Identifying and Quantifying the Role of Magnetic Reconnection in Space Plasma Turbulence.

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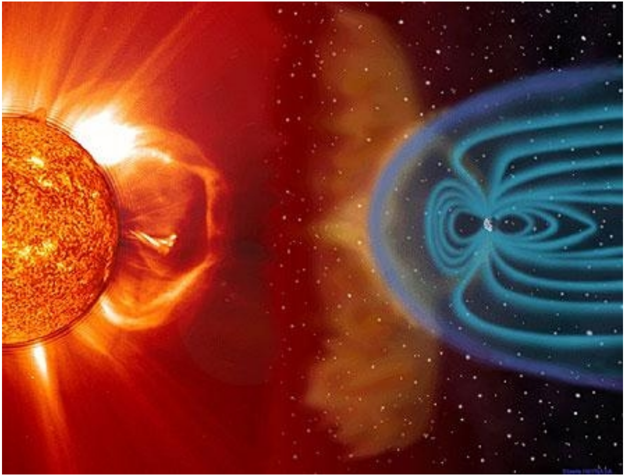
Introduction: The solar wind and collisionless energy dissipation

Solar Wind

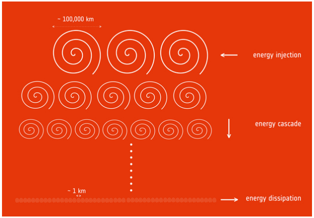
- Parameters change with distance;
- Solar wind heating;
- Nearly collisionless plasma;
- Energy dissipation;
- In-Situ measurements.

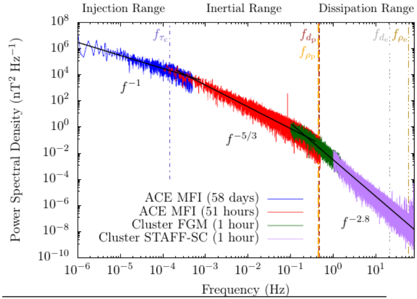
(Taken from NASA)



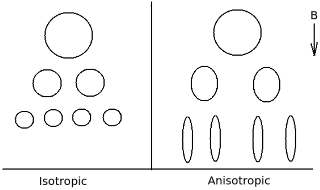
Turbulence in the Solar Wind

Top (ESA),Bottom (Verscharen et al., 2019)





- Anisotropy.



In the inertial range[1], $E \sim k_\perp^{-1.7}$, $E \sim k_\parallel^{-2}$;

CB: $k_\parallel \sim k_\perp^{2/3}$.

In the kinetic range[2], $E \sim (k_\perp^{-2.3} - k_\perp^{-2.8})$, $E \sim (k_\parallel^{-3.5} - k_\parallel^{-5})$;

CB: $k_\parallel \sim (k_\perp^{1/3} - k_\perp^{2/3})$.

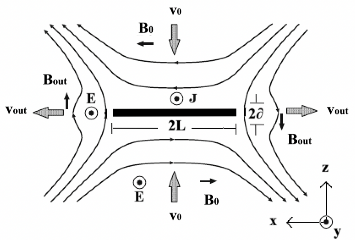
[1] Horbury et al, 2008; Alexandrova et al., 2009; Wicks et al., 2010; Goldreich & Sridhar, 1995.

[2] Chen C.H.K. et al., 2010, 2011, 2012; Alexandrova et al, 2013; Cho & Lazarian, 2004; Boldyrev & Perez, 2012.

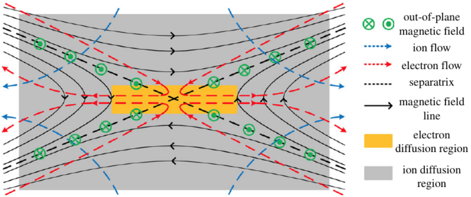
Magnetic Reconnection in the Solar wind

2D reconnection

Adapted from: (Top) Somov,(2012); (Bottom) Zweibel & Yamada, (2016)

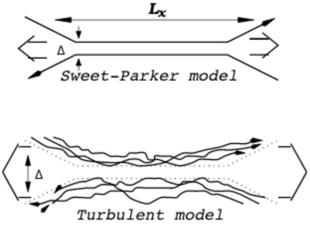


Adapted from Zweibel & Yamada, (2016)



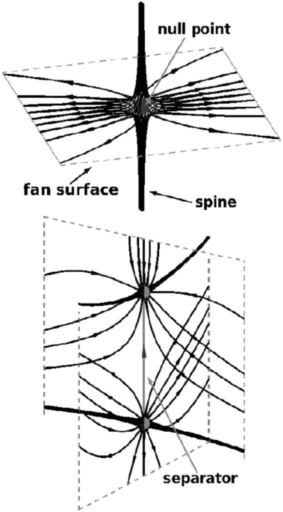
- Plasmoid instability speeds up reconnection;
- X points outside of current sheets due to guide field and anisotropies, (Eastwood et al., 2013; Wang et al., 2014);
- Wandering of the magnetic field lines and suppression of plasmoid instability in 3D (Lazarian et al., 2020).

