Turbulent Reconnection: Motivation, Objections and a Possible Solution

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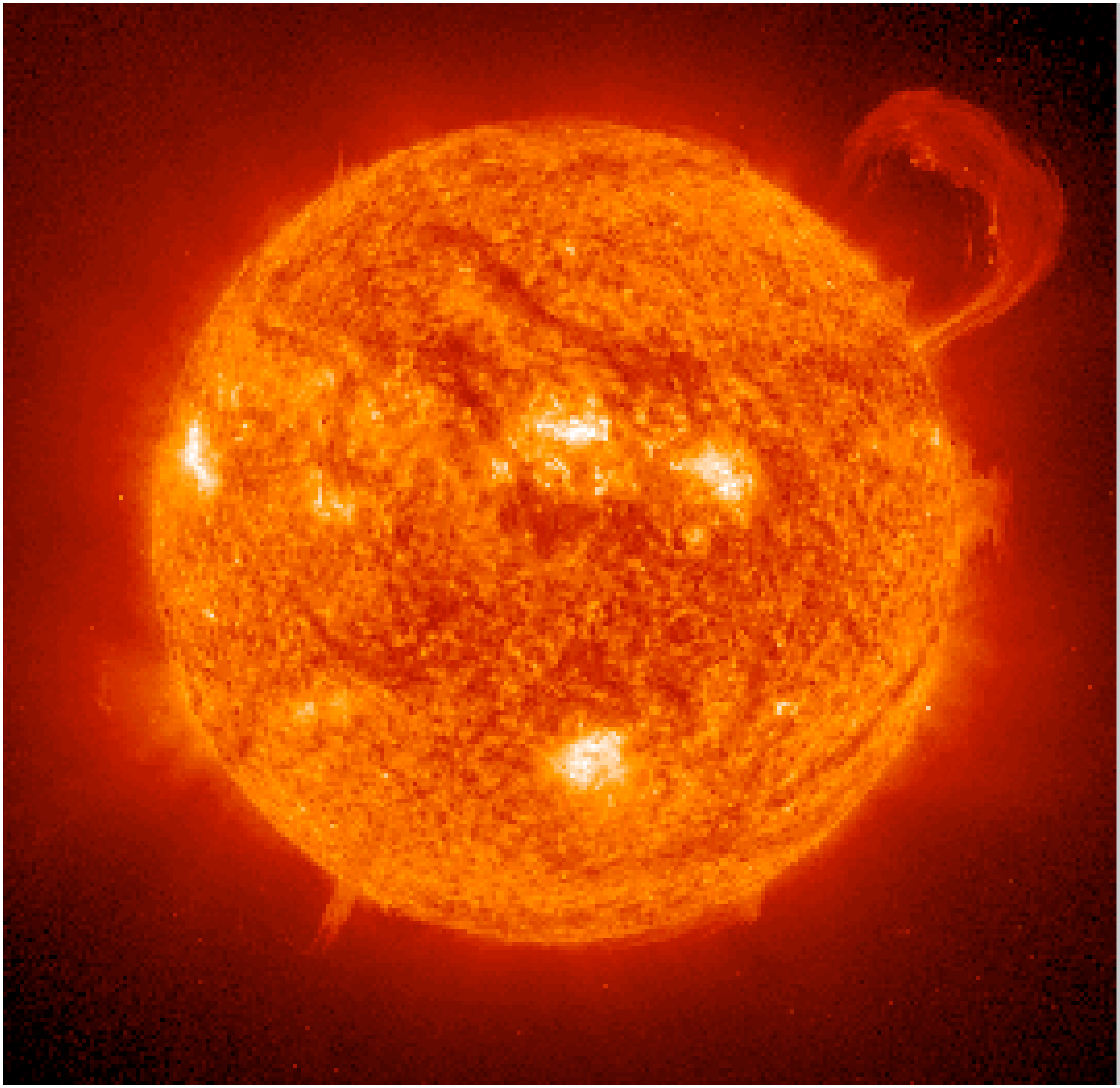
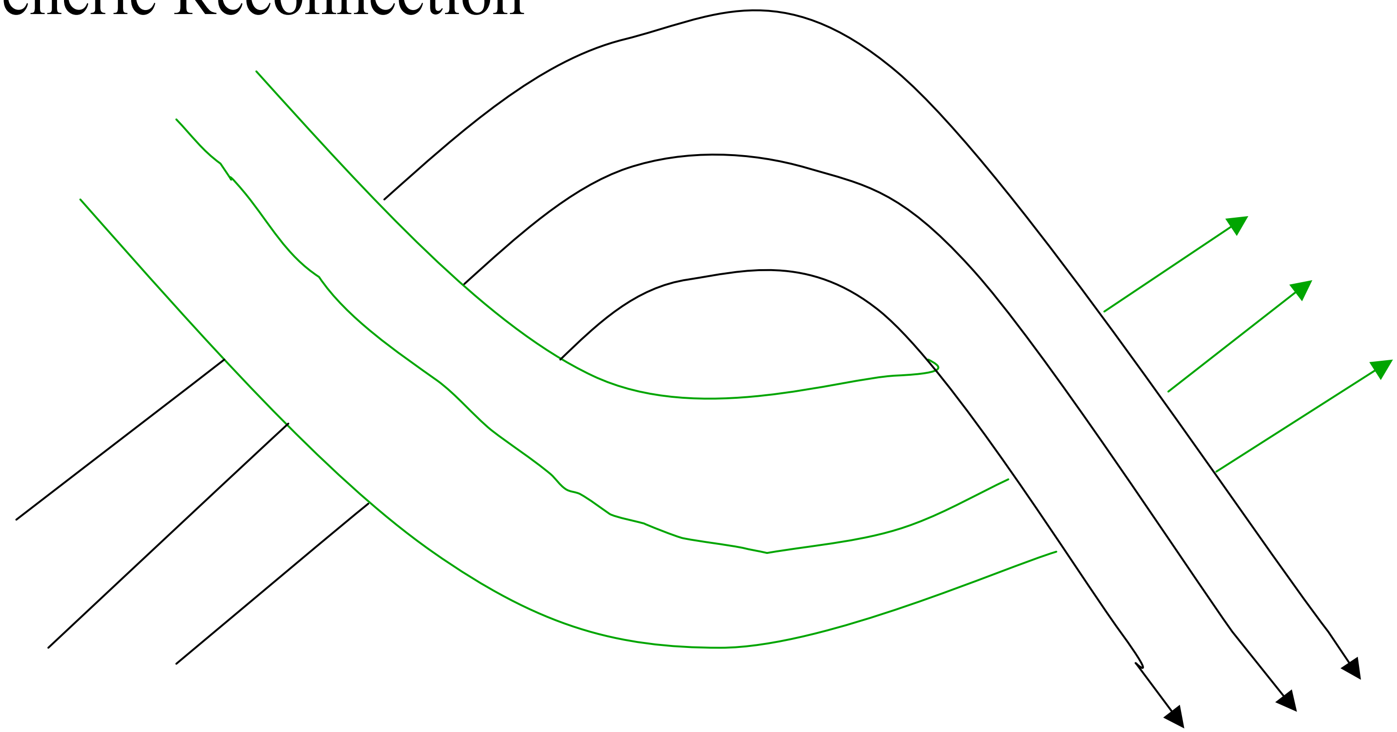


