Magnetic Reconnection in Astrophysical Systems

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ABSTRACT

The main subject of my talk is the question: in what kind of astrophysical systems magnetic reconnection is interesting and/or important? To address this question, I first put forward three general criteria for selecting the relevant astrophysical environments. Namely, reconnection should be: fast; energetically important; and observable. From this, I deduce that the gas density should be low, so that the plasma is: collisionless; force-free; and optically thin. Thus, for example, the requirement that reconnection is fast implies that Petschek’s reconnection mechanism must be operating, which is possible, apparently, only in the collisionless regime. Next, I argue that the force-free condition implies that the magnetic field be produced in, and anchored by, a nearby dense massive object, e.g., a star or a disk, strongly stratified by gravity. I then stress the importance of field-line opening (e.g., by differential rotation) as a means to form a reconnecting current sheet. Correspondingly, I suggest the Y-point helmet streamer as a generic prototypical magnetic configuration relevant to large-scale reconnection in astrophysics. Finally, I discuss several specific astrophysical systems where the above criteria are met: stellar coronae, magnetically-interacting star–disk systems, and magnetized coronae above turbulent accretion disks. In the Appendix I apply the ideas put forward in this talk to the solar coronal heating problem.

1. Introduction

1.1. Warnings and Disclaimers

This writing is loosely based on an invited talk the author gave at the Harry S. Petschek Memorial Symposium at the University of Maryland (College Park, Maryland, March 21–23, 2006).

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What I am going to talk about today is not going to be universally applicable to everything in astrophysics, but I just want to advance a certain perspective, a certain line of reasoning that, I think, should be considered mainstream. So mainstream in fact, that it may appear trivial. But I think it is worth to systematically re-emphasize some basic things from time to time.

Thus, I would like to start out by warning the audience that what I am going to say may be found either trivial or simply incorrect. And rightfully so. Nevertheless, here I go.

From the start, I would like to make one important reservation. My discussion applies only to individually-discernible, large-scale, energetic reconnection events (I shall call them flares), and not to a background of numerous little reconnections that may be encountered, for example, at the bottom of a turbulent MHD cascade. Such small-scale reconnections (e.g., nano-flares) may be even ultimately responsible for the bulk of energy dissipation in MHD turbulence. However, I will not discuss them in this talk.

My final disclaimer is about completeness of my reference list. My choice of toices and astrophysical examples is rather arbitrary and I don’t claim it to be comprehensive. Similarly, my reference list is not complete and does not pretend to be complete.

1.2. Talk Outline

The subject of this session and the subject of my talk is *Reconnection in Astrophysical Systems*. So, when I started preparing this talk, I first had to ask myself: well, indeed, *in what astrophysical systems does it make sense to talk about magnetic reconnection?* So, my talk is going to be devoted entirely to trying to answer this question.

In the first part of my talk I will put forward the following three general criteria that I think one should use when selecting reconnecting astrophysical systems. Reconnection should be:

1. fast
2. energetically important
3. observable

I will then go briefly through each of these conditions and discuss what each of them means for the physical environment in question. I will argue that these criteria can be translated into the following three physical requirements:
1. collisionless

2. force-free

3. optically-thin

In the second part of my talk I will apply these criteria to determine logically in what types of astrophysical systems reconnection plays a role and should be studied. I will first argue that, generically, the force-free requirement implies that one deals with a magnetosphere or a corona of a nearby colder and denser gravitating object (e.g., a star or an accretion disk), with gravity being responsible for gas stratification. The magnetic field originates in this dense plasma. Then I will discuss field-line opening (driven by sheared footpoint motion, a wind, or by relativistic effects) as a common and natural way to create a large-scale current sheet in the coronal plasma, which is necessary for reconnection. Correspondingly, I will advocate a \textit{Y-point Helmet Streamer} as one of the most important and generic magnetic structures relevant to astrophysical reconnection.

In the last part of my talk, I will discuss several specific astrophysical examples where reconnection is believed to be playing an important role.

Finally, in the Appendix I describe solar coronal heating as a self-regulated process keeping the coronal plasma marginally collisionless.