Adapted from Lazarian et al. (2019)



3D reconnection

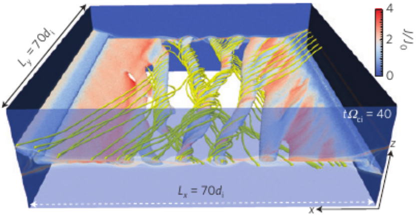
Adapted from Pontin, (2011)



- Magnetic reconnection requires the presence of a dissipation region, $E_{||} \neq 0$ (Schindler & Hesse, 1988).

$$\boxed{\int_{fl} E_{||}\, ds \neq 0,}$$

Adapted from Daughton et al. (2011)



What is the link between reconnection and turbulence?

Turbulence in reconnection

- AWs generate turbulence and CSs (Howes, 2016);
- In the Harris CS, plasmoid instability enhance reconnection rate (Daughton et al., 2011; Boldyrev & Loureiro, 2017 (2019)).

Reconnection in turbulence

- At the smallest scales decoupling of electrons and ions;
- Reconnection as a dissipation channel of turbulent energy. (Luca et al., 2017, Cerri et al., 2017; Grošelj et al. 2018).

Questions to answer

1. Is reconnection generated by the turbulent cascade?
2. How 3D reconnection looks like?
3. How reconnecction dissipates energy?

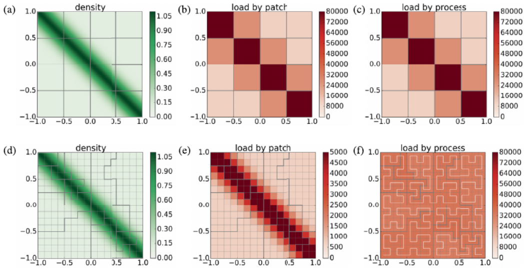
The PIC code (Germaschewski, et al. 2016)

Plasma simulation code

- Why this PIC?
- Why this code?
- Explicit Particle In Cell (PIC);
- Code with explicit discretization of fields and particles motion;
- Highly parallelizable;
- Load balancing makes the work per patch roughly similar.

Computational facilities

- TRILLIAN, UNH;
- DiRAC: Data Intensive at Leicester, UK.

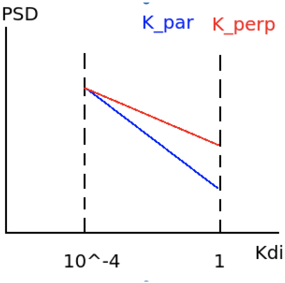


Adapted from Germaschewski, et al. (2016)

Set up to produce anisotropic kinetic turbulence

Initialisation and numerical set up

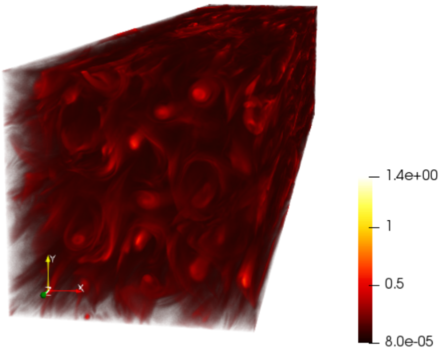
$$\frac{\delta \mathbf{v}_m^\alpha}{v_A} = \mp \frac{\delta \mathbf{B}_m^\alpha}{B_0};$$
$$k_{m,\parallel}\rho_i = C\left(|\mathbf{k}_{m,\perp}|\rho_i\right)^{2/3}.$$



Counter propagating AWs. Random phases (ψ). Periodic boundary conditions.
$L_x \times L_y \times L_z = 24d_i \times 24d_i \times 125d_i$.
$\Delta x = \Delta y = \Delta z = 0.06d_i$. $\rho_i = \sqrt{\beta}d_i$
$m_i/m_e = 100$. $V_A/c = 0.1$,
$\beta_i = \beta_e = 1$, $\beta = \frac{nk_B T 2\mu_0}{B^2}$
$T_{i,\perp}/T_{i,\parallel} = T_{e,\perp}/T_{e,\parallel} = 1$.
$n_e = n_i = 100$. $\mathbf{B}_0 = B_0\hat{z}$.
The time step is $0.06/\omega_{pi}$ where ω_{pi} is ion plasma frequency. Outputs stored every $24/\omega_{pi}$ or $0.02\ \tau_A$.