Some critical issues in reconnection:

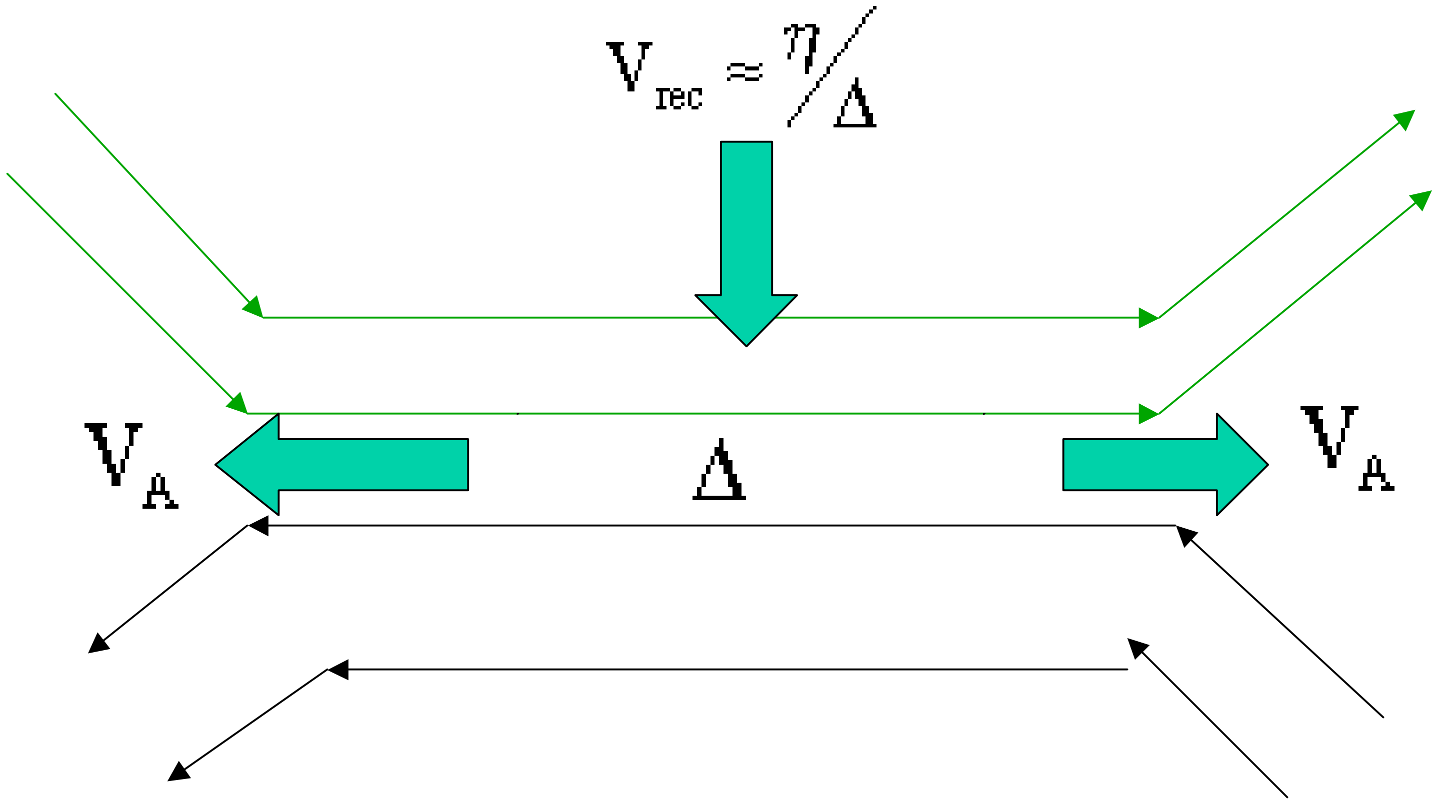
- Reconnection, when it occurs, is generally fast. It does not always occur.
- We ***see*** reconnection in the solar corona and chromosphere, where the plasma is diffuse and collision rates are (somewhat) low.
- Dynamo activity inside the Sun(and other stars) requires efficient reconnection in an environment where the collision rate is high and resistive MHD should be a very good description of the dynamics.
- Observations suggest that reconnection is not always efficient, but can wait for some unspecified (environmental?) trigger.

