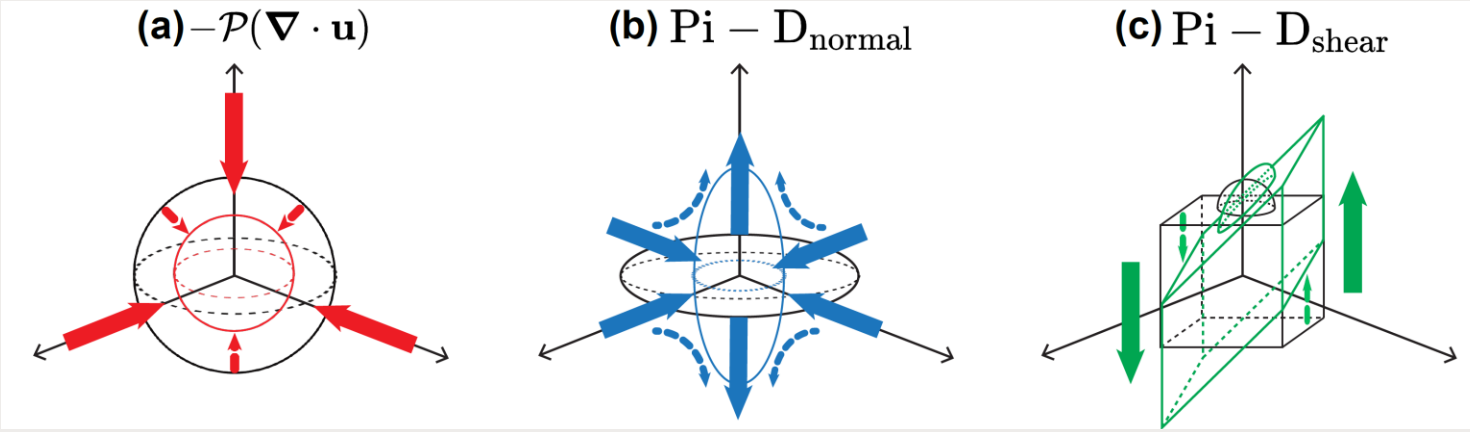
Alternative Decomposition of Pressure-Strain Interaction

- **By decomposing Pi-D into its <u>shear</u> and <u>normal</u> parts, we isolate the heating due to pure converging/diverging flow and flow shear (*Cassak & Barbhuiya 2022, PoP, submitted*)**

