What can test particles tell us about magnetic reconnection in the solar corona?

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Overview

- Motivation (solar flares)
- Background (reconnection and particle acceleration)
- The test particle approach
- Our applications/findings:
  - 3D magnetic separators (analytical/numerical comparison)
  - MHD active region simulation
  - Analytical flux rope eruption model
  - Multi-thread MHD loop cascade/eruption
credit: Morgan/Druckmuller
Observing Solar Eruptions with the Solar Dynamics Observatory
Clear evidence of **restructuring of magnetic fields** here (and most flares).

Tangled/twisted coronal fields "**reconnect**" to relax to lower energy state.

Released energy: heats, bulk plasma motion and **accelerates particles**.
Background
Magnetic Reconnection

• First conceived to explain generation of high energy particles during flares (Giovanelli, 1946).

• Historically studied using 2D steady state models - highly idealised:
  ‣ In 2D, reconnection only occurs at (X-type) null points.
  ‣ Nulls mark intersection of four topologically distinct flux domains.
  ‣ Likely sites of current sheet formation.
  ‣ 2D reconnection relatively well understood [e.g. books of Biskamp (2000), Priest & Forbes (2000), Birn & Priest (2007)]
  ‣ Notable exception: kinetic effects
3D reconnection

• **No** fundamental restriction on where reconnection occurs.

• Necessary and sufficient condition for reconnection:

\[ \int E_{||} ds \neq 0 \]

(e.g. Schindler et al. 1988; Hesse and Schindler 1988)

• "Cut and paste" field line picture no longer holds:
  3D reconnection happens continuously and continually within finite volume.

• How can we probe this mysterious region?
How to model?

• Several ways to model a plasma:

  ✦ Single fluid (MHD)
  * treat plasma as a continuum (i.e., a single fluid) so solve just the one set of fluid equations and Maxwell’s equations.

  ✦ 2-fluid
  * Treat electrons and ions as separate continuum (solve the electron & ion fluid equations + Maxwell’s equations involving both the electrons and ions).

  ✦ Kinetic
  * Use distribution functions for each particle species & solve for motion of each species.

  ✦ Individual particles
  * For each particle solve for motion due to surrounding magnetic and electric fields.

All have advantages/limitations!
Particle models

• In uniform B-field, particles gyrate orbit field lines with Larmor/gyro-radius:

\[ r_g = \frac{mv_\perp}{eB} \]

• Averaging over gyro-motion (the "guiding centre approximation") reduces complexity (provided that environment does not change over an orbit).

• Typically leads to fast parallel motion (particularly when some component of E-field parallel to B) and slower perpendicular drifts.

• Downside: Orbits affected by collisions and back-react upon the fields (solved by PIC but omitted here - PIC also has big limitations!)
Particle Orbit Equations

Particle guiding centre behaviour (Northrop, 1963)

\[ \frac{d\mathbf{v}_\parallel}{dt} = \frac{qE_\parallel}{m_0} - \frac{\mu_B}{m_0} \frac{\partial B}{\partial s} + \mathbf{u}_E \cdot \left( \frac{\partial \mathbf{b}}{\partial t} + v_\parallel \frac{\partial \mathbf{b}}{\partial s} + (\mathbf{u}_E \cdot \nabla) \mathbf{b} \right), \]  

(1a)

\[ \frac{dE_K}{dt} = q\dot{\mathbf{R}} \cdot \mathbf{E} + \mu_B \frac{\partial B}{\partial t}, \]

\[ E_K = \frac{m_0 v_k^2}{2} + \mu_B B + \frac{m_0 u_E^2}{2}, \]  

(1c)

(1a) **Parallel equation of motion** (think \( a = F/m \)) - if present, \( E_\parallel \) typically dominates.