Generic Reconnection



Colliding sets of field lines will usually share some common component, and will tend to curve around each other, producing a concave contact surface. **If this is typical, then it imposes severe constraints on the physics of reconnection**.

The Sweet-Parker scheme assumes that the essential physics is retained if we represent this situation by two sets of anti-parallel field lines confined to a plane. We include the constraint that the two regions are prevented from mixing (due to their common component).



So over a contact distance L, mass and flux conservation requires that

$$V_{rec} \approx V_A \left(\frac{\eta}{V_A L} \right)^{1/2}$$

Which is many orders of magnitude too small to explain observations.

Turbulent Reconnection

- Dividing the magnetic field into large and small scale components we can derive an effective turbulent diffusivity

$$D_{turb} = \langle v^2 \rangle \tau_{corr} / 3$$

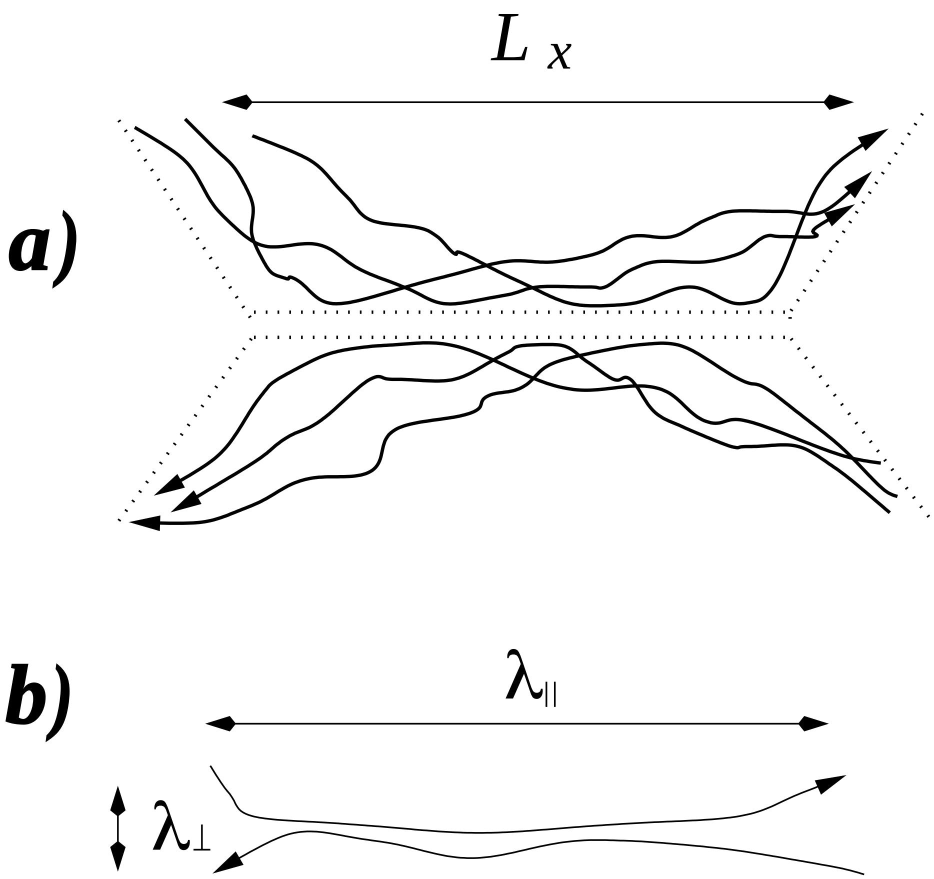
- This solves the problem of fast reconnection in resistive MHD. Astrophysical environments are often turbulent, and dynamos occur in turbulent, differentially rotating environments. We expect broad current sheets and flux transport $(D_{turb} \bullet \nabla)\vec{B}$

- Unfortunately, this is deceptive. Magnetic field line tension prevents small scale mixing of large scale fields with significantly different orientations (Parker 1992). Turbulent reconnection, in this sense, certainly does not exist (see also Kim and Diamond 2002).