PDU, pure flow convergence/divergence

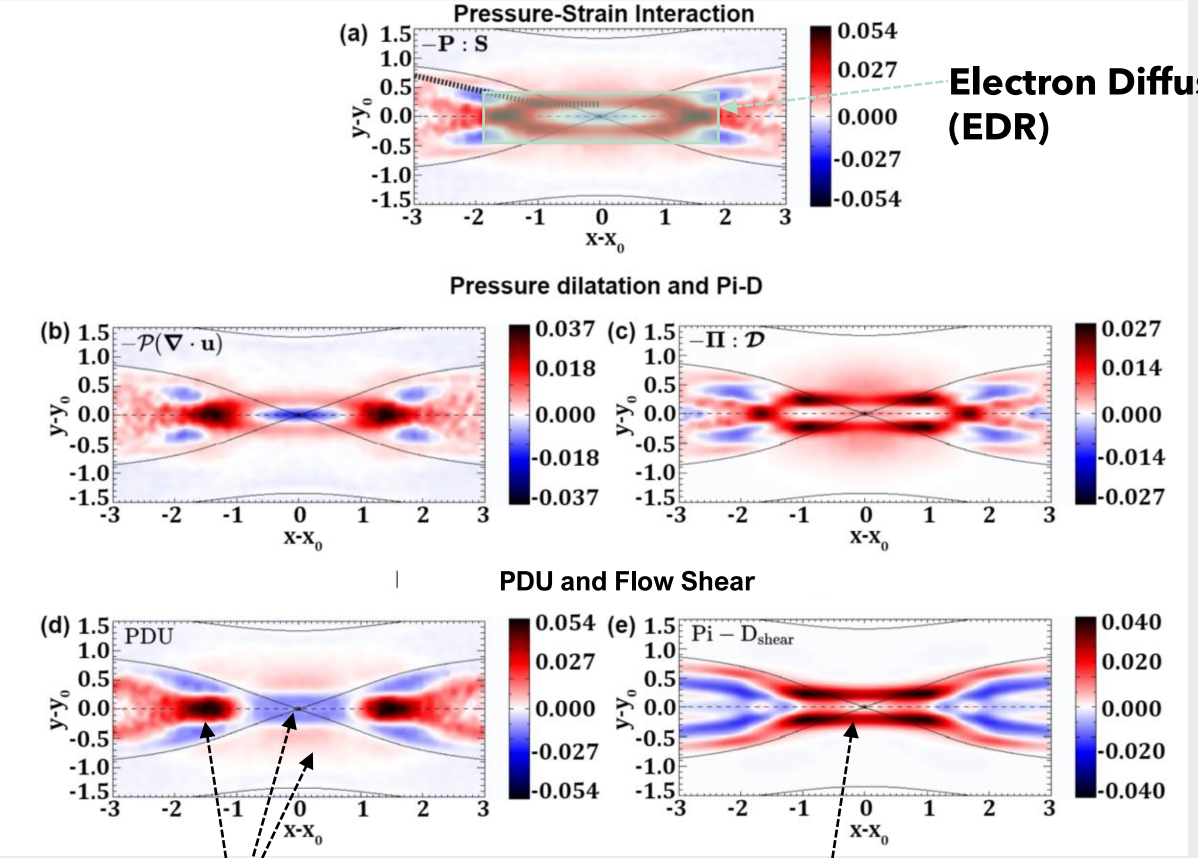
Pi-D$_{shear}$, pure flow shear

$$-(\mathbf{P}\cdot\nabla)\cdot\mathbf{u} = -\mathcal{P}(\nabla\cdot\mathbf{u}) - \mathbf{\Pi}:\mathcal{D}_{\text{normal}} - \mathbf{\Pi}:\mathcal{D}_{\text{shear}}$$



Comparison of Decompositions in a Reconnection Simulation

- **Domain size = 12.8 x 6.4**
- **Particles per grid = 25,600**
- **Time = during onset (*Barbhuiya & Cassak 2022, PoP submitted)*)**
- **Power densities for electron**
  (a) Pressure-strain interaction
  (b) Pressure dilatation
  (c) Pi-D
  (d) PDU
  (e) Pi-D_{shear}



Electron Diffusion Region (EDR)

Both terms have the same features as $(\mathbf{P} \cdot \nabla) \cdot \mathbf{u}$ near and far from the EDR

Both terms have different features as $(\mathbf{P} \cdot \nabla) \cdot \mathbf{u}$ near and far from the EDR, splits off flow converging from flow shear

Features due to pure bulk flow converging/diverging

Features due to pure bulk flow shear

Pressure-Strain Interaction in Field-Aligned Coordinates

- **By writing $\mathbf{u} = e_\alpha u_\alpha, \mathbf{P} = P_{\alpha\beta} e_\alpha e_\beta, \boldsymbol{\nabla} = \mathrm{e}_\alpha \nabla_\alpha$, we decompose pressure-strain interaction as (*Cassak, Barbhuiya & Weldon 2022, PoP, submitted*) :**

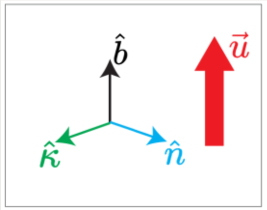
$$-(\mathbf{P} \cdot \boldsymbol{\nabla}) \cdot \mathbf{u} = -P_{\alpha\beta}(\nabla_\alpha u_\beta) - P_{\alpha\beta} u_\delta [\mathbf{e}_\beta \cdot (\nabla_\alpha \mathbf{e}_\delta)]$$

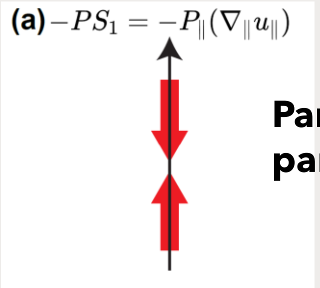
Note here that the Greek letters go from $\hat{\mathbf{b}}, \hat{\boldsymbol{\kappa}}, \hat{\mathbf{n}}$

- **Flow gradients including converging/diverging and shear**
- **When coupled to pressure, it gives the various ways flow converging and shear can contribute to heating**

