Magnetic Reconnection:
Simple Ideas

Russell Kulsrud

CMSO General Meeting, July 8, 2008

In collaboration with members of MRX group and NSF-DoE Center of Magnetic Self-organization

SOLAR FLARES

- **Flux freezing:**

  Makes it possible to store energy in solar magnetic fields by twisting the foot points in the photosphere.

- **Magnetic reconnection:**

  Allows field lines to break converting this magnetic energy into other forms: radiation, particle acceleration, and also the kinetic energy of the solar wind.

Ingredients

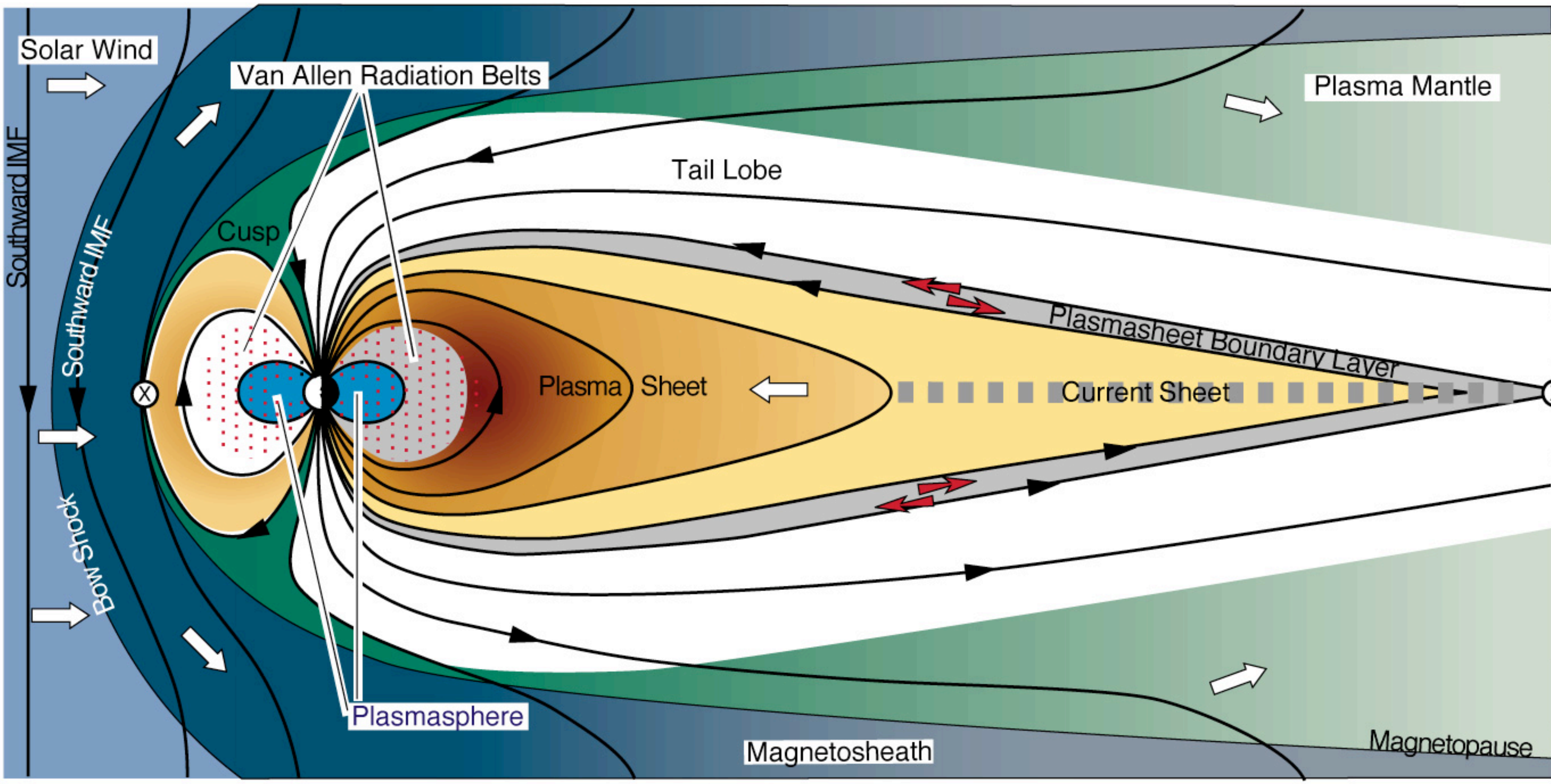
- **Flux freezing:**

  Makes it possible to store energy in solar magnetic fields by twisting the foot points in the photosphere.

