Electric fields in the Corona: Linking Kinetic and Magnetohydrodynamic Scales

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Outlook

- Radio and X-ray observations -> more and more details about the electron acceleration in the corona
- While the corona accumulates energy at large scales for electron acceleration small, plasma scales are relevant, e.g.
  - for resonant wave-particle interaction,
  - for stochastic acceleration in magnetic islands, shocks
  - for B-field dissipation and reconnection at current sheets
- Here: concentration on the latter
- Prediction by magnetic topology (Nulls, separatrices, QSL)
- Perpendicular acceleration near B-Nulls (ideal MHD E-fields)
- Parallel in current channels of crossing separatrices in 3D
- Problem of building up parallel E-fields in the corona
- Consequences of turbulence and cascading reconnection
Topology Predictions by Nulls, Separatrices and QSL (finite B case)

Nulls and separatrix-footprints obtained for a monopoles ([D. Longcope's] MPole) ->
Green dots: Main polarities
Red dots: Main magnetic nulls as they survive in a smooth B-field extrapolation (see below)

Regions of small or vanishing B fields (Nulls) predict the location of current concentrations
A 3D coronal null resulting from a quadrupolar photospheric B-field via its fan and spine field lines it is connected to the B-maxima.

Eigenvalues of the Jacobian of B around the null: \{+2; -1.7; -0.3\} \{Spine, Fan; Fan\}.

According to [Priest & Pontin 2009]: whether torsional Spine / Fan or Shear flow reconnection \(\rightarrow\) is decided by flows!
Null-point reconnection simulation

3D magnetic null-related reconnection dynamics
[from Büchner 2008]
Eperp of ideal MHD can accelerate only de-magnetized particles as near Nulls with their strong Böfield gradients and curvatures. Analytical models (see later talk by the Manchester group):
Electron acceleration in the Eperp of ideal MHD is not at all efficient from [Guo, Büchner et al., 2010]
For Epar a non-ideal, resistive MHD description is needed.

Set of MHD equations:

\[
\begin{align*}
\frac{\partial \rho u}{\partial t} &= -\nabla \cdot \rho uu - \nabla p + j \times B - \nu \rho (u - u_0) \\
\frac{\partial B}{\partial t} &= \nabla \times (u \times B - \eta j)
\end{align*}
\]

\[
E = -u \times B + \eta j, \quad \nabla \times B = \mu_0 j, \quad p = 2n \kappa_B T
\]

+ closing energy equation
Possible energy equation

\[ \frac{\partial p}{\partial t} = - \nabla \cdot p \mathbf{u} - (\gamma - 1) p \nabla \cdot \mathbf{u} + (\gamma - 1) S \]

**ohmic dissipation**

\[ S = \eta j^2 - \nabla \cdot q - L_r \]

where

- \[ \nabla \cdot q = \nabla \cdot (\kappa \nabla T) \]
- \[ \kappa \approx 10^{-11} T^{5/2} \]
- \[ L_r = n n_n \chi T^\alpha \text{ W/m}^3 \]

**heat conduction**

**along magnetic field**

**radiative cooling**
Cross-fan clockwise motion

Shown are the velocity vectors of a clockwise plasma motion near the footpoints of the two fans out of the magnetic null.

$\rightarrow$ velocity shear in the center.
If the plasma at the footpoints of the fan field lines is moved clockwise -> strong central shear -> Formation of a current channel below the Null

[Santos, Büchner, Otto, 11]
(from the title page of Astronomy & Astrophys., January 2011)
Parallel electric fields can accelerate particles to high energies, up to run away, if strong enough.