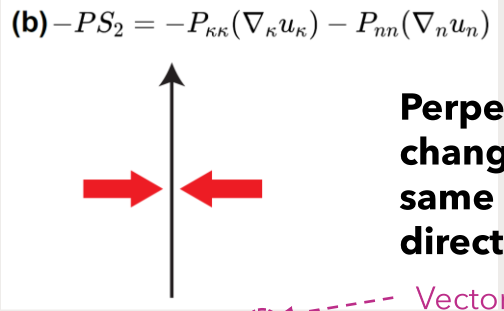
- **Geometrical terms comes from the geometry of the field lines**
- **When coupled to pressure, it gives the various ways field line geometry can produce effective compression and shear heating contributions**

Dominant Terms in Field-Aligned Coordinates around the EDR

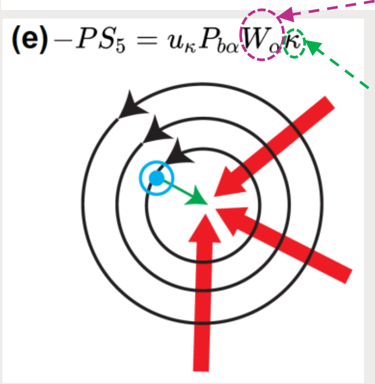




Parallel flow changing in parallel direction



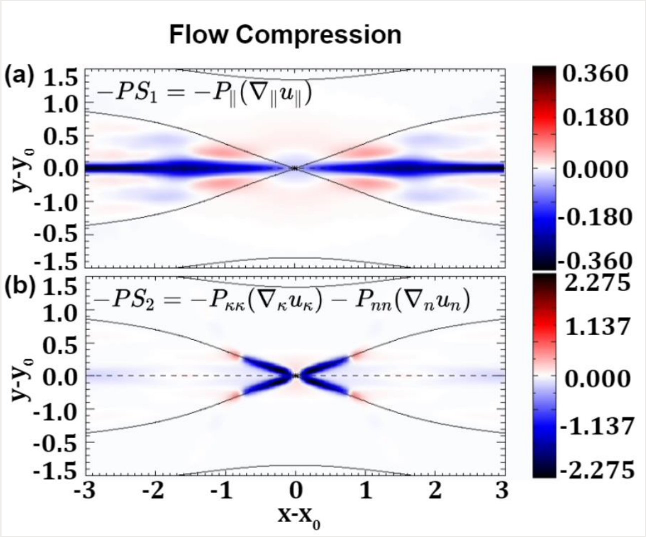
Perpendicular flow changing in the same perpendicular direction

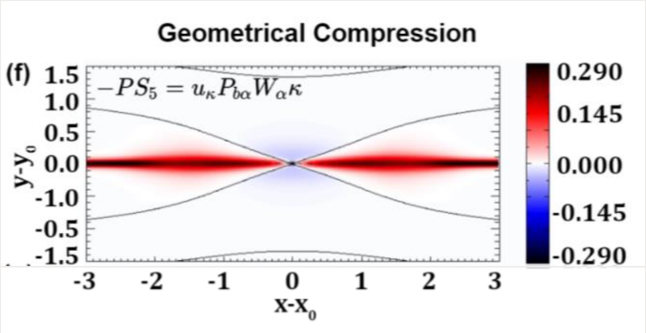


Vector **W** $W_b = 1,$ $W_\kappa = (\hat{\boldsymbol{\kappa}} \cdot \nabla_\kappa \hat{\mathbf{b}})/\kappa,$ $W_n = -(\hat{\boldsymbol{\kappa}} \cdot \nabla_n \hat{\mathbf{n}})/\tau$

Curvature $|\hat{\mathbf{b}} \cdot \boldsymbol{\nabla} \hat{\mathbf{b}}|$

Curvature flow compressing due to field-line curvature (quantified by κ)