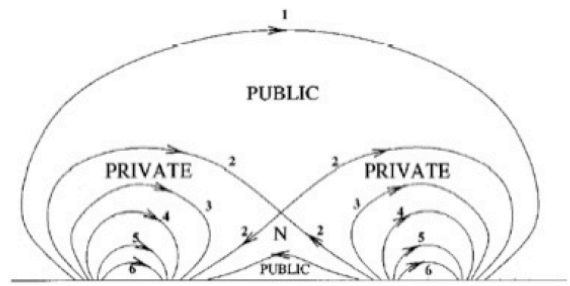
- **Magnetic reconnection:**

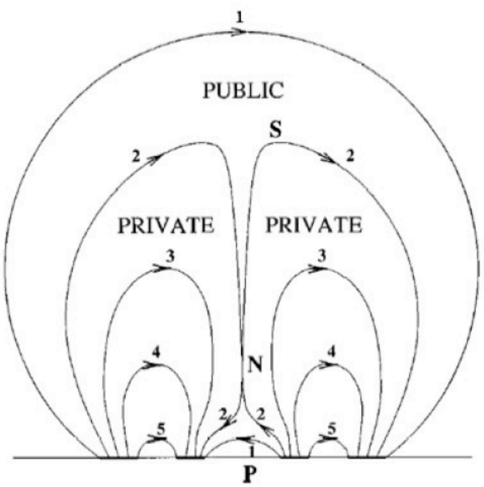
  Allows field lines to break converting this magnetic energy into other forms: radiation, particle acceleration, and also the kinetic energy of the solar wind.