But:

- All these calculations used ad hoc (resistive) electric fields, whose generation and strength in the corona, which are due to microscopic plasma effects, are not well-understood, yet.
Epar in the collisionless corona

If e & i are both considered -> generalized Ohm`s law:

\[
\frac{4\pi}{\omega_{pe}^2} \frac{dJ}{dt} = \frac{E}{ne} + \frac{F}{J \times B} + \frac{1}{ne} \nabla p_e - \eta J
\]

- \( \frac{F}{c/\omega_{pe}} \) <- spatial -> electron inertia
- \( \frac{F}{\rho_i} \) <- scales ->
- \( \frac{F}{c/\omega_{pi}} \) <- scales ->
- \( \frac{F}{\text{off-diagonal elements of the pressure tensor}} \)
- \( \frac{F}{\text{dissipation due to plasma turbulence}} \)
- \( \frac{F}{\text{electron - ion decoupling, „Hall“ term“}} \)
Self-consistent E-fields solar in the collisionless corona

Ensemble averaging:

\[
\langle \delta f_j \rangle = \langle \delta \tilde{E} \rangle = \langle \delta \tilde{B} \rangle = 0.
\]

\[
f_j = f_{0j} + \delta f_j \quad E_\parallel = \langle E_\parallel \rangle + \delta E_\parallel
\]

-> Modified Vlasov equation, after velocity averaging

-> momentum exchange in the parallel direction

\[
\frac{\partial f_{0e}}{\partial t} + \vec{v} \cdot \frac{\partial f_{0e}}{\partial \vec{r}} + \frac{e}{m_e} \vec{E} \cdot \frac{\partial f_{0e}}{\partial \vec{v}} = -\frac{e}{m_e} \left\langle \left( \delta \tilde{E} + \vec{v} \times \delta \tilde{B} \right) \cdot \frac{\partial \delta f_e}{\partial \vec{v}} \right\rangle
\]

-> correlation of e/m fluctuations and plasma density /current fluctuations

\[
\left( \frac{d}{dt} n m_e v_{y,e} \right)_{eff} = \langle \delta E_y \delta \rho_e + \delta j_{z,e} \delta B_x - \delta j_{x,e} \delta B_z \rangle
\]

-> Correlations due to wave-particle i.a.; cannot be taken from theory (e.g. quasilinear) -> kinetic simulations are needed!
Epar in large-β plasmas

3D Kinetic (micro-) turbulent reconnection coupled to due to LHD/kink-sausage turbulence

Note: without initial guide field, i.e. plasma beta ~ unity like near magnetic Nulls
For smaller $\beta$: transition LH -> IA

$\beta = 0.1$

Linearily unstable modes $\gamma > 0$ (colors) in $k_{\parallel}$ vs. $k_\perp$

For very small $\beta$: most unstable are B-field aligned compressional waves

$\beta = 0.01$
Nonlinear evolution - small $\beta$ case

electrostatic potential

fe (forward current)

$\tau_{\omega_{pe}} = 188$

[Büchner, Elkina, 2006; Munoz, Lee, Büchner, 2012]
Very small plasma-β limit: very thin and turbulent sheets

Use random $f_1(t = 0) \propto k_x^{-1} k_y^{-1} + \text{small v-space perturbation}$

- Islands in $A_\parallel$ (left)
- Current sheets visible in $j_\parallel$ (right), aligned to magnetic potential, typical scale $\lambda = d_e = \frac{c}{\omega_{pe}}$

[From Jenko, Büchner et al., 2012]
Large scale observed convection, extrapolated magnetic fields -> $E_{\text{perp}}$

In between: inertial range - $E_{\text{par}} = ???$

At smallest scales: Selfconsistent $E_{\text{par}}$ due to non-ideality by microturbulence
Epar in chromosphere & corona

Epar via current density and resistivity parametrized by an effective „collision frequency“, which is dominated:

In the (lower) chromosphere:
by binary particle collision rate
[Spitzer-Härm–Braginski Theory 1958-63]

In the TR / corona:
by plasma turbulence as obtained by Vlasov code simulations for coronal conditions, Te~Ti etc:
[Büchner & Elkina 2006/2007]
– for higher beta plasma -> 1D: IA double layers
– for lower beta plasma -> 2D: LH turbulence
But: as threshold: a large current carrier drift velocity $j/ne > v_{te}$ (-> thin sheets!)
Epar in RMHD by resistivity