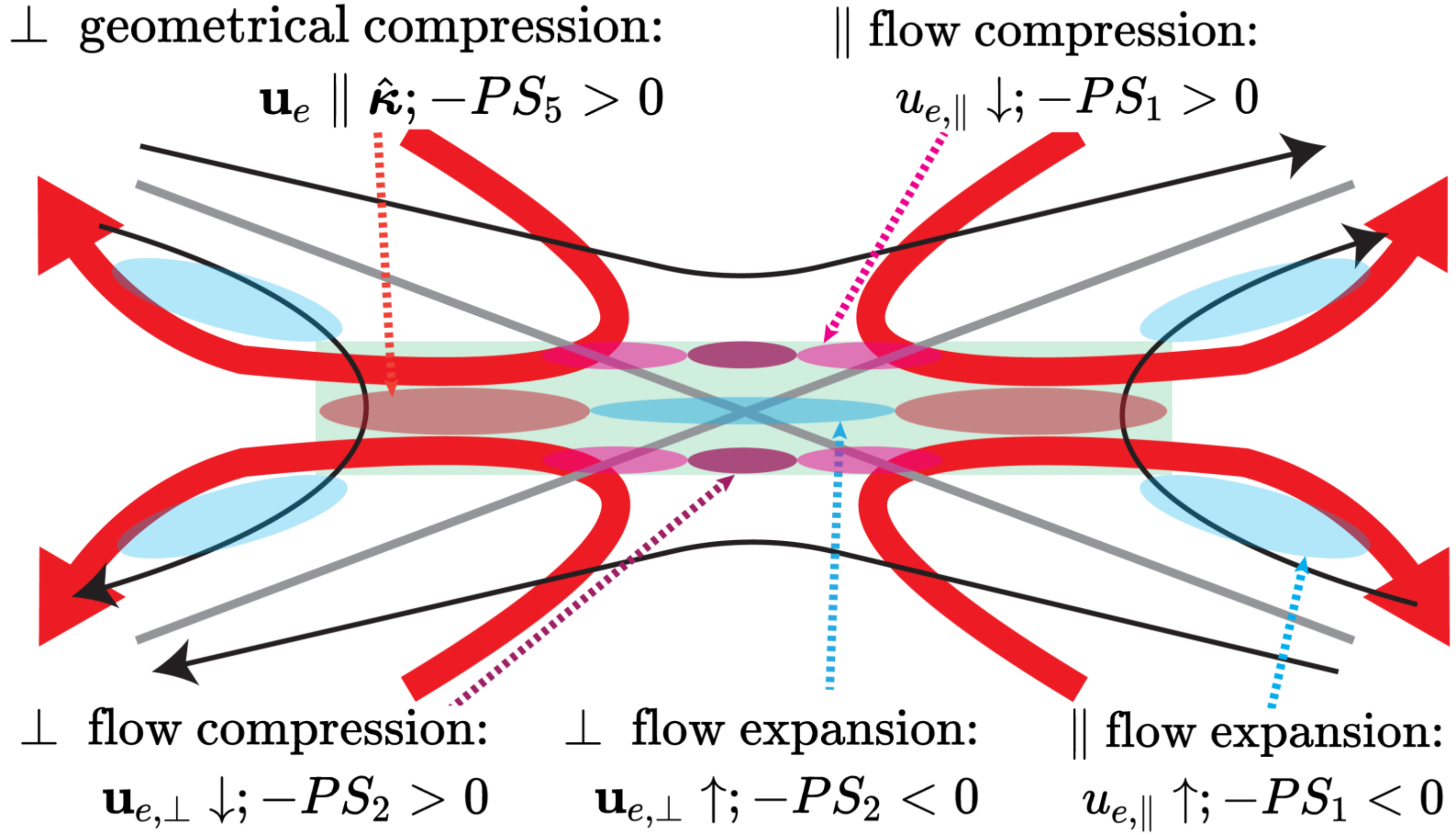




(Barbhuiya & Cassak 2022, PoP, submitted)

Pressure-Strain Interaction – Contribution from Dominant Terms

- **Red thick arrows shows electron bulk flow, green box denotes EDR**
- **Ellipses in shades of red show varies heating contributions to pressure-strain interaction**
- **Ellipses in shades of blue color show varies cooling contributions to pressure-strain interaction**
- **Full physical understanding of <u>heating/cooling contributions to pressure-strain during onset phase of reconnection near EDR</u> is obtained**
  (Barbhuiya & Cassak 2022, PoP, submitted)



Scaling Analysis of Pressure-Strain Interaction

- For antiparallel reconnection, a scaling analysis is used to find the characteristic scale of heating/cooling via pressure-strain interaction (*Barbhuiya & Cassak 2022, PoP, submitted*):

$$-(\mathbf{P}_\sigma \cdot \nabla) \cdot \mathbf{u}_\sigma \sim \pm \frac{P_{\sigma,up} c_{A,\sigma,up}}{\delta_\sigma}$$