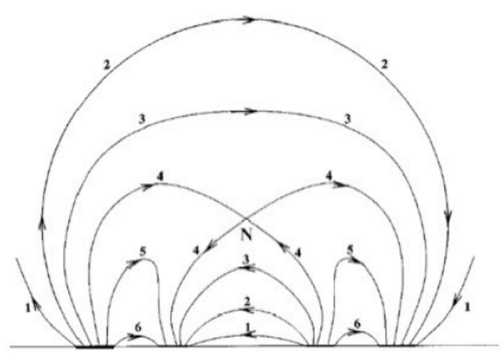
The magnetosphere



Sweet Model

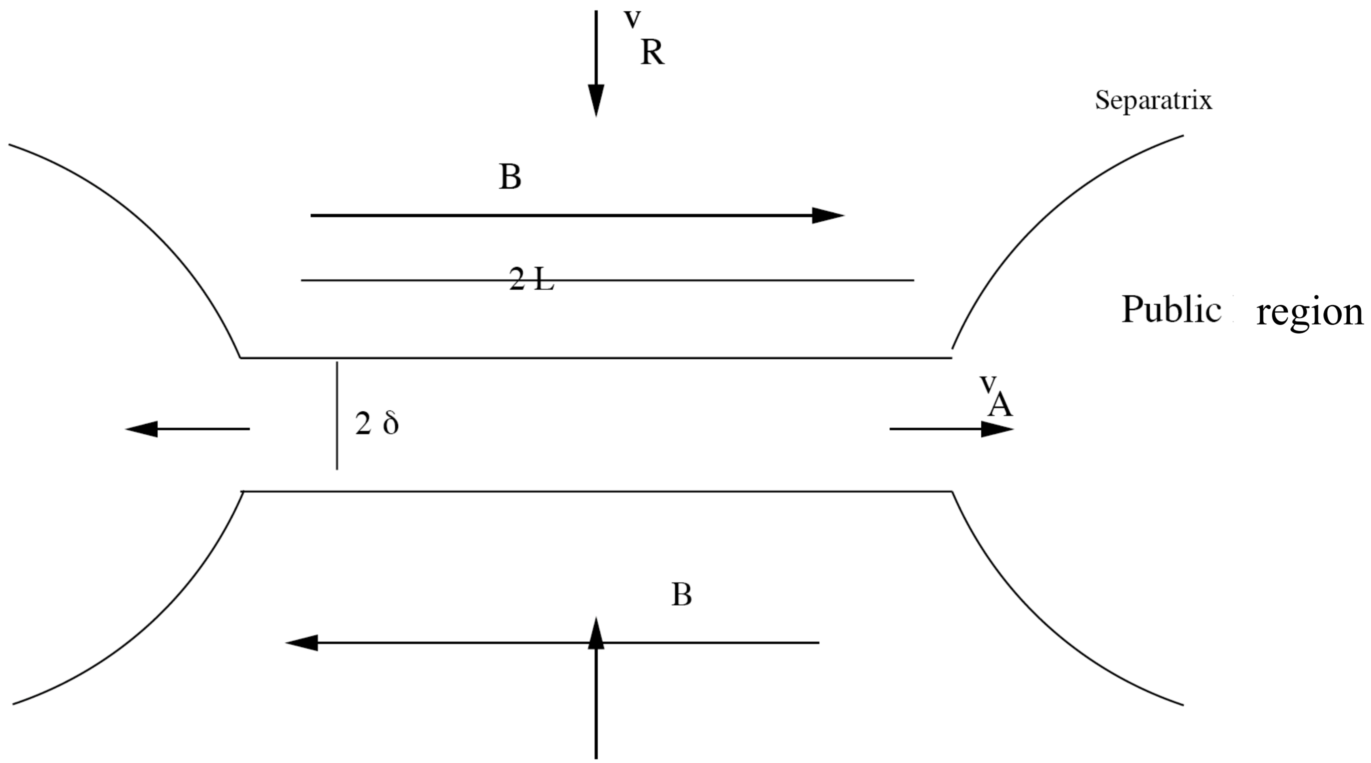

1
PUBLIC
PRIVATE
PRIVATE
2
3
4
5
6
N
PUBLIC


1
PUBLIC
S
2
PRIVATE
PRIVATE
3
4
N
5
P


2
3
4
N
5
6
1

Sweet-Parker Layer

Private region



THE SWEET PARKER RECONNECTION MODEL

- The basics of magnetic reconnection are line breaking and mass conservation
- The line breaking equation is:

$$v_R = \frac{\eta}{\delta} \tag{1}$$

  Thus, the smaller δ the faster the line breaking,

- The mass conservation equation is:

$$v_R = \frac{\delta}{L} v_A \tag{2}$$

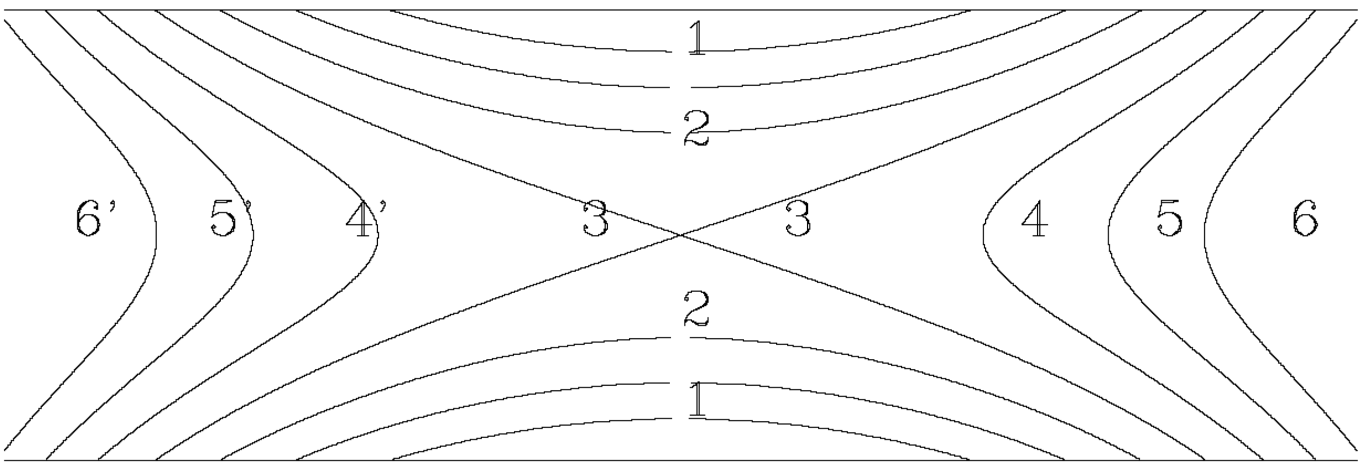
  Thus, the larger δ the faster mass flow.