2. Fast Reconnection

First, what is \textit{fast reconnection}? Usually in the magnetic reconnection literature, a reconnection mechanism is called “fast” if the reconnection rate is independent (or scales only logarithmically with) the classical resistivity. In my talk, I will use a somewhat broader definition. I will call a reconnection process fast when the reconnection rate (defined as the ratio of reconnection velocity to the Alfvén speed) is independent of (or depends only relatively weakly on) the global size $L$ of the system. In other words, in this definition reconnection is fast when its dimensionless rate is determined (almost) entirely by the local physical parameters near the center of the reconnection layer. In this sense, for example, the classical Sweet–Parker reconnection is slow, because its rate scales as $L^{1/2}$, whereas the maximum Petschek reconnection rate is (almost) fast, since it scales only logarithmically with $L$. 
2.1. Main Mechanism of Fast Reconnection in Astrophysics

In Astrophysics, *reconnection* is a magic word (a “tooth fairy”, as it would be called in Peyton Hall),\(^1\) in the sense that it has become customary to invoke reconnection when it is needed to solve one’s problems and to assume that it always works when called upon.

It has to be noted that the main reconnection mechanism in Astrophysics is NOT Petschek reconnection, nor is it Hall reconnection, nor anomalous-resistivity reconnection. No, the most important reconnection mechanism in Astrophysics invokes waves, a certain type of waves, in fact. Called *handwaves*\(^2\) (See Fig. 1). The mechanism works like this: *Well, we know that fast reconnection happens in the Solar corona, and in the Earth magnetosphere. So it should also happen in OUR astrophysical system.*

Following this well-established and respected astrophysical tradition, I will also make extensive use of hand-waving arguments throughout my talk :)

Fig. 1.— Main Reconnection Mechanism in Astrophysics.

2.2. Fast Reconnection: Petschek’s Legacy

Those who are not satisfied with the mechanism described in the previous subsection, have to rely on actual thought. An excellent example of a brilliant thinker, who contributed a lot to our understanding of reconnection, is Harry Petschek. Why are Petschek’s ideas on reconnection important? People now associate fast reconnection with Petschek’s (1964)

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\(^1\)Another well-known astrophysical “tooth fairy” is *magnetic field* itself.

\(^2\)I acknowledge first hearing a satirical mentioning of handwaves as a playful “real” physical mechanism from Henk Spruit (2005, private communication).
reconnection mechanism. A great non-trivial idea due to Petschek is that the main bottleneck stifling the reconnection process in the classical Sweet–Parker (Sweet 1958; Parker 1957) model can be circumvented if one can set up a special magnetic field and flow configuration — the Petschek configuration. The bottleneck arises because of the necessity to have a reconnection layer that is simultaneously thin enough for the resistivity to be important and thick enough for the plasma to be able to flow out of the layer. Petschek’s key idea was that the thin current layer and the thick outflow channel do not have to be the same if the reconnection region is not a simple rectangular box, as it was in the Sweet–Parker theory, but has a somewhat more complicated structure, with four standing slow shocks attached to a central diffusion region. As a result, there is an additional geometric factor that can lead to faster reconnection.

This geometrical enhancement is especially important in astrophysics, for the following reason. What distinguishes astrophysical and space systems from Earth-bound laboratory experiments is a huge contrast in length-scales. Astronomical systems are astronomically large: the system size $L$ is usually much greater than the microscopic physical scales, e.g., the ion gyro-radius $\rho_i$, the ion collisionless skin-depth $d_i$, and the Sweet–Parker reconnection layer thickness $\delta_{\text{SP}}$. Hence, the reconnection rate problem is especially severe in astrophysical systems. Hence, we need a clever idea. For example, the idea of geometric enhancement due to Harry Petschek.

What this means is that, unless one has a special mechanism like this, no microphysics (e.g., the Hall effect or anomalous resistivity) can give reconnection rates that are rapid enough to be of interest to observations. For example, when the reconnection layer’s thickness becomes comparable with the collisionless ion skin depth $d_i$, the layer enters the Hall regime. Then, in a simple Sweet–Parker-like analysis, the mass conservation condition would result in a reconnection velocity that is by a factor of $d_i/L$ smaller than the Alfvén speed $V_A$. Since $d_i$ is usually much smaller than $L$, this rate would be much too slow to be of practical interest.

### 2.3. Fast Reconnection Means Collisionless Reconnection

Thus, we see that Petschek’s mechanism, or a variation thereof, is absolutely indispensable for astrophysical reconnection. Unfortunately, however, several numerical and analytical studies (e.g., Biskamp 1986; Scholer 1989; Uzdensky & Kulsrud 2000; Erkaev et al. 2001; 3)By the way, I will assume the audience to be familiar with both the Sweet-Parker and Petschek models of reconnection.
Kulsrud 2001; Malyshkin et al. 2005) have shown that in resistive MHD with uniform resistivity (and, by inference, with resistivity that is a smooth function of plasma parameters, e.g., Spitzer) Petschek’s mechanism fails and Sweet–Parker scaling applies instead. The same conclusion was achieved in laboratory studies by the Magnetic Reconnection Experiment (MRX), lead by Masaaki Yamada at Princeton Plasma Physics Laboratory, in the high-collisionality regime (Ji et al. 1998; Trintchouk et al. 2003).

