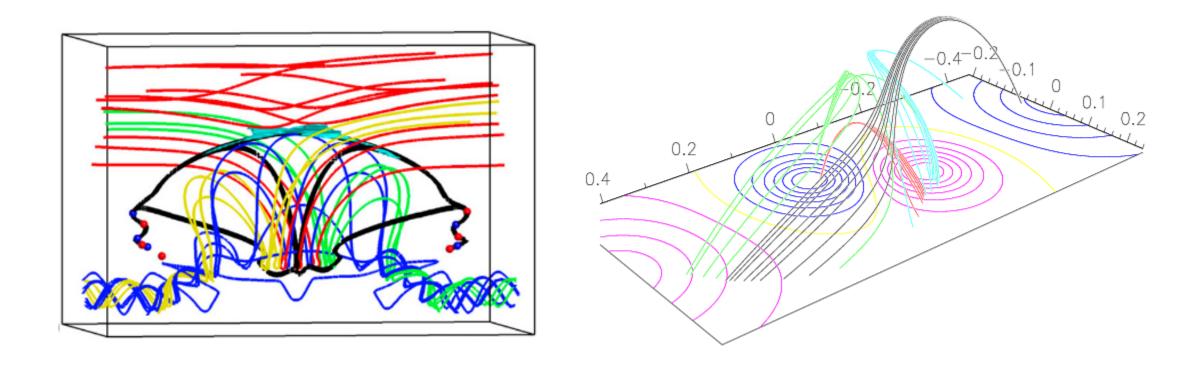


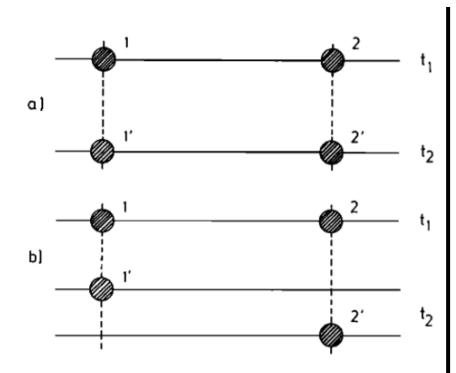
3D magnetic reconnection



Parnell et al. 2010, ApJ

Aulanier et al. 2006, Solar Phys.

General magnetic reconnection (GMR)



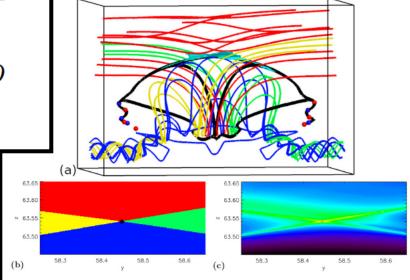
Schindler et al. 1988, JGR

$$E + u \times B = R$$
 in $D \subset \mathbb{R}^3$

$$m{E} + m{u} imes m{B} = m{R} \quad ext{in} \quad D \subset \mathbb{R}^3$$
 $m{E} + m{u} imes m{B} = m{0} \quad ext{in} \quad \mathbb{R}^3 \setminus D$

Reconnection rate:

$$R_D = \max_D \int \mathbf{R} \cdot \mathbf{b} \, \mathrm{d}x$$



Parnell et al. 2010, ApJ

Eyink's critique (Eyink 2015, ApJ)

In turbulent plasmas, there are no discrete and isolated $oldsymbol{D}$.

In a turbulent inertial range, $oldsymbol{R}$ can by tiny but $\
abla imes oldsymbol{R}$ need not be.

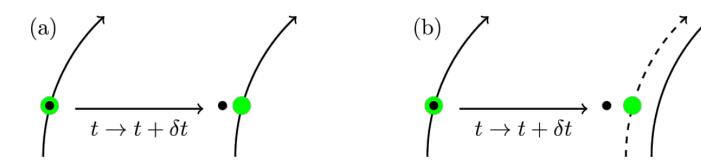
Magnetic reconnection is related to:

the slip velocity source

$$oldsymbol{\Sigma} = -rac{(
abla imes oldsymbol{R})_{oldsymbol{oldsymbol{\perp}}}{|oldsymbol{B}|}$$

This is the rate of velocity slip per unit arclength along a field line.