- The best value of δ gives the Sweet–Parker value

$$\begin{aligned} \delta &= \sqrt{\eta L / v_A} = \frac{L}{\sqrt{S}} \\ v_R &= \frac{v_A}{\sqrt{S}} \end{aligned}$$

- S is the Lundquist number $S = v_A L/\eta$. which is very large in space and astrophysics. $\approx 10^{12}$

Magnetic field lines in Sweet -Parker layer



EXTENSION OF THE PHYSICS

The Sweet–Parker model turned out to be correct, but no one liked the answer.

The Petschek model gave the desirable answer but was not correct.

- In collisionless plasmas the Sweet–Parker layer is thinner than the ion skin depth, δ_i.

  This introduces new physics.

- The electron ion drift velocity is greater than the ion acoustic speed making enhanced resistivity.

  However, the layer cannot be thicker than δ_i which still limits the reconnection rate because of the mass flow condition. skin depth.

HALL AND ELECTRON INERTIA EFFECTS

- The ions and electrons have different velocities introducing Hall and electron inertial effects. and electron inertial terms. This also increases the reconnection rate.

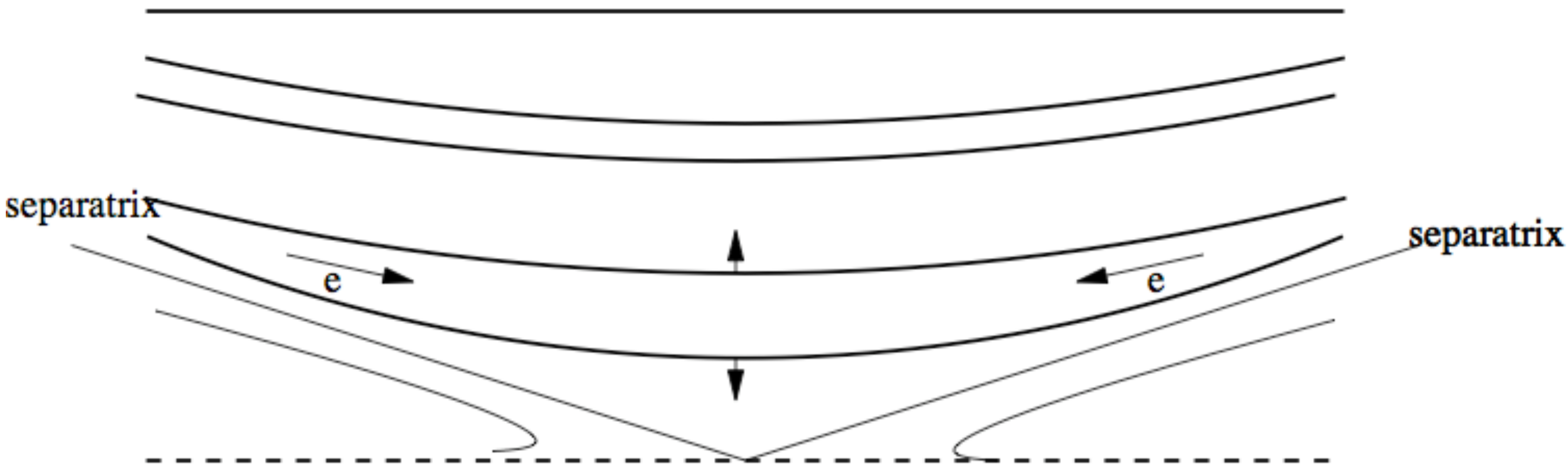
- Recent research has mainly focused on these two–fluid effects. Some of the results can be traced to charge neutrality. Others to electron inertial effects.

Two fluid Effects: The Quadrupole Field

In the two fluid limit, the ions are nearly unmagnetized and form an essentially uniform positive density.

However, the electrons are magnetized and under the line tying assumption their density is need not be nonuniform. in the absence of parallel electron veloicities.