What all this means is that, whenever classical resistive MHD applies, one does not get fast reconnection. This implies that fast reconnection can happen only when the plasma is relatively collisionless so that resistive MHD doesn’t apply. This condition of fast reconnection can be formulated roughly as (e.g., Yamada et al. 2006)

$$\delta_{\text{SP}} \ll d_i \equiv \frac{c}{\omega_{pi}}.$$ (1)

What this condition means is the following. As a reconnection layer is forming, its thickness $\delta$ is getting smaller and smaller. If condition (1) is not satisfied, then this thinning saturates at $\delta = \delta_{\text{SP}}$, and reconnection then proceeds in the slow Sweet–Parker regime. However, if condition (1) is satisfied, then various two-fluid and/or kinetic effects kick in as soon as $\delta$ drops down to about $d_i$ or so, well before the collisional resistive effects become important. Then, the reconnection process necessarily involves collisionless, non-classical-resistive-MHD physics.

Thus, in the collisional regime, when classical resistive MHD applies, fast Petschek reconnection does not appear to be possible. Does going to the collisionless regime help? There is a growing consensus that the answer to this question is YES. In Space/Solar physics, of course, there has long been a very serious evidence for fast collisionless reconnection; it has been further significantly strengthened by recent laboratory measurements in the MRX (Ji et al. 1998; Yamada et al. 2006). These measurements, however, have not been able to elucidate the special role of the Petschek mechanism in accelerating reconnection. On the other hand, over the past decade or so, several theoretical and numerical studies have indicated that fast reconnection enhanced by the Petschek mechanism (or a variation thereof) does indeed take place in the collisionless regime. It appears that there may be two regimes of collisionless reconnection. Physically, these two possibilities are very different from each other; nevertheless, they both appear to lead to the establishment of a Petschek-like configuration, which enhances the reconnection rate. The two regimes in question are:

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4If the guide component of the magnetic field is not zero, this condition may be somewhat different, although similar in concept. For simplicity, however, in this paper we shall consider the fast reconnection condition only as given by equation (1).
• **Hall-MHD reconnection**, involving two-fluid effects in a laminar flow configuration (e.g., Shay et al. 1998; Birn et al. 2001; Bhattacharjee et al. 2001). [See, however, recent particle simulations by Daughton et al. (2006) and by Fujimoto (2006) that cast doubt on Hall reconnection as a possible fast reconnection mechanism.]

• Spatially-localized anomalous resistivity due to micro-turbulence; this seems to lead to a Petschek configuration with the inner diffusion region having a width of the order of the resistivity localization scale (e.g., Ugai & Tsuda 1977; Sato & Hayashi 1979; Scholer 1989; Biskamp & Schwarz 2001; Erkaev et al. 2001; Kulsrud 2001; Malyshkin et al. 2005).

At present, it is still not clear which one of these two mechanisms works in a given physical situation (if at all). Also not known is whether these two mechanisms can coexist and perhaps even enhance each other. Recent experimental evidence from the MRX experiment suggests that both regimes do exist in reality and that they may operate simultaneously in a given system (Yamada 2006, private communication).

In any case, it seems that one does get a Petschek-enhanced fast reconnection process if the plasma is collisionless [in the sense of equation (3)]. To sum up, in order for astrophysical reconnection to be fast, it needs Petschek’s mechanism to operate and that in turn requires the reconnection layer to be collisionless. Thus, for the purposes of this talk, I will put an equal sign between collisionless reconnection and fast Petschek’s reconnection.

In fact, whenever we observe violent and rapid energetic phenomena that we interpret as reconnection, it is always in relatively tenuous plasmas. Please correct me if this is not so. I would be very interested in learning about counter-examples. Is there any evidence for fast large-scale reconnection events in collisional astrophysical environments?