A simpler interpretation



$$rac{\partial m{b}}{\partial t} = rac{1}{|m{B}|}igg(rac{\partial m{B}}{\partial t}igg)_{ot}$$
 Induction equation

$$rac{\partial m{b}}{\partial t} = rac{1}{|m{B}|} (
abla imes (m{u} imes m{B}) -
abla imes m{R})_{ot} = rac{1}{|m{B}|} (
abla imes (m{u} imes m{B}))_{ot} + \Sigma_{ot}$$

Further connections

$$oldsymbol{j} = oldsymbol{B} imes rac{oldsymbol{F}}{\left|oldsymbol{B}
ight|^2} + lpha oldsymbol{B}, \quad ext{where} \quad oldsymbol{F} = oldsymbol{j} imes oldsymbol{B}, \quad lpha = rac{\left(
abla imes oldsymbol{B}\right) \cdot oldsymbol{B}}{\left|oldsymbol{B}
ight|^2}$$

Further connections

$$oldsymbol{j} = oldsymbol{B} imes rac{oldsymbol{F}}{\left|oldsymbol{B}
ight|^2} + lpha oldsymbol{B}, \quad ext{where} \quad oldsymbol{F} = oldsymbol{j} imes oldsymbol{B}, \quad lpha = rac{\left(
abla imes oldsymbol{B}
ight) \cdot oldsymbol{B}}{\left|oldsymbol{B}
ight|^2}.$$

$$oldsymbol{j} = \lambda oldsymbol{B}_{f\perp} + lpha oldsymbol{B}, \quad ext{where} \quad oldsymbol{B}_{f\perp} = oldsymbol{B} imes rac{oldsymbol{F}}{|oldsymbol{F}|}, \quad \lambda = rac{(
abla imes oldsymbol{B}) \cdot oldsymbol{B}_{f\perp}}{|oldsymbol{B}|^2}.$$

Further connections

$$j=m{B} imesrac{m{F}}{|m{B}|^2}+lpham{B}, \quad ext{where} \quad m{F}=m{j} imesm{B}, \quad lpha=rac{(
abla imes m{B})\cdot m{B}}{|m{B}|^2}.$$
 Field-aligned current $m{j}=\lambda m{B}_{f\perp}+lpham{B}, \quad ext{where} \quad m{B}_{f\perp}=m{B} imesrac{m{F}}{|m{F}|}, \quad \lambda=rac{(
abla imes m{B})\cdot m{B}_{f\perp}}{|m{B}|^2}.$ Lorentz force $m{F}=\lambda m{B}_{f\perp} imes m{B}=\lambda |m{B}|^2rac{m{F}}{|m{F}|}.$

For resistive MHD:

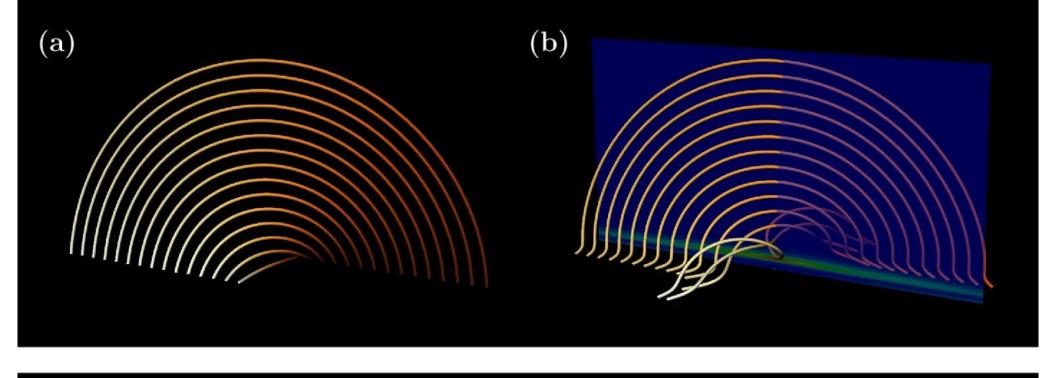
$$egin{align} \Sigma &= -rac{1}{|oldsymbol{B}|}(oldsymbol{C}_1 + \eta oldsymbol{C}_2), \ oldsymbol{C}_1 &= & lpha
abla \eta imes oldsymbol{B} - \lambda (
abla \eta \cdot oldsymbol{B}) rac{oldsymbol{F}}{|oldsymbol{F}|}, \ oldsymbol{C}_2 &= & (\lambda \omega_1 -
abla \lambda \cdot oldsymbol{B}) rac{oldsymbol{F}}{|oldsymbol{F}|} + \lambda (lpha + \omega_2) oldsymbol{B}_{f\perp} +
abla lpha imes oldsymbol{B}, \end{aligned}$$