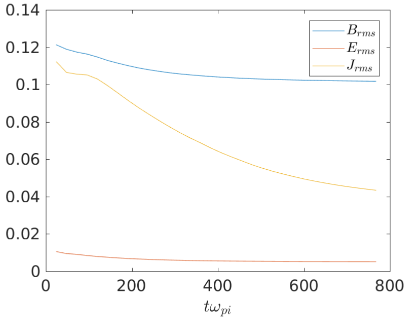
Evidences of turbulence in the simulation domain

$|J|$ isosurfaces at $t\omega_{pi} = 120$



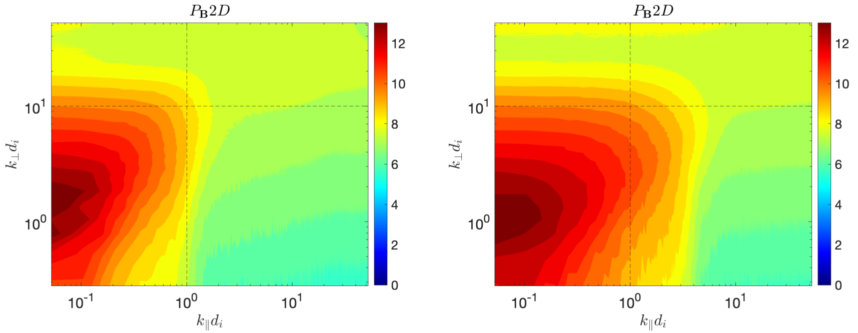
Formation of small scale structures.

Time evolution



Highly turbulent state between $\omega_{pi} t = 72$ and $\omega_{pi} t = 144$.

Turbulent features



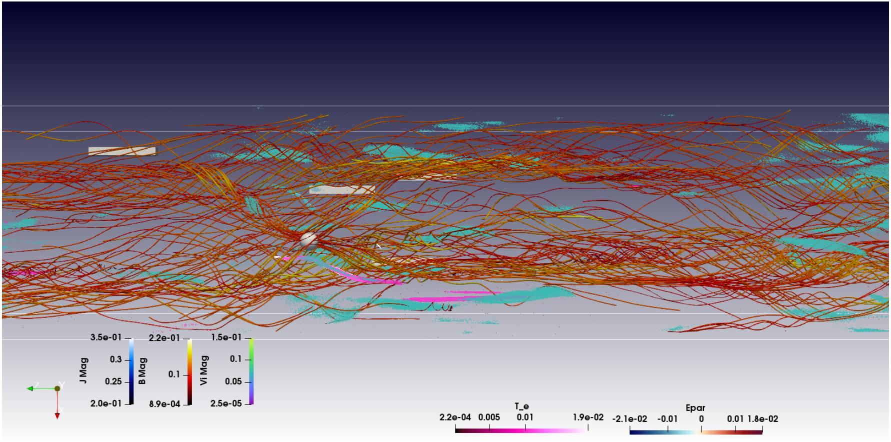
(a) $\omega_{pi} t = 24$ (b) $\omega_{pi} t = 120$

Isocontours of the reduced 2D PSD in the $(k_\parallel, k_\perp)$ for magnetic field at $\omega_{pi} t = 24$ (a) and $\omega_{pi} t = 120$ (b). Broadening of the parallel cascade.

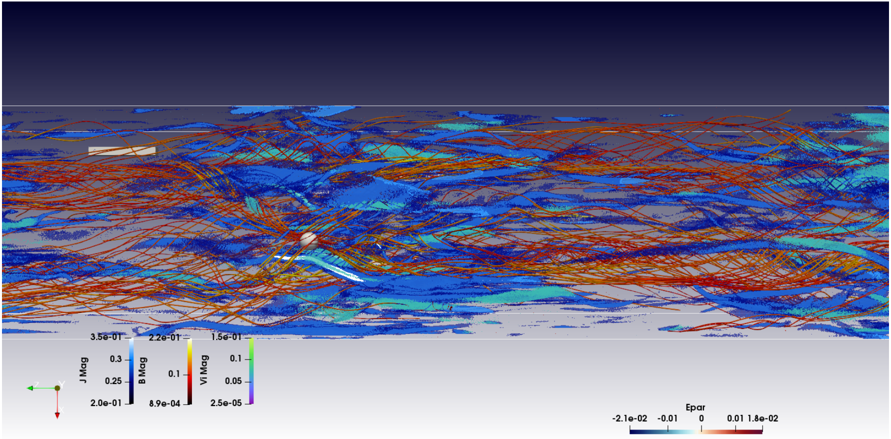
Finding reconnection sites in the simulation domain