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### 2.4. Fast Reconnection: Range of Densities in Astrophysics

Note that the statement of collisionality is scale-dependent. This is because $d_i$ is a microscopic scale, independent of $L$, whereas $\delta_{SP} \sim \sqrt{L}$. In astrophysics $L \gg d_i$ is very large, and so one might expect $d_i \ll \delta_{SP}$ for large enough systems. However, in practice, this doesn’t always have to be so. Indeed, notice that $\delta_{SP} \sim 1/\sqrt{S} \sim V_A^{-1/2} \sim \rho^{-1/4}$, whereas $d_i \sim \rho^{-1/2}$. Thus,

$$\frac{\delta_{SP}}{d_i} \sim \rho^{1/4},$$

so it depends on density. This dependence is weak but, in astrophysics, one has to deal not only with a huge dynamic range in $L$ but also with an enormous dynamic range in $\rho$. For
example,

- $\rho \sim 10^{14} \text{g/cm}^3$ inside a neutron star;
- $\rho \sim 1 \text{g/cm}^3$ average solar density;
- $n_e \sim 10^{10} \text{cm}^{-3}$ in the solar corona;
- $n_e \sim 1 \text{cm}^{-3}$ in the ISM.

— 38 orders of magnitude variation in density! Thus, one can readily find many astrophysical systems that are not only large but also rarefied and collisionless.

### 2.5. The Fast Reconnection Condition

How can one quantify condition (1) of collisionless reconnection? It is pretty straightforward to show (Yamada et al. 2006) that

$$\frac{\delta_{\text{SP}}}{d_i} \sim \left( \frac{L}{\lambda_{e,\text{mfp}}} \right)^{1/2} \left( \frac{\beta_e}{m_i} \right)^{1/4},$$

where I have neglected numerical factors of order 1. Here, $\beta_e$ is the ratio of the plasma pressure inside the layer to the pressure of the reconnecting magnetic field component ($B_0^2/8\pi$) outside the layer; $\lambda_{e,\text{mfp}}$ is the classical electron mean free path due to Coulomb collisions. Thus, using equation (1), we see that reconnection is collisionless when

$$\lambda_{e,\text{mfp}} > L\sqrt{\beta m_e/m_i} \simeq L\beta^{1/2}/40.$$  \hspace{1cm} (3)

[The condition suggested by Yamada et al. (2006) differs from equation (3) by a factor of 2. Since the discussion here is very qualitative, I regard this difference as unessential. We are not going to quibble about factors of 2, are we?]

We can go a little bit further. The mean free path $\lambda_{e,\text{mfp}}$ can be written as

$$\lambda_{e,\text{mfp}} \simeq 7 \cdot 10^7 \text{cm} \, n_e^{-1} T_e^2,$$  \hspace{1cm} (4)

where we have taken the Coulomb logarithm equal to 20 and where $n_{10}$ and $T_7$ are the electron density $n_e$ and temperature $T_e$ given in units of $10^{10} \text{cm}^{-3}$ and $10^7 \text{K}$, respectively. These parameters are to be taken at the center of the reconnection layer. Combining equations (3) and (4), the criterion for fast collisionless reconnection can now be formulated as a condition on the layer’s length $L$ in terms of the central values of $n_e$ and $T_e$:

$$L < L_c \equiv 40 \beta^{-1/2} \lambda_{e,\text{mfp}} \simeq 3 \cdot 10^9 \text{cm} \, \beta^{-1/2} \, n_{10}^{-1} T_7^2.$$  \hspace{1cm} (5)
Now, what about the plasma-\(\beta\) parameter? For definiteness, let us focus on the extreme case of a reconnecting configuration with no guide field. Then the condition of pressure balance across the layer dictates that

\[
\beta \equiv \frac{8\pi n_e k_B (T_e + T_i)}{B_0^2} = 1, \tag{6}
\]

where we have neglected the outside thermal pressure.

Furthermore, assuming for simplicity that \(T_e = T_i\), we can then express the central electron temperature in terms of \(B_0\) and \(n_e\) as

\[
T_e = \frac{B_0^2/8\pi}{2k_B n_e} \simeq 1.4 \times 10^7 \text{ K} B_{1.5}^2 n_{10}^{-1}, \tag{7}
\]

where \(B_{1.5}\) is the outside magnetic field \(B_0\) expressed in units of 30 G. Upon substituting this estimate into equation (4), we get

\[
\lambda_{e,\text{mfp}} \simeq 1.5 \times 10^8 \text{ cm} n_{10}^{-3} B_{1.5}^4, \tag{8}
\]

and correspondingly,

\[
L_c(n, B_0) \simeq 6 \times 10^9 \text{ cm} n_{10}^{-3} B_{1.5}^4. \tag{9}
\]

We see that the condition \(L < L_c\) is easily satisfied for solar flares, for example. Also, this result has interesting implications for the coronal heating problem, as I will discuss in the Appendix.