NB. \( \mathbf{b} = \frac{\mathbf{B}}{|\mathbf{B}|}, \mathbf{u}_E = \frac{\mathbf{E} \times \mathbf{b}}{|\mathbf{B}|}, v_\parallel = \mathbf{v} \cdot \mathbf{b}, \mu_B = \frac{mv_g^2}{2B} \) for gyro-velocity \( v_g \),
\[ s = \text{line element along } \mathbf{b}, \text{ particle charge } q, \text{ mass } m. \]
Particle Orbit Equations

Particle guiding centre behaviour (Northrop, 1963)

\[
\frac{dv_{\parallel}}{dt} = \frac{qE_{\parallel}}{m_0} - \frac{\mu_B}{m_0} \frac{\partial B}{\partial s} + u_E \cdot \left( \frac{\partial b}{\partial t} + v_{\parallel} \frac{\partial b}{\partial s} + (u_E \cdot \nabla) b \right),
\]

\[
\dot{R}_{\perp} = \frac{b}{B} \times \left[ -E + \frac{\mu_B}{q} \nabla B + \frac{m_0}{q} \left( v_{\parallel} \frac{\partial b}{\partial t} + v_{\parallel}^2 \frac{\partial b}{\partial s} ight. \right.
\]

\[
\left. + v_{\parallel} (u_E \cdot \nabla) b + \frac{\partial u_E}{\partial t} + v_{\parallel} \frac{\partial u_E}{\partial s} + (u_E \cdot \nabla) u_E \right],
\]

(1c)

(1a) **Parallel equation of motion** (think \( a = F/m \)) - if present, \( E_{\parallel} \) typically dominates.

(1b) **Perpendicular drift of guiding centre** (RHS: \( E \times B, \nabla B \) and lower order drifts).

**NB.** \( b = \frac{B}{|B|}, \ u_E = \frac{E \times b}{|B|}, \ v_{\parallel} = v \cdot b, \ \mu_B = \frac{mv_g^2}{2B} \) for gyro-velocity \( v_g \),

\( s = \) line element along \( b \), particle charge \( q \), mass \( m \).
Particle Orbit Equations

Particle guiding centre behaviour (Northrop, 1963)

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\frac{dv_{\parallel}}{dt} = \frac{qE_{\parallel}}{m_0} - \frac{\mu_B}{m_0} \frac{\partial B}{\partial s} + u_E \cdot \left( \frac{\partial b}{\partial t} + v_{\parallel} \frac{\partial b}{\partial s} + (u_E \cdot \nabla) b \right),
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+ v_{\parallel} (u_E \cdot \nabla) b + \frac{\partial u_E}{\partial t} + v_{\parallel} \frac{\partial u_E}{\partial s} + (u_E \cdot \nabla) u_E \right],
\]

\[
\frac{d}{dt} E_K = q \dot{R} \cdot E + \mu_B \frac{\partial B}{\partial t}, \quad E_K = \frac{m_0 v_{\parallel}^2}{2} + \mu_B B + \frac{m_0 u_E^2}{2},
\]

(1a) **Parallel equation of motion** (think \(a = F/m\)) - if present, \(E_{\parallel}\) typically dominates.

(1b) **Perpendicular drift of guiding centre** (RHS: \(E \times B, \nabla B\) and lower order drifts).

(1c) **Change in KE** via work done by \(E\)–field on guiding centre and induction effect of time-dependent field.

(1c) **KE divided between parallel, perpendicular and gyro-motion.**
We use a relativistic form of guiding centre equations, solved using 4th order Runge Kutta scheme - only needs $E$ and $B$.

Assumes spatial and temporal scales of gyro-motion and field environment are well separated (checked and also check that $B \neq 0$).

Adapted to take input from analytical fields or various MHD codes.

Code available on github: https://github.com/jwt104/party_orb
Our Applications
What configurations to probe?

*(shameless self-promotion warning)*

- Isolated topological features - separators

- Non-flaring Active Region model (MHD)

- Non-topological coronal reconnection model
  *(Threlfall et al., Solar Physics, 2017a)*

- Multi-thread avalanche energy release (MHD)
  *(Threlfall et al., A&A, 2017b, accepted)*
Isolated topological configs: **separators**

- Separators also common, **spatially extended** reconnection sites (prone to current sheet formation).
- Locally intersect 4 distinct topological domains (like 2D nulls!).
- Commonly identified in numerical simulations of solar atmosphere (e.g. by Parnell, Haynes, etc).
- Separator reconnection **observed/inferred** in solar corona (**Longcope et al. 2005**) and Earth's magnetotail (**Deng et al. 2009, Guo et al. 2013**).
- Begin with analytical model..

