Space Plasma Physics

Thomas Wiegelmann, 2012

Physical Processes

8. Plasma Waves, instabilities and shocks
9. Magnetic Reconnection

Applications

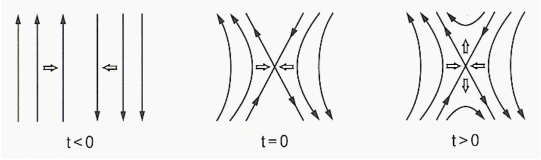
10. Planetary Magnetospheres
11. Solar activity
12. Transport Processes in Plasmas

Magnetic reconnection

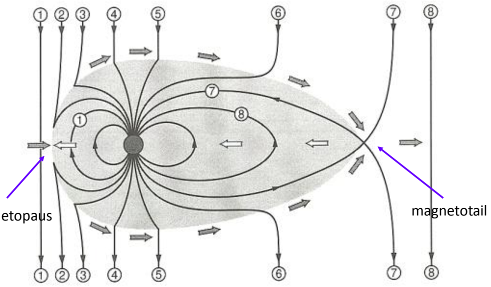
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma_0} \nabla^2 \mathbf{B}$$

Assuming the plasma streams at bulk speed *V*, then the induction equation can be written in simple dimensional form as:

$$\frac{B}{\tau} = \frac{VB}{L_B} + \boxed{\frac{B}{\tau_d}}$$

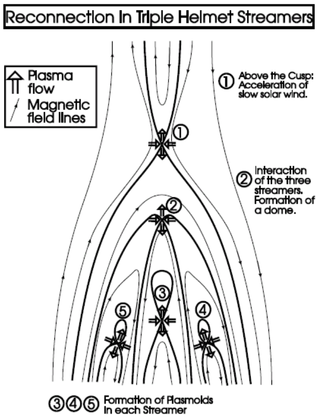


Field line merging and reconnection in the Earth‘s magnetosphere



magnetopause

magnetotail



How to model magnetic reconnection?

- In ideal MHD, plasma is frozen into the magnetic field => field line topology conservation and magnetic reconnection is not possible.
- Resistive MHD in 2D
- Resistive MHD in 3D
- Collisionless reconnection, kinetic treatment
- Hybrid models, e.g. treat the ions with a kinetic model and electrons as fluid.

Magnetic reconnection, 2D MHD

Source: Priest et al. JGR 108, A7, 2003

- Kinematic approach (not to be confused with kinetic theory !!): One studies the induction equation and ignores the equation of motion for simplicity:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B})$$

- We derived this equation in exercises earlier from Ohms law:

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{\mathbf{j}}{\sigma}$$

- In most space plasmas the Reynolds number is very large and resistive effects can be neglected.

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{0}.$$

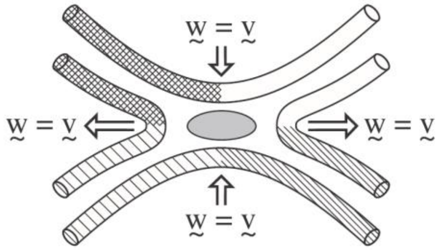
Magnetic reconnection, 2D MHD

- An exception are strong current concentrations with high gradients in the magnetic field. Here resistive effects become important and magnetic reconnection can occur.
- In generally we can describe the motion of magnetic flux, if a flux-conserving velocity **w** exists:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{w} \times \mathbf{B})$$

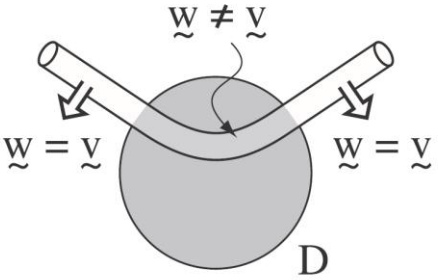
- How is flux-conserving velocity **w** related to the plasma flow velocity **v**?

Magnetic reconnection, 2D MHD



Breaking and rejoining of two flux tubes in 2-D to form two new flux tubes. Outside the diffusion region the flux-conserving velocity is identical with the plasma velocity.
Source: Priest et al. 2003

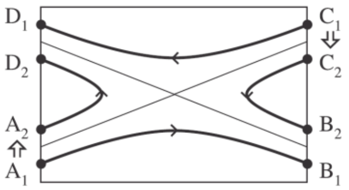
Magnetic reconnection, 2D MHD



Inside the diffusion region these two velocities are NOT identical, because the plasma is not frozen in the magnetic field here. Source: Priest et al. 2003