A reservation: this was just a simple example, presented in order to illustrate the basic idea. In general, the physics is more complicated and less certain. In particular, in the above example I have assumed the plasma pressure at the center of the current layer to be equal to the outside magnetic pressure outside (the background gas pressure in the corona outside the layer is negligible since the corona is almost force-free), i.e., that \(\beta \simeq 1\). However, if there is a guide magnetic field, then the cross-layer pressure balance is modified; in particular, \(\beta\) can be much less than 1, determined by thermal transport processes along the layer, e.g., the electron thermal conduction (radiative losses are small on the timescale of transit through the layer). Just as important, since collisions are rare, and since the collisional electron-ion energy-equilibration rate is suppressed due to the large mass ratio, the electron and ion temperatures in the layer need not be equal. For example, ions may be much hotter than the electrons and may provide the bulk of the pressure support against the outside magnetic field. The electron temperature in this case would be far below the equipartition value (about \(10^7\) K). Correspondingly, the electron mean-free path would be much lower than that given by equation (8).
2.6. Fast Reconnection: Caveats and Alternatives

With all this said, there is still room for caveats and alternative ideas. I will mention just some of them here:

- Recent numerical work by Cassak et al. (2005) shows an intriguing evidence for **bistable reconnection**: once fast Hall reconnection has begun, it is hard to switch it back to the slow Sweet–Parker mode, even if the resistivity is raised to the level that violates (1).

- **Turbulent Reconnection**: Lazarian & Vishniac (1999) suggested that fast reconnection may happen in pure resistive MHD, although only in 3D, in the presence of externally imposed MHD turbulence (see also Bhattacharjee & Hameiri 1986; Strauss 1988; Kim & Diamond 2001).

  We don’t know really whether this mechanism works, but certainly it is an interesting idea. And a testable one! Numerical tests should now be possible. It is worth pursuing and may be a good topic for a PhD thesis project!

- **Bursty, impulsive reconnection**: e.g., Bhattacharjee (2004)

- **3D reconnection**: e.g., Longcope (1996)

- **Additional Physics**: e.g., reconnection in partially-ionized plasmas in the context of molecular clouds (e.g., Zweibel 1989).

3. Energetically-Important Reconnection

3.1. Energetically-Important Reconnection: Go where the Energy is!

In addition to the question “where can it occur?”, one also can ask the question: *where does fast reconnection matter?*

Often in Astrophysics, when judging the relative importance of various components of the system, one tends to look at *where the energy is*. From this point of view, one can say that reconnection matters when it results in a *significant* transfer of magnetic energy to the gas, that is, when the transferred energy is larger than the internal in the gas before reconnection. Since the energy source in reconnection is the magnetic field, this means that we expect for a reconnection event to have a significant effect on the system only when the plasma is initially magnetically-dominated, $\beta \ll 1$, i.e., the when field is force-free.
This condition, of course, goes in the same direction as the previous condition that the system be collisionless and therefore of low density. But actually the two conditions are not equivalent, as the force-free condition involves the magnitude of the magnetic field, for example.

3.2. Energetically-Important Reconnection: Externally-Generated Force-Free Field and Gravitational Stratification.

Generically, where can we expect to encounter a situation described above.

The requirement that the plasma is magnetically-dominated means that the magnetic field has to be external to the medium in which reconnection is taking place. That is, it needs to be produced in, and anchored by, a denser (\( \beta > 1 \)) plasma that lies somewhere else, but somewhere nearby. Thus, reconnection is important only in situations where one has a low-density plasma next to a high-density plasma. This requires a strong density stratification, with the density decreasing with distance faster than the magnetic field. This can be most easily achieved in the presence of a gravitational field. Thus, we logically arrive to the conclusion that we are dealing with magnetospheres or coronae of massive objects with dense gas. Two main examples of such systems are: (i) stars and (ii) accretion disks.

The basic physical picture is that magnetic field is produced in these dense plasmas by a dynamo action and then escapes buoyantly into the less dense, largely force-free, corona. At some point in the corona, the emerging magnetic loops reach the regions where the density is so low that the plasma becomes collisionless. When this happens, fast energetic reconnection events (i.e., flares) become possible.