Acceleration at 3D nulls well studied (e.g. Dalla, Browning, Gordovskyy, etc)

![Diagram of topological configurations](image-url)

*Parnell et al. (2015)*
Analytical model

Threlfall et al. (2015)

Peak KE gain: $100 \frac{[B/10G][L/10Mm]^2[T/100s]}{}^{-1}$ keV

Electrons/Protons accelerated along null spines ($\leq 140$ keV)
Numerical MHD model

Threlfall et al. (2016a)

Peak KE gain: $1.55 [B/10G][L/1Mm]^2[T/20s]^{-1}$ MeV

Higher energies

Thicker twisted current sheet

Broader impact sites
Electron response over time

- Particle energy falls with time as current dissipates.
- Impact sites move away from spines as more fan field drawn into reconnection region.

Threlfall et al. (2016a)
MHD Active Region Model

- Use snapshot from cutting-edge MHD simulation of non-flaring active region (Bourdin et al. 2015).

Findings:
- Runaway electron acceleration to 42 MeV (but no flare!)
- Identify novel electric-field trapping of the majority of orbits
- Design of future large scale MHD simulations should take into account the electric field configuration resulting from chosen parameters
Flux rope eruption

- Non-topological reconnection model
- Orbit results contain two populations:
  - Strongly accelerated population moves **parallel to flux rope axis** (achieves MeV energies), slower population moves **perpendicular to PIL**.
  - Similar to some two-ribbon flare features (|| motions and footpoint widening).
- Analytical model - retain **full control** of electric field: guarantee size/extent appropriate. Also can **rescale** findings!

Threlfall et al. (2017a)
Ongoing: Multi-thread cascade

- **Hood et al. (2016)**
- First demo of single coronal loop thread destabilising neighbouring threads, leading to a cascade
- MHD
- Kink instability
- Energy release in discrete bursts (nanoflares?)
- Study up to 23 threads
Multi-thread cascade

- **Hood et al. (2016)**
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- MHD
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- Energy release in discrete bursts (nanoflares?)
- 23 threads
Multi-thread loop cascade

• Study 2 loop case using particles

• Questions:
  • What are energies, final positions?
  • How compare to single loop case (Gordovskyy et al., 2011, 2012)
Multi-thread loop cascade

Threlfall et al. (2017b, acc.)

Initial state

Boundary "impact sites" and midplane current $|j|$
Multi-thread loop cascade

Kink instability onset

Acceleration signatures ONLY in left hand loop core

Threlfall et al. (2017b, acc.)

Orbit energy gain $[B/10G][L/1Mm]^2[T/\tau]\text{eV}$

upper boundary final positions

lower boundary final positions
Multi-thread loop cascade

Current dissipated; sheath field distorted

Few MeV orbits observed
Multi-thread loop cascade

Second loop disrupted

Acceleration signatures spread THROUGHOUT boundaries
Common themes?

In all cases:

- **Final state** (inc. energy distrib.) **dominated by E-fields**.
- Initial conditions almost irrelevant
- Analytical models agree well with numerics, but are better able to handle key aspects.

Need to improve:

- Relationship with observations (through e.g. spectra, model design, constraining coronal parameters)
- Effects of collisions and back-reaction upon global fields**
Summary
("What can test particles tell us.."?!")

- 3D reconnection fundamentally different to 2D.
- Guiding centre theory is **not new**: careful application to 3D magnetic reconnection configurations is!
- **Parallel electric field is crucial** and sometimes overlooked!
- Orbits can reveal/constrain **magnitude and extent of electric fields in MHD simulations** and **identify trapping mechanisms**.
- Analytical models actually do a pretty good job of reflecting numerical ones, without constraints (e.g. grid size/parameters) and with scalability.
- **Peak energies, locations, temporal evolution of accelerated orbits** can be compared to flare obs., particularly when reconnection embedded in coronal config.