More realistically there will be 3D magnetic field stochasticity

This can be caused by local turbulence, or external motions. For example, foot point motion for a magnetic arcade on the sun.

Consequently, field lines will be at least slightly tangled in any real plasma.



In this case, matter will diffuse out of a very much broader layer, whose width is set by the level of field line wandering.

What are the effects of stochasticity?

- Tangling field lines in this way does not change the location of the current sheet, or the role of resistivity within it, unless the field lines are very nearly parallel. For generic reconnection the current sheet will be rippled, but still well-defined.
- There is a topological effect. The ejection of plasma is no longer confined to the current sheet. Plasma can leave the current sheet in a short distance without crossing field lines. As the plasma moves the length of the current sheet, it will move away from by an amount which will depend on the nature of the field line stochasticity.
- Calculating this topological effect will require, among other things, a model of the nature of the field line stochasticity.   For a given current sheet width there will be a corresponding parallel correlation length after which the ejected plasma will have left the current sheet.

What limits the reconnection speed in a stochastic MHD model?

1. The local reconnection speed for a single eddy?

2. The speed with which the plasma can be ejected from the entire region of size L?

3. The speed with which the flux of the shared magnetic field component can be ejected from the whole contact region?

4. The ability of reconnection flux elements, that cross the current sheet, to move through one another and escape from the reconnection region?

The Local Reconnection Rate?

Each individual eddy, with a width comparable to the current sheet thickness, will reconnect at a speed:

$$V_{rec} \approx V_A \left(\frac{\lambda_\perp}{\lambda_\parallel} \right) \approx V_A \left(\frac{\eta}{V_A \lambda_\parallel} \right)^{1/2}$$

There will be an enhancement in the global speed due to the simultaneous reconnection of roughly $L/\lambda_\parallel$

independent reconnecting segments along any line parallel to the magnetic field adjoining the current sheet. In other words

$$V_{rec} \approx \mathrm{Min}\left[\frac{L\lambda_\perp}{\lambda_\parallel^2(\lambda_\perp)} \right] V_A, \forall \lambda_\perp \in \left[\Delta_{current}, L \right]$$

For strong, resistively damped turbulence this implies that the most important constraint comes from the largest scales. For viscously damped turbulence this has to be evaluated on a case by case basis (marginally important in the ISM.)

2. (and 3.) Large scale flows of plasma and magnetic flux?

Entrained plasma and magnetic flux will slow reconnection unless they can escape from the entire reconnection region, that is, move a distance ~ L.

We can express this by modifying the Sweet-Parker constraint so that the width of the current sheet is replaced by the width of the diffusion layer. This requires us to estimate the rms distance a field line will wander perpendicular to the current sheet over a distance comparable to the length of the current sheet. This in turn requires that we choose a particular model for the field lines stochasticity. Here we assume that it can be described by a local turbulent cascade and adopt the model of Goldreich and Sridhar (1995).

Field line wandering in the GS95 model of MHD turbulence

If energy is injected isotropically on a scale l with some typical velocity

$$V_T \leq V_A$$

Then we get an energy cascade in the perpendicular direction (waves with nearly constant parallel wavenumber).

This cascade breaks down into strong turbulence when

$$V_S \equiv V_{\lambda_\perp} \approx \frac{V_T^{\,2}}{V_A}$$

and

$$\lambda_\perp \approx l\frac{V_T^{\,2}}{V_A^{\,2}}$$

On smaller scales we have eddies with $k_\parallel \propto k_\perp^{\,2/3}$

The field line diffusion coefficient is scale dependent. The rms separation between two points will grow as:

$$\frac{d\Delta_y^{\,2}}{dx} \approx \Delta_y^{\,2} k_{\parallel}(k_{\perp}), \qquad \Delta_y k_{\perp} = 1$$