Properties of 2D MHD-reconnection

- A differentiable flux tube velocity **w** exists everywhere except at null points. The magnetic flux moves at the velocity **w** and slips through the plasma, which moves at **v**.
- Mapping of field lines are discontinuous



Moving over the separatrix from A_1 to A_2, there is a jump from B_1 to D_2 => field lines break

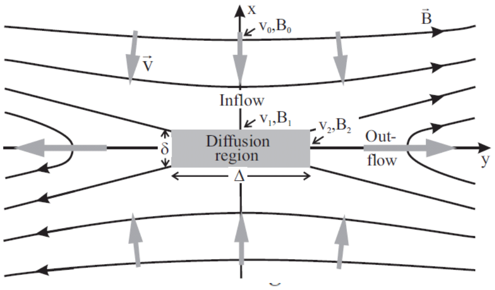
Source: Priest et al. 2003

Properties of 2D MHD-reconnection

- Field lines preserve their connections in the diffusion region. The exception is the X-point, where the field lines break and their connections change.
- Reconnecting flux tubes join perfectly and outside the diffusion region **v**=**w**.
- For a flux tube partly in the diffusion region, the part of the flux tube in the zone slips through the plasma. (Outside: frozen in)
- Different models have been suggested for 2D reconnection, which based on details of reconnection zone (e.g. Sweet-Parker model, Petschek reconnection)

Source: Priest et al. 2003

Sweet Parker 2D-model



$$L \geq \Delta \geq \breve{\delta}.$$

Source: Schindler & Hornig, 2001
Magnetic Reconnection, in Encyclopedia of Astronomy and Astrophysics

2D MHD-reconnection, Sweet Parker (1956)

- Reconnection is described as diffusion on scales smaller than typical macroscopic scales.
- Properties in the inflow region (flow velocity, magnetic field strength, convection electric field) are related to the outflow region and allow to calculate the reconnection rate (amount of flux reconnected per time, ratio of in and outflow velocity) $V_{out} \sim V_A \equiv \frac{B_{in}}{\sqrt{\mu_0 \rho}}$
- Reconnection rate is much slower as observed in space plasmas, but faster than global diffusion.

Source: Wikipedia

2D MHD-reconnection, Petschek model (1964)

- The reconnection rate in the Sweet-Parker model is too slow.
- Aspect-ratio of current sheet has to be large for high Lundquist numbers because of the relation

$$S \equiv \frac{\mu_0 L V_A}{\eta}.$$

$$\frac{V_{in}}{V_A} \sim \frac{1}{S^{1/2}}$$

- Petschek refined the Sweet-Parker model in 1964. In and out-flow regions are separated by slow mode shocks.
- Reconnection does hardly depend on aspect ratio and fast reconnection is possible:

$$\frac{V_{in}}{V_A} \approx \frac{\pi}{8 \ln S}.$$

Source: Wikipedia

Magnetic reconnection: energy conversion

- From the resistive MHD-simulations we derive equations for the balance of mechanical and electromagnetic energy:

$$\frac{\partial}{\partial t}\left(\frac{\rho v^2}{2} + u\right) + \nabla \cdot \left(\left(\frac{\rho v^2}{2} + u + p\right) \boldsymbol{v}\right) = \boldsymbol{j} \cdot \boldsymbol{E}$$

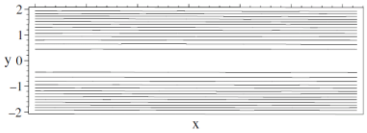
$$\frac{\partial}{\partial t}\left(\frac{B^2}{2\mu_0}\right) + \nabla \cdot \left(\frac{1}{\mu_0} \boldsymbol{E} \times \boldsymbol{B}\right) = -\boldsymbol{j} \cdot \boldsymbol{E}.$$

- For magnetic reconnection j and E have the same sign (why? Think about it in exercise)
  => Electromagnetic energy decreases
  Thermic and kinetic energy increases

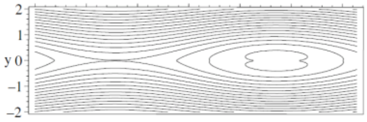
Source: Schindler & Hornig, 2001
Magnetic Reconnection, in Encyclopedia of Astronomy and Astrophysics

Time dependent reconnection

- Sweet-Parker and Petschek models investigated stationary reconnection.
- In Space plasmas reconnection happens often spontaneously as an instability process.