Indicators of reconnection

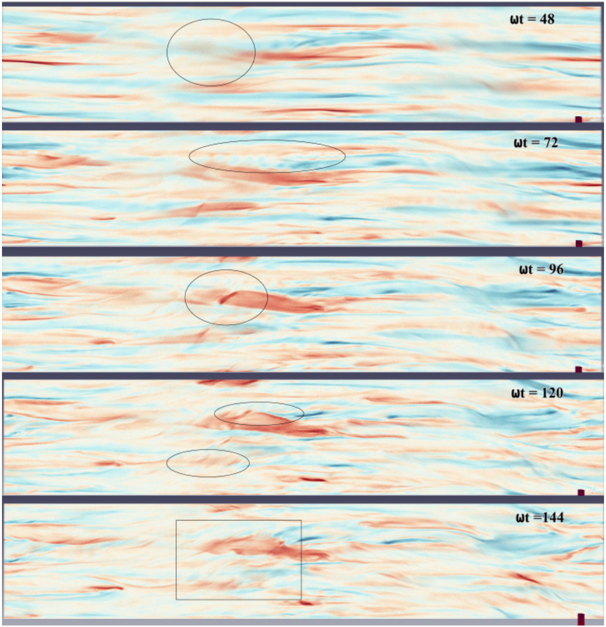
- Current sheets structures, $|J| \geqslant \langle J \rangle + N_{th} * \sigma_{st}(J)$, where $\langle ... \rangle$ represents the mean value taken over the entire simulation domain and $\sigma_{st}(J) = \sqrt{\langle J^2 \rangle - \langle J \rangle^2}$;
- Strong gradients in at least one of the components of the magnetic field and magnetic null points;
- Fast ions and electrons, $|v_{i,e}| \geqslant \langle v_{i,e} \rangle + N_{th} * \sigma_{st}(v_{i,e})$,
- Heated particles $|T_{i,e}| \geqslant \langle T_{i,e} \rangle + N_{th} * \sigma_{st}(T_{i,e})$,
- Non zero parallel electric fields $E_{\|} \geqslant \langle E_{\|} \rangle + N_{th} * \sigma_{st}(E_{\|})$, where $E_{\|} = \mathbf{E} \cdot \mathbf{B}/|\mathbf{B}|$.



The white sphere marks the reconnection site in which magnetic streamlines intersect and a filament of heated electrons and fast ions is present. Regions with $E_{\parallel} \neq 0$ are marked with elongated boxes. The boxes are far from reconnection site.



Extended electric current structure (current sheet-like) above the sphere. The dissipation region is a current filament.



Volume rendering of J_z at different times. Blue is negative, white is zero and red is positive. At $\omega_{pi}t = 72$ a instability is taken place. At $\omega_{pi}t = 96$ rupture in a current structure. At $\omega_{pi}t = 120$ and 144 shear spikes associated with particles exhaust.

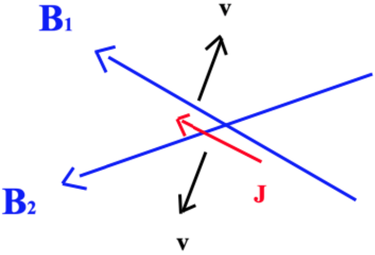
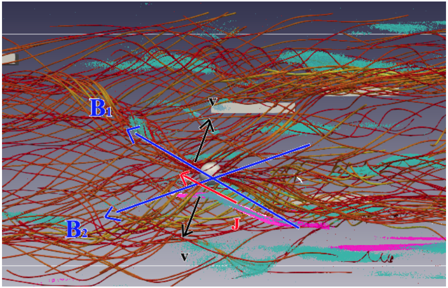


Figure: Schematic representation of our reconnection event.



- $E_{\|}$ is not a good indicator for reconnection in our simulation.

Future work

Develop a method that:

- Quantify the number of reconnection sites;
- Quantify the role of reconnection in the energy dissipation;
- Analyse how variables change along a 1D trajectory.

Future runs

- Start earlier in the inertial range (coupling of the large to small scale cascade matters);
- Closer output steps to study wave propagation;
- More realistic mass ratio.

Summary and conclusions

- We aiming to study dissipation in collisionless plasmas, specifically whether turbulence gives rise to reconnection, and if so how important the role of reconnection is;
- Counter propagating AW with CBGS95 as initial conditions develop a turbulent cascade consistent with observations;
- Using a general list of criteria, we identified a potential reconnection site and show that magnetic field is topologically changed. Particles are accelerated and heated near the reconnection region;
- Further work needs to be done to quantify the number of reconnection sites, the energy balance in dissipation between reconnection and other mechanisms.

Acknowledgements

- This project is funded by ESA and ICETEX (Colombia);
- Simulations are performed in DiRAC, DiL.