But if the Debye length is very small charge neutrality must be preserved and this is done by parallel electron flows and current if one calculates these flows one finds that they produce a torodal field B_T and this field agrees quatitatively with the observed toroidal field.


separatrix
e
e
separatrix

Indeed one can show that

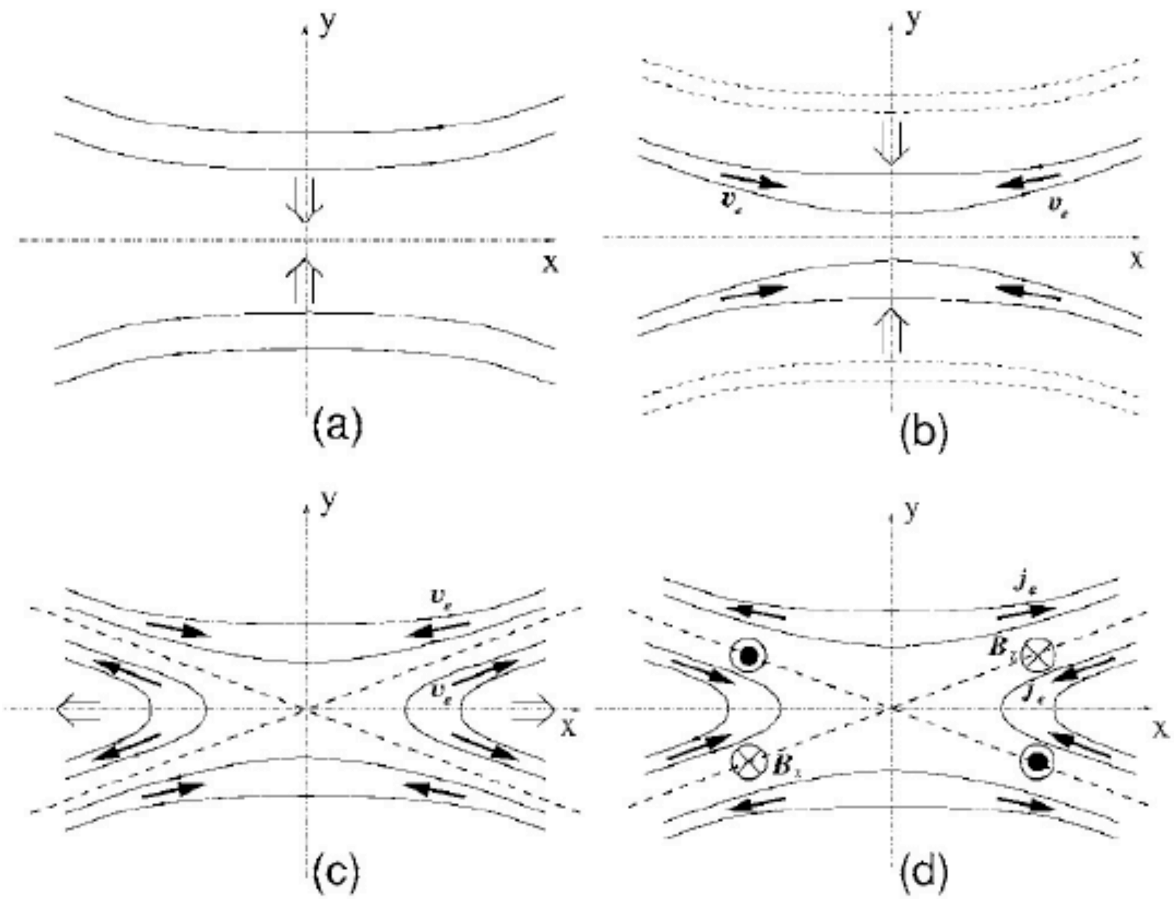
$$B_T = 4\pi neEV(x,z)$$

where $V(x,z)$ is the so-called volume per flux.

$$V(x,z) = \int \frac{dl}{|B|}$$

taken along a line of force from the x axis to the point x, z.