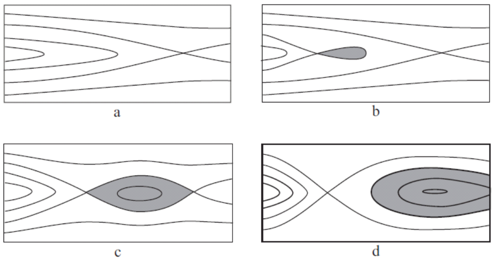
Unperturbed 1D-Harris sheet



Linear tearing instability leads to formation of a plasmoid.

Source: Schindler & Hornig, 2001

Time dependent reconnection



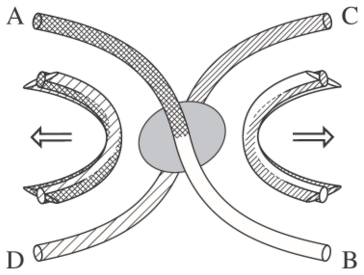
Streched configurations (modified Harris-sheet) are often used as models for the magnetotail and coronal helmet streamers. Time dependent reconnection occur in models for substorms and coronal mass ejections.

Source: Schindler & Hornig, 2001

Magnetic reconnection, 3D MHD

- Some concepts on 2D-reconnection cannot be generalized to the 3D-case.
- Reconnection at an X-point (magnetic null) becomes structual unstable in 3D:
  - 2D X-point becomes an x-line in 3D.
  -We can add a magnetic field parallel to this line (perpendicular to 2D reconnection-plane) and the x-line is NOT a magnetic null anymore.
- One cannot generally find a flux-conserving velocity **w** in 3D. (Proof by Priest et al. 2003, omitted here)

Magnetic reconnection, 3D MHD



In 3D the flux-tubes not necessarily match perfectly. In 3D the flux-tubes break and rejoin only partly forming four new flux tubes.

Source: Priest et al. 2003

GEM magnetic reconnection challenge

Source: Birn et al. JGR 106, A3, 1999

- The Geospace Environmental Modeling (GEM) Reconnection Challenge.
- Magnetic reconnection was studied in a simple Harris sheet configuration with a specified set of initial conditions, including a finite amplitude, magnetic island perturbation to trigger the dynamics.
- The evolution of the system is explored with a broad variety of codes, ranging from fully electromagnetic particle in cell (PIC) codes to resistive MHD.
- Aim: Identify the essential physics which is required to model collisionless magnetic reconnection.

GEM: Initial Harris sheet

- We computed the 1D Harris sheet profile in the magneto-static section, but it is a kinetic equilibrium and solves the stationary Vlasov equation as well.

$$B_x(z) = B_0 \tanh(z/\lambda)$$
$$n(z) = n_0 \mathrm{sech}^2(z/\lambda) + n_\infty$$

The electron and ion temperatures, T_e and T_i, are taken to be uniform in the initial state. The pressure balance condition gives $n_0(T_e + T_i) = B_0^2/8\pi$. The computation is carried out in a rectangular domain $-L_x/2 \le x \le L_x/2$ and $-L_z/2 \le z \le L_z/2$.

Source: Birn et al. 1999

- Used simulation parameters
  $\lambda = 0.5,\ n_\infty/n_0 = 0.2,\ T_e/T_i = 0.2$
  $m_i/m_e = 25,\ L_x = 25.6$, and $L_z = 12.8$
- Physical quantities have been normalized with
  ion inertial length c/ω_{pi}
  ion cyclotron frequency $\Omega_i = eB_0/m_i c$
- So we have a thin current sheet (macroscopic length scale is of order of kinetic scales) and ions are hotter than electrons.
- Question: Why one chooses a mass ration of 25 instead of true mass ratio 1836 for protons and electrons?
- The initial Harris-sheet was perturbed:

$$\psi(x,z) = \psi_0 \cos(2\pi x/L_x)\cos(\pi z/L_z)$$

Source: Birn et al. 1999

BIRN ET AL.: GEM RECONNECTION CHALLENGE

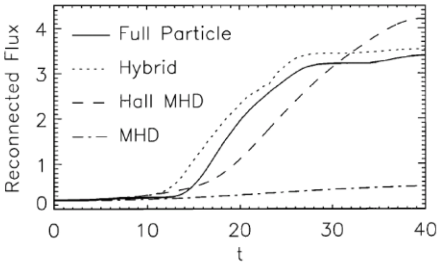


Figure 1. The reconnected magnetic flux versus time from a variety of simulation models: full particle, hybrid, Hall MHD, and MHD (for resistivity $\eta = 0.005$).

GEM: Results

- All models that include the Hall effect in the generalized Ohm's law produce essentially indistinguishable rates of reconnection, corresponding to nearly Alfvenic inflow velocities.
- Thus the rate of reconnection is insensitive to the specific mechanism which breaks the frozen-in condition, whether resistivity, electron inertia, or electron thermal motion.
- The reconnection rate in the conventional resistive MHD model, in contrast, is dramatically smaller unless a large localized or current dependent resistivity is used.