The rms spread in field line position over a parallel distance L in the GS model of strong turbulence is

$$\Delta \approx (\mathrm{L}l)^{1/2}\left(\frac{\mathrm{V_T}}{\mathrm{V_A}}\right)^2 \mathrm{Min}\left\{\frac{\mathrm{L}}{l},1\right\}$$

From which we conclude that the limit on the reconnection speed is:

$$\mathrm{V_{rec}} \approx \mathrm{V_S}\ \mathrm{Min}\left[\left(\frac{\mathrm{L}}{l}\right)^{1/2},\left(\frac{l}{\mathrm{L}}\right)^{1/2}\right]$$

If we assume that the flow is approximately incompressible, then there is no distinction between the constraint imposed by mass conservation, and the constraint imposed by flux conservation. Reconnection will proceed at velocities typical of the largest strongly turbulent eddies, times a geometrical factor.

What about the pile-up of reconnected flux elements?

In general there will be some complicated topology around the current sheet, and flux tubes will not freely slide by one another.

Can this be important?

The contact surface between different flux elements is like a microcosm of the global process. If the tangle of flux elements limits reconnection then we can invoke the notion of self-similar cascade to study the overall scaling of the global reconnection speed with magnetic Reynolds number and the local turbulent velocities.

We conclude from this that the only self-consistent scaling is that the reconnection speed is insensitive to the resistivity.

Notwithstanding this argument, it is important, albeit difficult, to test this process in a numerical simulation.

General Characteristics of Stochastic Reconnection:

1. The current sheet is narrow and the process is insensitive to what actually occurs in the current sheet (tearing modes, standing whistler modes in diffuse plasmas etc.). Of course, these processes can broaden the current sheet, although tearing modes cannot by themselves lead to fast reconnection.

2. In collisional systems the magnetic field energy is recycled into bulk motions on the same scale. In collisionless systems it will depend on the physics of the current sheet.

3. This process is extremely sensitive to the level of noise. Quiet laminar field lines will reconnect very slowly. (However, the process may be self-exciting leading to runaway reconnection as the motion of reconnected field lines generates local turbulence.)

4. Turbulent diffusion is suppose to move flux around at a rate

$$V_{diffuse} \approx V_{eddy} \frac{\lambda_{eddy}}{L_B}$$

This process will do exactly this, assuming that current sheets form efficiently.

Cautionary Notes

1. Stochastic reconnection gives a route by which reconnection can be fast in all environments, but the actual rate depends sensitively on the level of noise in the system. Simulations!
2. In modeling stochastic reconnection we have assumed that the diffusion of field lines near a current sheet is much the same as it is elsewhere. This may, or may not, be true.
3. Assuming stochastic reconnection does work as advertised, a process very like turbulent diffusion can take place, but if the large scale field is force free, then magnetic helicity conservation suppresses turbulent diffusion.
4. None of this actually tells you anything about the physics of the current sheet itself. That will depend on the nature of the environment (collisional or collisionless etc.).
5. When there is strong viscous damping the field line diffusion will be greatly suppressed on some small scale. If this scale is greater than the current sheet thickness then there is the possibility that the upper limit on the reconnection speed will be much small than the large scale eddy turbulent velocity. Neutral damping in the ISM can produce a suppression of reconnection speeds by an order of magnitude, or more, in dense environments.

Simulating Stochastic Reconnection

1. This is an intrinsically 3D process.
2. Stochastic depends on a continuous distribution of field line perturbations on all scales between the current sheet thickness and the size of the reconnection region. Any simulation must either reproduce this effect via a turbulent cascade, or by direct forcing on scales that would otherwise be viscously damped.
3. A characteristic signature of the process is an outflow region whose width is much greater than the current sheet thickness.
4. The speed of reconnection will depend on the amplitude and power spectrum of field line stochasticity. If the stochasticity is directly forced on small scales, then the reconnection speed may be sensitive to the nature of the forcing. This can be checked by an explicit calculation of the width of the outflow region as a function of scale..