2-fluid & charge neutrality



Two fluid Effects: Magnetic Line Breaking

The y velocity an electron attains as it passes the X point is

$$v_y = \frac{eE\tau}{m}$$

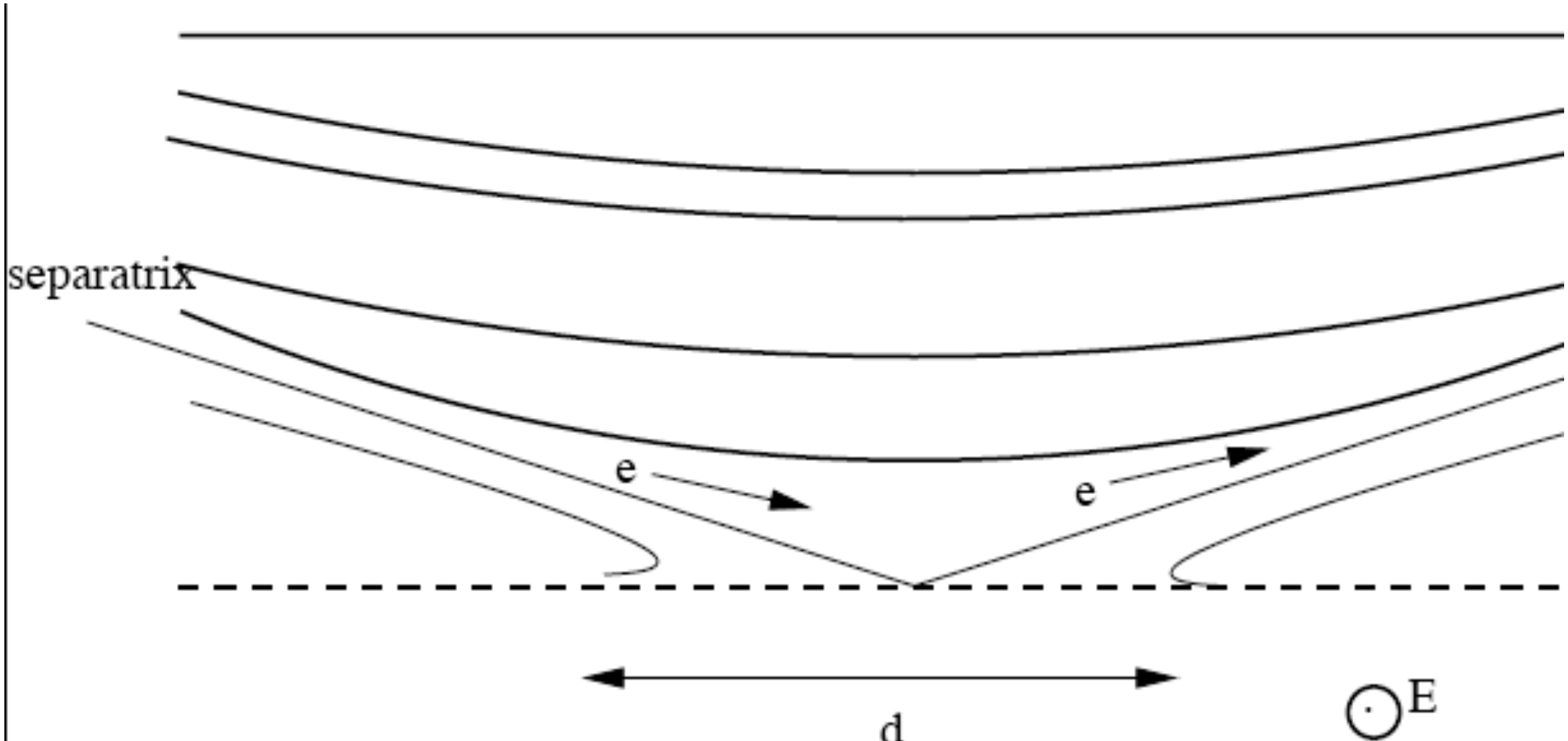
where

$$\tau = d/v_{th}$$

d is the length the electron goes during its acceleration time.

In collisional plasmas it is the mean free path λ .

In collisionless plasmas is the length of the orbit while the electron is unmagnetized.



$$v_y = \frac{eE\tau}{m}$$

$$\tau = \frac{d}{v_{th}}$$

If $d < \lambda$ then the plasma is collisionless and the current resistivity is enhanced over the Spitzer value by by λ/d

The rate of breaking of the lines is the electric field at X and if this E does not drive to large a current then the reconnection can proceed.

This is the case if d is short.

This line breaking is interpreted as a off diagonal component of the pressure tensor in Ohm's law, at the X point where B is zero, i.e.

$$E_y = \frac{1}{ne}\frac{\partial P_{yz}}{\partial z}$$

We can understand this in terms of the electron motion as follows. On the right side of the diagram (z¿0) electrons with $v_z > 0$ have passed by the X point and been accelerated and for them $v_y > 0$.