GEM: Results

- Remember the generalized Ohm’s law from our MHD-lecture:

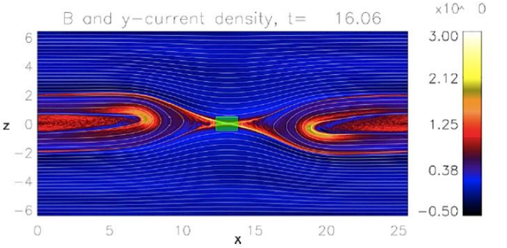
$$\frac{4\pi}{\omega_{pe}^2}\frac{d\mathbf{j}}{dt} = \mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{B} - \frac{1}{nec}\mathbf{j}\times\mathbf{B} + \frac{1}{ne}\nabla\cdot\vec{p_e} - \eta\mathbf{j},$$

Hall term

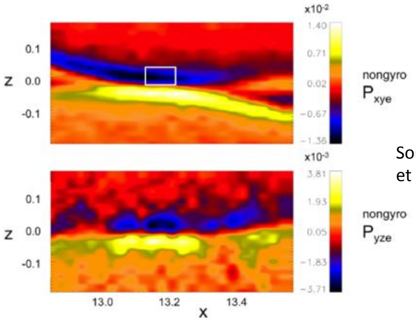
- The Hall term takes care about different motion of electrons and ions.
- Please note that in kinetic (PIC or Vlasov code) we do not have an Ohm’s law, but this law was derived in the fluid picture by substraction the momentum equations for ions and electrons.
- => Effect is naturally there in kinetic theory.

The diffusion region

Source: Hesse et al. Space Sci Rev 2011

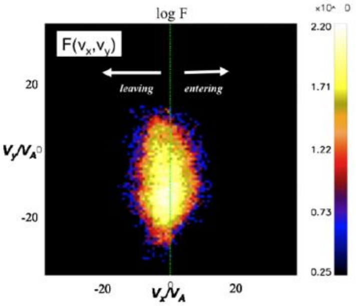


- As pointed out by Biskamp (Book:Nonlinear MHD 1993) the diffusion region is not treated correctly in Petschek-like-MHD-models)
- => Kinetic treatment necessary

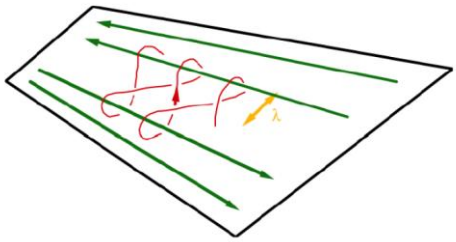


Source: Hesse et al. 2011

- Plasma pressure (electron pressure tensor) is not isotrop and not even gyrotropic in diffusion region.
- Simulations with mass ratio m_i/m_e=256, Hesse et al

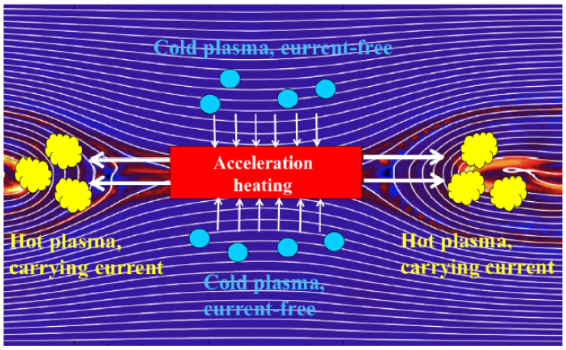


Reduced distribution F(vx, vy) in the outflow region. The distribution demonstrates the preferential loss of accelerated particles from the dissipation region. Source: Hesse et al. 2011



- Electrons become unmagnetized in diffusion region.
- Schematic picture of meandering electron orbits in a magnetic field reversal.

Source: Hesse et al. 2011



Source: Hesse et al. 2011

Magnetic reconnection

- Magnetic reconnection changes the magnetic field topology and magnetic energy is converted into thermal and kinetic energy.
- Reconnection was studied first in 2D resistive MHD with stationary and time-dependent models.
- In ideal MHD magnetic reconnection cannot happen.
- In the resistive (or diffusive) zone, basic assumptions of MHD break down and kinetic effects become important.
- Reconnection in 3D can happen at 3D-magnetic-Nulls and also for non-vanishing magnetic fields (active area of research and details are outside of scope of this indroductory lecture)