4. Observable Reconnection

4.1. Observable Reconnection: Optically-Thin Plasma

The third and final of the three conditions outlined in § 1.2 is that we want to be able to observe reconnection. Unfortunately, in Astrophysics we do not have the benefit of in-situ measurements (as opposed to Space Physics, where reconnection events are now routinely being studied with dedicated spacecraft flying through the Earth’s magnetosphere). Instead, we have to rely on whatever radiation that makes its way to us without being greatly absorbed or scattered. What this means is that we can observe only those reconnection events that happen in an optically-thin (or at least not very optically-thick) environment. This statement
is, of course, wavelength-dependent. If we are to observe the reconnection layer itself, the most relevant part of the spectrum is that corresponding to the expected temperature at the center of the reconnection layer. This usually falls in the X-ray band; for example, it can be as high as \(10^7 - 10^8\) K in the solar corona.

Of course, we would like to be able to directly observe the reconnection layer itself. Unfortunately, again, this is frequently not possible. For example, even in our best-studied example of astrophysical reconnection — the solar flare — direct observations of the reconnection layer itself have not been achieved. And this is so despite the fact that we do have X-ray satellites watching the Sun all the time! The reason for this is that the reconnection layer is so thin that not much radiation comes from it to us directly. An alternative then is to try to see the effect of reconnection on the nearby denser medium, which has a direct magnetic connection to the reconnection region. Two-ribbon solar flares present a classic example of this: the observed white-light radiation comes from the photospheric footpoints of newly-reconnected field lines. Hard X-rays come from the same footpoints and also from the fast shock formed at the spot where the reconnection jet slams into the closed post-flare loops; soft X-rays come from these post-reconnection loops.

### 4.2. Observable Reconnection: Particle Acceleration

The above example illustrates the fact that sometimes (e.g., in solar flares) a significant fraction of the dissipated magnetic energy is carried away not by the photons, which we could have observed on Earth, but by energetic particles. For example, it is now commonly believed that as much as a few tens of percent of the energy released in solar flares goes to fast, nonthermal electrons and ions (e.g., Emslie et al. 2004; Kane et al. 2005). Most of the rest of the energy is released as thermal and bulk kinetic energy of the plasma, with radiative losses playing only a minor part in the overall energetics of the reconnection layer. The mechanisms of particle acceleration by a reconnecting layer are still not well understood. Nevertheless, this observation implies that reconnection processes might also play a role in astrophysical particle acceleration, e.g., in cosmic-ray production. Physically, what is important here is not just the large amount of magnetically-stored energy that is rapidly released via reconnection, but also the fact that this energy is released in a low-density, collisionless environment. As a result, the nonthermal-particle acceleration via whatever mechanism can progress without prohibitive losses due to collisions. This makes the reconnection phenomenon especially important for High-Energy Astrophysics.

Before I move on to the second part of my talk, I would like to reiterate, once again, that I am here talking about large-scale reconnection events only. This is not to say that
reconnection does not occur inside the dense plasma itself (e.g., the solar convection zone). But note that:
1) The plasma below the solar photosphere is dense and hence collisional; therefore, no fast large-scale and individually-distinguishable reconnection events, such as flares, can occur there. Reconnection in the convection zone requires a development of very small scales at the bottom of the turbulent cascade, leading to a continuous and diffuse magnetic dissipation. (Another reason for a relatively slow rate of reconnection in a high-density plasma: reconnection rate usually is limited by the Alfvén speed, and the Alfvén speed is much smaller in the dense medium.)
2) The magnetic field does not dominate the dynamics there, it is below equipartition with turbulent motions, so, energetically, reconnection is not very important.
3) It is below the photosphere, and hence unobservable directly.

5. Reconnection in Astrophysics: current-sheet formation by field-line opening and the Helmet Streamer configuration

To get reconnection, one first needs to get him/herself a current sheet. So, it would be useful to try to understand how a current sheet can develop in a force-free plasma that is exterior to a denser plasma anchoring the magnetic field lines.

A natural, generic way to get a large-scale current sheet (capable of producing a large flare) is the field-line opening. Indeed, if our magnetic field is produced by a dynamo inside the dense conducting medium, the field lines that emerge into the low-density corona are are closed, essentially by design. What this means is that the field lines are anchored to the dense conductor at both ends, resulting in a dipole-like field topology. To get a current sheet, one needs the field to become open, that is to go from a dipole to split monopole
How does one open field lines? There are several ways to do it, each one having its own particular application niche:

- **non-relativistic force-free case:** opening by the sheared motion of the field-line footpoints on the surface of the dense plasma. Examples: turbulent random walk (solar photosphere); differential rotation (accretion disk).