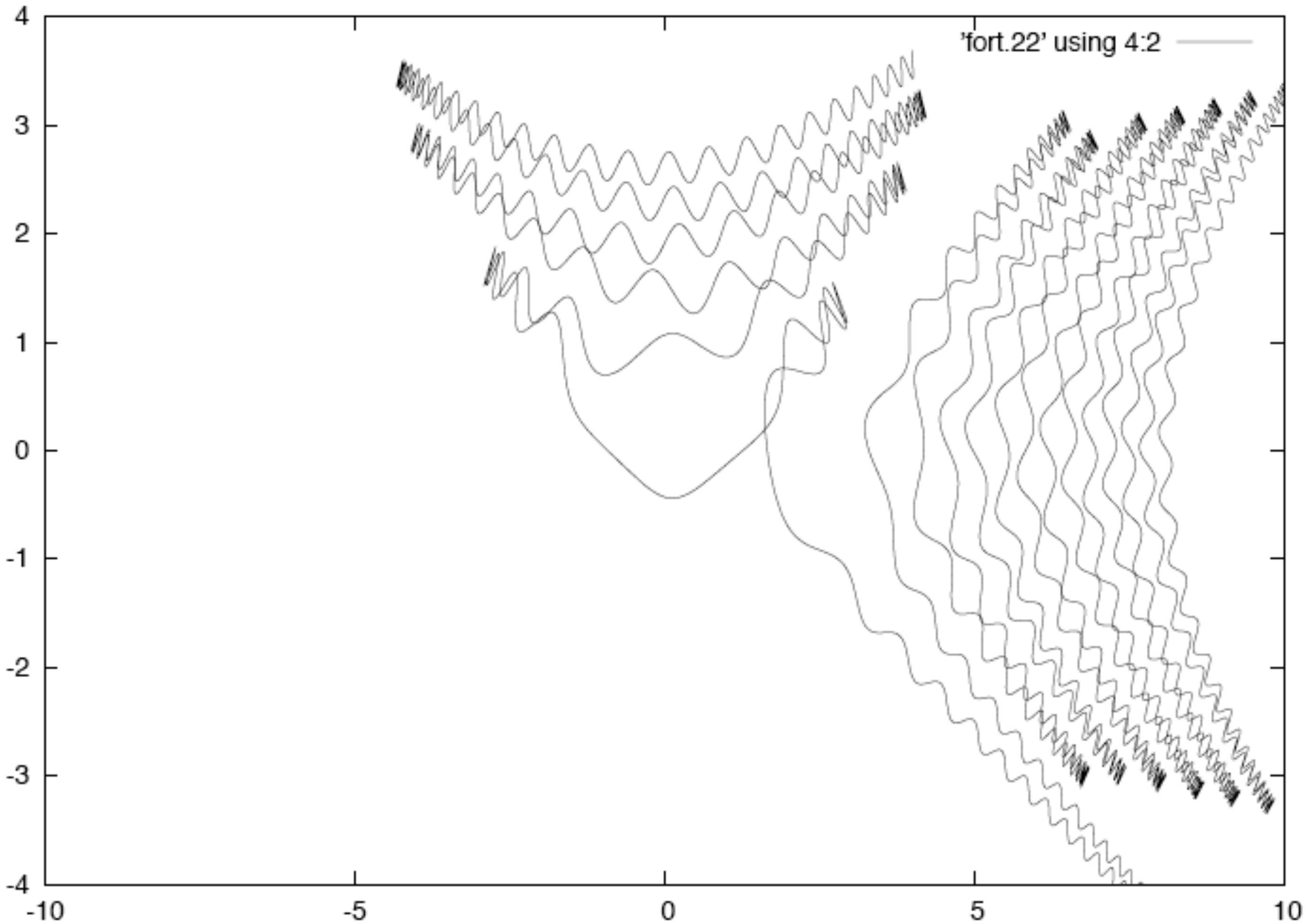
On the other hand, those with $v_z < 0$ have not passed the X point and have not been accelerated and for them $V_y = 0$. Thus, for $z > 0$

