Flare particle acceleration in the interaction of twisted coronal flux ropes

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Overview

- Motivation (solar flares)
- Background (reconnection and particle acceleration)
- The test particle approach
- Multi-thread MHD loop cascade/eruption (2 loops)
  - Single loop disruption
  - Single loop disruption triggers secondary destabilisation
Motivation
(New) motivation
- 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
3D Magnetic Reconnection

• Reconnection historically studied using 2D steady state models: limitations and properties reasonably well known and understood

• In 3D: **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" 2D field line picture no longer holds: 3D reconnection happens continuously and continually within finite volume.
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 and limitations!
Test Particles

- In uniform B-field, particles gyrate orbit field lines with Larmor/gyro-radius:
  \[ r_g = \frac{mv_\perp}{eB} \]

- **Averaging over gyro-motion** ("guiding centre approximation") reduces complexity (provided environment does not change during 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 e.g. PIC but omitted here - PIC also has big limitations!)
Particle Orbit Equations

Particle guiding centre behaviour (Northrop, 1963)

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

(1a)

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

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**

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

\[
\dot{R}_\perp = \frac{b}{B} \times \left[ -E + \frac{\mu_B}{q} \nabla B + \frac{m_0}{q} \left( v_{||} \frac{\partial b}{\partial t} + v_{||}^2 \frac{\partial b}{\partial s} + v_{||} (u_E \cdot \nabla) b + \frac{\partial u_E}{\partial t} + v_{||} \frac{\partial u_E}{\partial s} + (u_E \cdot \nabla) u_E \right) \right],
\]

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

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

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

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

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\]

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\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} \right) + 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], \tag{1b}
\]

\[
\frac{d}{dt} E_K = q \dot{R} \cdot E + \mu_B \frac{\partial B}{\partial t}, \quad E_K = \frac{m_0 v_{\parallel}^2}{2} + \mu_B B + \frac{m_0 u_E^2}{2}, \tag{1c}
\]

(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).

(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 \( \mathbf{E} \) and \( \mathbf{B} \).

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

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

• Code available on github:  [https://github.com/jwt104/party_orb](https://github.com/jwt104/party_orb)
What configurations to probe?

*(shameless self-promotion warning)*


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

- Multi-thread avalanche energy release (MHD) *(Threlfall et al., A&A, 2018, accepted)*
Brief aside: Energy Scaling

- See e.g. Threlfall et al. (2016)
- Initial analytical/numerical field model often contains **dimensional** AND **non-dimensional scales**.
- Particles accelerated by "field aligned potential difference"
- Resulting energies determined by non-dimensional parameters, THEN scaled by dimensional values
- Can estimate how energy gains will scale

\[
\Delta = \int E_{||} ds = \frac{l_{scl}^2 b_{scl}}{t_{scl}} \int \tilde{E}_{||} d\tilde{s} = \frac{l_{scl}^2 b_{scl}}{t_{scl}} \tilde{\Delta}.
\]

(i.e. 10-fold increase in length should yield 100-fold increase in energy gains!)
Multi-thread avalanche energy release (MHD) (Threlfall et al., A&A, 2018, accepted)
Multi-thread cascade

- Tam et al. (2015), Hood et al. (2016)
- First demo of single coronal loop thread destabilising neighbouring threads, leading to a cascade
- MHD
- Energy release in discrete bursts (nanoflares?)
- Study up to 23 threads

More details: Asad's Talk(!)
Multi-thread cascade

- If this is a "nanoflare storm", how do particles respond?
Our Study

• First step: Study particle behaviour in two loop config.

• Cases:
  • One loop does not destabilise second loop
  • One loop triggers second loop disruption
Gordovskyy et al. (2011, 2012), studied single loop destabilisation using test particles.

How do our final positions and energy distributions compare?
Case 1
Case 1 - single loop disruption

- Single loop benchmark (background AND anomalous resistivity acting above $j_{\text{crit}}$)
- Blue loop initially kink unstable
- Green initially marginally stable
- Can we disentangle the effects of both resistivities?

$\text{purple} = \text{current} > j_{\text{crit}}$
Case 1 - single loop disruption

- Define three phases based on energy changes
- Study particle behaviour in each phase
- Use random initial positions, pitch angles, Maxwellian energies..

![Graph showing change in energy over time](image)

- Three phases are defined:
  - Phase one
  - Phase two
  - Phase three

![3D plots showing particle behavior in each phase](image)
Case 1: Phase 1

- \( j < j_{\text{crit}} \) in Phase 1
- \( \eta_{\text{bkg}} \) causes acceleration in both tubes (even unstable one)
- Weak \( \eta_{\text{bkg}} \) and weak current still yield big energy gains over large distances

Final boundary positions

**Upper boundary final positions**

**Lower boundary final positions**

Orbit energy gain \([B/10G][L/1Mm]^2[T/\tau]\)^eV
Case 1: Phase 1

- $\eta_{bkg} = 0$, little/no accn.
- Energy dist: $\eta_{bkg}$
Case 1: Phase 2

- Thin beams of accelerated particles at top and bottom boundaries.
- More keV-MeV orbits when including $\eta_{bkg}$

Helical currents $> j_{crit}$
Case 1: Phase 3

- Broader regions of accelerated orbits
- Energy dists well-matched with and without $\eta_{\text{bkg}}$:

Thin current sheets rapidly dissipate to sub-critical levels
Case 2
Case 2

- How do things change when a second loop becomes destabilised?
Differences between Cases

Case 1:
- Secondary disruption
- Key differences:
  - Orientation of initial helical instability
  - $\eta_{\text{bkg}} = 0$
  - Insert particles at multiple stages (blue arrows)

Case 2:

Change in Energy (relative to initial state)
- $dE$ (% of total energy)
- Magnetic energy
- Kinetic energy
- Thermal energy

Change in Energy over time ($t/\tau_A$):
- Left loop kink instability onset
- Right loop destabilises

Graph showing change in energy over time with different energy components.
Case 2: Initial State

Boundary locations and midplane current $|j|$
Case 2: kink instability onset

Acceleration signatures ONLY in left hand loop core
Case 2: intermediate phase

current $> j_{\text{crit}}$ dissipates

sheath field distorted

Few MeV orbits observed
Case 2: Secondary disruption

Fragmented currents >j_{crit}

Acceleration signatures spread THROUGHOUT boundaries
Case 2: Energetics

- Proton and electron energisation nearly identical
- Energy distrib. follow reconnection rate
- Hard-soft-hard pattern for two loops
- Pattern less clear-cut if more loops included

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

• 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!

• Multi-thread MHD loop cascade/eruption (2 loops):
  ★ Orbit findings in single loop destabilisation align with findings of Gordovskyy et al. (2011,2012)
  ★ Secondary loop disruption can be triggered by different orientation of helical instability.
  ★ Energised orbit final positions fill volume of both loops during second eruption
  ★ Spectra repeatedly harden then soften in-line with reconnection rate.

http://arxiv.org/abs/1801.02907