Background \( \eta_0 \) Spitzer-level > \( Rm \sim 10^9 \) in the corona

While current-carrier-velocity dependent anomalous resistivity in the corona: \( \eta_{\text{eff}} = 10^6 \) times the Spitzer resistivity!

\[
\eta = \eta_0 + \begin{cases} 
0, & \text{if } |u_{ccv}| < u_{\text{crit}} \\
\eta_{\text{eff}} \left(\frac{|u_{ccv}|}{u_{\text{crit}}} - 1\right), & \text{if } |u_{ccv}| \geq u_{\text{crit}} 
\end{cases}
\]

\( \eta_{\text{eff}} = \frac{\nu_{\text{eff}}}{\varepsilon_0 \omega_p^2} \)

\( \eta_{\text{eff}} \) is due to high frequency plasma turbulence, obtained by Vlasov code simulations for coronal conditions \((T_e \sim T_i \text{ et c.)} \) in [Büchner & Elkina 2005-2008):
- for low beta conditions -> 1D: IA double layers
- for higher beta plasma –> 2D: LH turbulence

Note: large velocities \( j/\pi e \) -> \( V_{te} \) needed -> thin sheets c/ \( \pi \), not resolved by MHD – „Filling factor“ and smoothed current sheets
Multiple current sheet tearing

Multiple tail current sheet tearing obtained by 2.5 D adaptive grid MHD simulation [Bártá, Büchner et al., 2011, ApJ paper 1]
After islands are formed $\rightarrow$ coalescence continues the cascade $\rightarrow$ smaller scale islands [Bárta, Büchner et al. 2011, ApJ paper 1]
many small magnetic islands, where electrons are accelerated

Due to cascading reconnection (tearing+coalescence) -> wider acceleration regions rather than the original currents sheets, a large number of particles can become accelerated!
Observables: size spectrum

Magnetic field profile:

\[ B(x) = B_0 \frac{x}{L} \]

Magnetic energy in a single plasmoid of size \( L \):

\[ E_{SP}^M(L) = \int \frac{B_0^2}{2\mu_0} dV = \int_0^L \frac{2\pi B_0^2}{2\mu_0 L^2} x^2 \, dx = \frac{\pi}{4\mu_0} B_0^2 L^2 \]

Plasmoid size distribution:

\[ n(L) \propto L^{-2} \]

Energy at scale \( L \):

\[ dE_M(L) = E_{SP}^M(L) n(L) dL = E_M(k) dk \]

\[ k = \frac{2\pi}{L}, \quad dk = -\frac{2\pi}{L^2} dL \]

Spectral energy density:

\[ E_M(k) \propto k^{-2} \]
In our simulation the cascade ends at the smallest dissipation scale which still can be resolved. The spectral index of the island size distribution is about 2.14, is now compared to observations [Bemporad et al. 2012]
Cascading reconnection: Acceleration in the 3D islands
... and after their coalescence

-> Particles are ejected out of the islands parallel to the magnetic field letting them precipitate down to the chromosphere
Derived Observables

Flare-ribbon structure of the mapped acceleration regions

Comparison to radio observations

Flare-ribbons structures observed by the Ondrejov MCF Spectrograph, from [Kotrč et al. 2009]
Flare-ribbon X-ray / accelerated electron structures as observed by RHESSI, from [Nishizuka et al., ApJ, 2009]
Ideal MHD E-fields near Nulls do not provide efficient acceleration.

Instead: parallel, non-ideal MHD E-fields due to current concentrations, e.g. by 3D separatrix crossings.

But: non-ideal E-par fields form at small scales, coronal energy is accumulated by large scale motion.

Solution: Cascading and turbulent reconnection.

Signatures: e.g. ribbons already found in radio- and X-ray observations.