- **relativistic force-free case:** opening due to field-line rotation (non-differential!) beyond the light cylinder. Examples: pulsar magnetosphere (outer light cylinder); the magnetosphere of a disk around a Kerr black hole (inner light cylinder). In the first case, the field lines that are tied to the rotating pulsar and extend beyond the light cylinder open out to infinity. This important fact has been known since the classical paper by Goldreich & Julian (1969); however, the actual opening process itself was demonstrated in time-dependent numerical simulations only recently (see Komissarov 2006; McKinney 2006; Spitkovsky 2006). In the second case, that of a black hole, the field lines that are tied to the disk open into the black hole (similar to Koide 2003; Beskin 2004; Komissarov 2005).

- **non-relativistic MHD case:** field-line opening by a wind. Examples: solar wind; accretion disk wind.

![Fig. 3.— The Helmet Streamer. The configuration consists of two regions of oppositely-directed open field lines and a region of closed field lines. The green line represents the magnetic separatrix current sheet that separates these three regions.](image-url)
In any case, an important and very generic magnetic structure that one gets as a result of a (partial) field-line opening is the *Helmet Streamer* (Fig.
3), with magnetic separatrices joining at a Y-point (or a cusp-point; see Uzdensky & Kulsrud 1997).

6. Examples of Astrophysical Reconnection

Examples of astrophysical systems where reconnection is important:

- **Stellar corona**: a classic example, very important (solar flares); it has been discussed at length, so I am not going to talk about it. AT ALL!
  
  Except, I will mention one special, rather exotic case:

- **Relativistic reconnection in the magnetar magnetosphere** (see Fig. 4), as a model for *SGR flares* (Thompson et al. 2003; Lyutikov 2003; 2006).

![Fig. 4.— Current-sheet formation in the magnetar magnetosphere (after Lyutikov 2006).](image)

This case represents a manifestation of so-called *relativistic magnetic reconnection*, in which the Alfvén velocity is ultra-relativistic and hence special-relativistic effects, such as the Lorentz contraction, play a significant role. It has to be noted that relativistic reconnection is a relatively new, emerging area of research: only a handful of papers devoted to relativistic reconnection have been published to date (e.g., Blackman & Field 1994; Lyutikov & Uzdensky 2003; Lyubarsky 2005; Watanabe & Yokoyama 2006). Despite the fact that the importance of reconnection processes in relativistic plasmas is being recognized more and more by the high-energy astrophysics community, this field is still not over-crowded. Therefore, in my view, relativistic reconnection represents an attractive and promising direction of research. Note that the relevant physics can be very rich and perhaps somewhat alien for a garden-variety plasma or space/solar...
physicist. For example, in addition to special-relativistic effects, one will have to take into account the interaction of plasma with electro-magnetic radiation, e.g., pair production/annihilation and very non-trivial radiation transport inside the reconnection layer. Nevertheless, I am hopeful that we will witness rapid theoretical progress in this exciting and important area in the next few years.

My main two examples will be magnetospheres and coronae of accretion disks.

- **Accretion disk magnetosphere**: star-disk interaction: current-sheet formation due to differential star–disk rotation (§ 6.1).

- **Accretion disk corona**: reconnection controls magnetic scale-height, and hence the vertical extent of the corona (§ 6.2).

Here I distinguish between a large-scale (comparable to the global system size) magnetosphere and a corona, formed by small-scale (compared with the global system size, i.e., the disk radius) magnetic structures.

### 6.1. Reconnection in the Accretion-Disk Magnetosphere: Star–disk Magnetic Interaction

Let us consider the common star–disk magnetosphere. We are interested in the case in which the star has a large-scale, dipole-like magnetic field, and we are interested in the magnetic interaction between this star and an accretion disk around it (see Uzdensky 2004 for a recent review). This fundamental-physics problem is of great importance both for accreting Young Stellar Objects (YSO), e.g., T Tauri stars, and for accreting compact stars in binary systems, e.g., neutron stars (NSs) in X-ray binaries.

During the past 30 years there have been a number of theoretical studies of such magnetically linked star–disk systems. One of the most important early works is that by Ghosh & Lamb (1978) in the context of accreting neutron stars. They proposed a steady-state model in which the stellar dipole-like magnetic field penetrates into the disk over a wide range of radii. This star–disk magnetic coupling results in the exchange of angular momentum between the star and disk, and thus regulates the long-term evolution of the star’s rotation rate. It also has a significant effect on the accretion flow; in particular, close enough to the star the magnetic field may become so strong that it disrupts the disk completely and channels the accreting matter directly onto the polar caps (as is believed to be the case for
X-ray pulsars). Subsequently, Königl (1991) has extended this model to YSOs, and this concept of magnetospheric accretion has become a standard paradigm in this field as well.