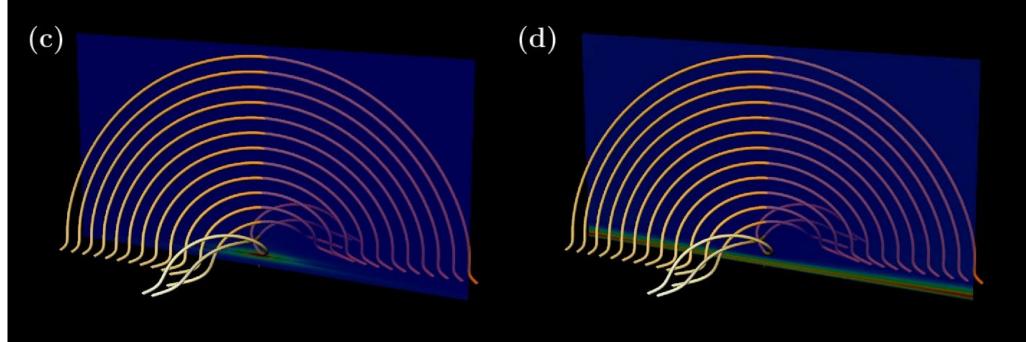
where

$$\omega_1 =
abla imes oldsymbol{B}_{f\perp} \cdot rac{oldsymbol{F}}{|oldsymbol{F}|}, \quad \omega_2 = rac{\left(
abla imes oldsymbol{B}_{f\perp}
ight) \cdot oldsymbol{B}_{f\perp}}{|oldsymbol{B}|^2}.$$

First moral - the slippage rate links reconnection to important magnetic field elements: the Lorentz for and field-aligned currents

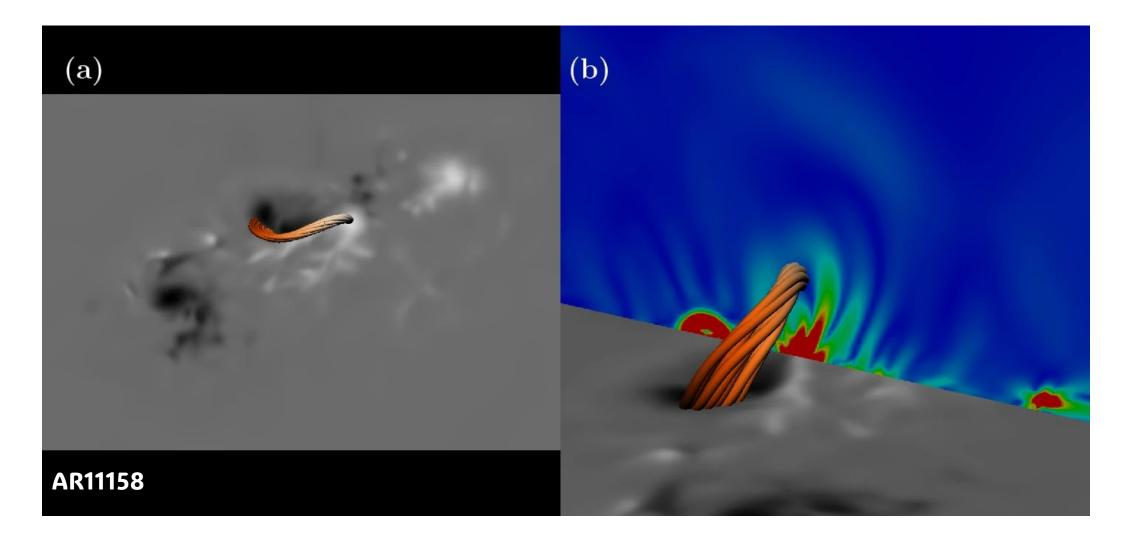
Second moral - all quantities are pointwise, i.e. they are local to small neighbourhoods



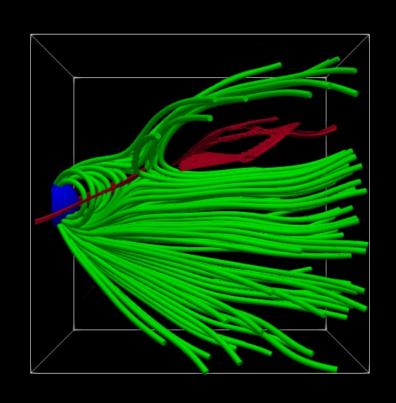


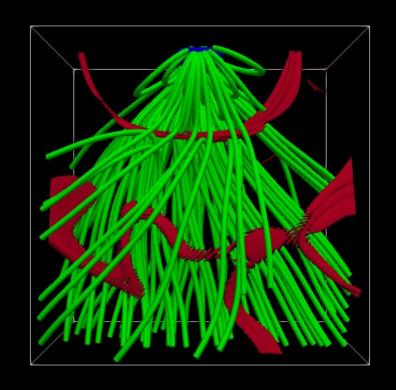
Force-free fields

$$\Sigma_{
m NLFF} = -\eta
abla lpha imes m{b}.$$



Magnetosphere (nightside)





00:00UT 11th May 2024

Summary

- A general description of reconnection (can describe turbulent and laminar plasmas)
- Connects reconnection to important magnetic properties (Lorentz force & FAC)
- It is a local theory (pointwise and easy to compute in simulations and extrapolations)

For further details see

MacTaggart 2025, On field line slippage rates in the solar corona, Solar Physics, 300, 48