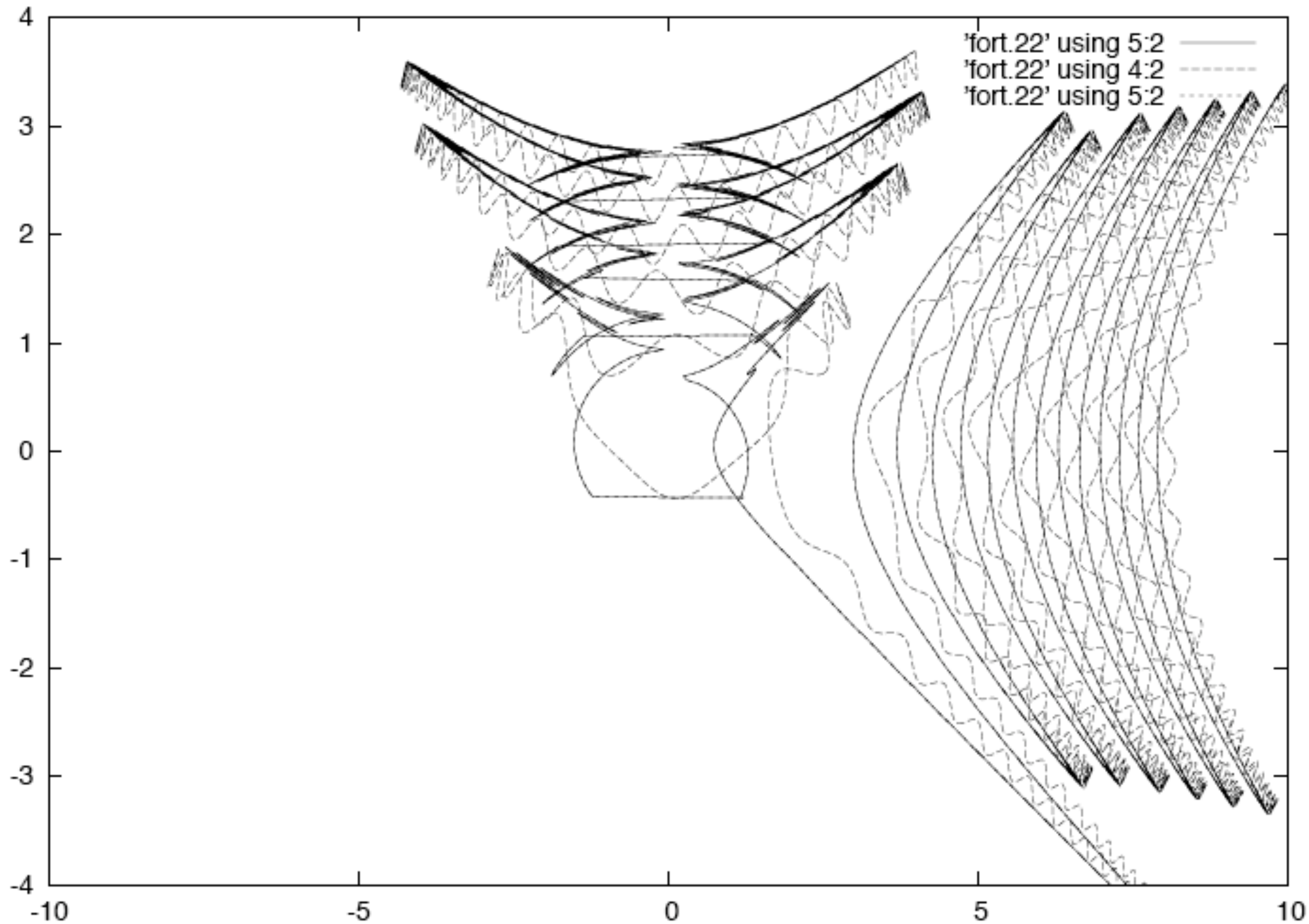
$$P_{yz} =< v_y v_z > \quad > 0$$

For $z < 0$ the opposite happens. Electrons with $v_z < 0$ x have $v_y > 0$ whilc electrons with $v_z > 0$ have zero v_y so

$$P_{yz} =< v_y v_z > \quad < 0$$

These estimates for the two $P'_{yz} s$ show that Ohm's law is satisfied.


'fort.22' using 4:2
4
3
2
1
0
-1
-2
-3
-4
-10
-5
0
5
10



'fort.22' using 5:2
'fort.22' using 4:2
'fort.22' using 5:2
4
3
2
1
0
-1
-2
-3
-4
-10
-5
0
5
10

RECONNECTION CURRENT LENGTHS

- In general asymmetric equilibrium, current layer lengths may be much shorter than the global length L leading to faster reconnection.

- This is borne out by the distribution of solar flares.

- This could be a way out of the reconnection problem

Frequency of solar flares