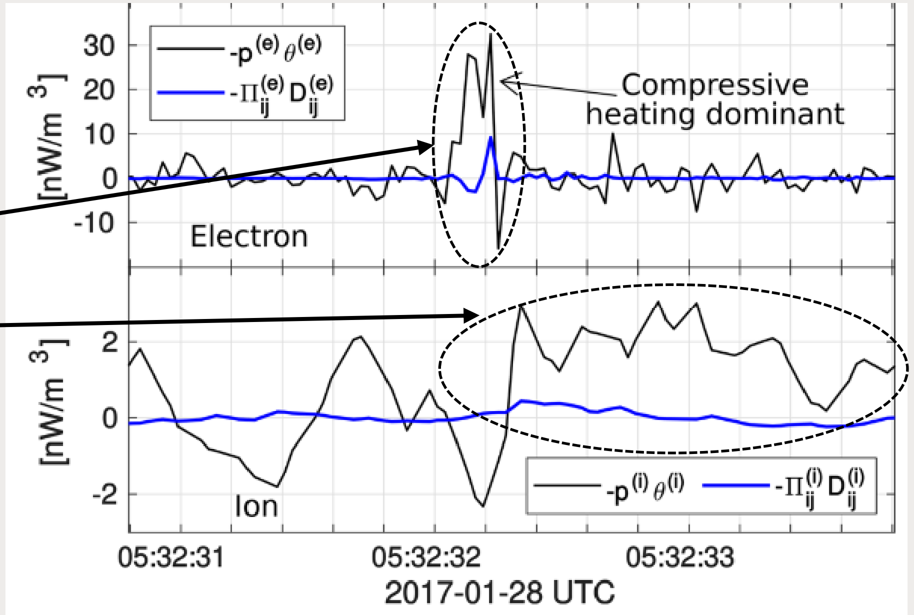
- $P_{\sigma,up}$ is the upstream species (effective) pressure
- $c_{A\sigma,up}$ is the Alfven speed based on the EDR (for electron)/IDR (for ion) upstream magnetic field
- δ_σ is the gradient scale which comes out to be a range depending on whether the gradient is along inflow or outflow
  - For electrons, $\delta_\sigma \simeq 1 - 5 d_e$ (where d_e = electron skin depth)
  - For ions, $\delta_\sigma \simeq 1 - 10\ d_i$ (where d_i = ion skin depth)
- $-(\mathbf{P}_\sigma \cdot \nabla) \cdot \mathbf{u}_\sigma$ is of the order of $P_{\sigma,up}\Omega_{c,\sigma}$ where $\Omega_{c,\sigma}$ is the cyclotron frequency of species σ

Comparison with Observations

- **We can compare with an observation (shown previously) by MMS (*Bandyopadhyay+ 2021*) of pressure-strain interaction**

For electrons, we get a range $24 - 120\ \mathrm{nW/m^3}$ which <u>agrees well</u>

For ions, we get a range $0.49 - 4.9\ \mathrm{nW/m^3}$ which <u>agrees well</u>



Their ratio scales as $\frac{T_{e,up}}{T_{i,up}} \frac{B_{e,up}}{B_{i,up}} \frac{m_i}{m_e}$ (*Liu+ 2022*) which is ~ 20 for observation and 25 for simulation <u>which agrees well</u>

(Barbhuiya & Cassak 2022, PoP submitted)

Conclusions

- **Reconnection simulation results of an alternative decomposition to pressure-strain interaction in Cartesian coordinates (*Cassak & Barbhuiya 2022, PoP, submitted*) was presented**
  - **PDU** which captures only bulk flow convergence/divergence physics,
  - **Pi-D$_{shear}$** which captures only bulk flow shear physics.
- **Reconnection simulation results of the decomposition of pressure-strain interaction in field-aligned coordinates, applicable to magnetized plasmas (*Cassak, Barbhuiya & Weldon 2022, PoP, submitted*) was presented**
  - **First set** ⇒ flow compression and shear effects,
  - **Second set** ⇒ geometrical compression and shear effects arising from curved path-lines of field-aligned coordinate geometry.
  - **A complete picture of dominant contributions (-PS$_2$, -PS$_1$ and -PS$_5$) to pressure-strain interaction is found in a reconnection simulation (*Barbhuiya & Cassak 2022, PoP, submitted*)**
- **Pressure Strain tells you where bulk flow energy ↔ thermal energy**
  - The results are useful for not just reconnection but also for turbulence, and shocks