However, it is easy to see that a steady-state model like this requires the disk to have an unrealistically-large resistivity. If the resistivity is small (which is more likely), then the footpoints of the magnetic field lines can be regarded as being frozen into the disk on the time-scale of interest. The differential star-disk rotation then leads to the twisting of the field lines and hence to the generation of the toroidal field in the magnetosphere above the disk. The pressure of this toroidal field pushes out the poloidal field lines, they expand dramatically and effectively open up. This line of reasoning has lead Lovelace et al. (1995) to propose a different steady-state configuration, shown in Figure 5. In this configuration, the magnetic link between the star and the disk has been almost completely severed, with the exception of a small inner disk region forced to be in rigid corotation with the star by the strong magnetic field.

![Current-sheet formation by field-line opening due to the differential rotation in the magnetically-linked star-disk system (after Lovelace et al. 1995).](image)

Fig. 5.— Current-sheet formation by field-line opening due to the differential rotation in the magnetically-linked star-disk system (after Lovelace et al. 1995).

The process of opening of an axisymmetric magnetosphere subject to differential foot-point rotation has been studied extensively in Solar Physics (e.g., Barnes & Strurrock 1972; Aly 1984; Mikic & Linker 1994). There have been a number of studies of this process in the context of accretion disks (van Ballegooijen 1994; Lynden-Bell & Boily 1994; Lovelace et al. 1995; Hayashi et al. 1996; Miller & Stone 1997; Goodson et al. 1997, 1999; Romanova et al. 1998; Uzdensky et al. 2002a,b; Uzdensky 2002a,b; Matt et al. 2002; Fendt 2003). From the
point of view of this talk, the most important feature of this opening is the formation of a conical current sheet along the separatrix between the oppositely-directed stellar and the disk open field lines (see Uzdensky 2002a for more details). This current sheet can be clearly seen in Figure 5. An important question that arises is whether this configuration will persist indefinitely, as in the Lovelace et al. (1995) steady-state model, or will be subject to periodic reconnection events, as was seen in several resistive MHD simulations (e.g., Hayashi et al. 1996; Romanova et al. 1998; Goodson et al. 1999). Another, related question is what would be the amplitude and the frequency of the plasmoids that are formed by reconnection and ejected along the current sheet (see, e.g., Fendt 2003). These questions have important implications for the formation and structure of YSO jets, for example. Notice that reconnection processes are at the very heart of the difference between the Lovelace et al. (1995) and Goodson et al. (1999) models. Therefore, it is unlikely that even the most sophisticated resistive MHD simulations will be able to settle this issue satisfactorily until basic physics of reconnection is sufficiently well understood.

6.2. Reconnection in Accretion-Disk Coronae

Galeev et al. (1979) have proposed a compelling physical picture of how a magnetic corona is formed above an accretion disk. The scenario is based on the analogy with the solar corona. In both cases, there is a dense turbulent medium (the solar convection zone or a turbulent accretion disk) whose behavior obeys MHD equations. Magnetic fields are generated by the MHD dynamo and amplified to a rough equipartition with the kinetic energy density of the turbulence. The medium is in an external gravitational field and therefore the plasma density drops off rapidly with height. The Parker instability develops and leads to the buoyant rise of magnetic flux tubes and their emergence into the lower-density corona above the dense medium. Because of the strong gravitational stratification of the cold plasma, the energy density in the corona is dominated by the magnetic field, which is hence force-free almost everywhere in the corona. Finally, a portion of the turbulent energy in the disk (or in the convection zone) is not dissipated locally, but instead is transported vertically by the Poynting flux associated with the rising flux tubes and with the work done on the coronal magnetic loops by the footpoint motions. This energy builds up as free magnetic energy and is episodically dissipated through reconnection events (e.g., flares). Alternatively, the energy may be transported vertically by waves that dissipate in the corona via mode conversion. In any case, this dissipated energy heats the rarefied coronal gas and may also lead to non-thermal particle acceleration. The basic elements of this picture have been confirmed in 3D MHD simulations by Miller & Stone (2000) and by Machida et al. (2000).
In order to understand how the coronal magnetic field is structured, one needs a statistical description. A promising way to achieve this is to represent the coronal field by an ensemble of closed magnetic loops of different sizes and to study the distribution function of these loops (Tout & Pringle 1996; Uzdensky & Goodman 2006). The evolution of this loop distribution function and its steady-state shape are determined by the interplay between the various physical processes that govern what happens to the individual magnetic loops after they emerge from the surface. In the accretion disk context, two of the most important such processes are (i) the strong shear due to the Keplerian differential rotation and (ii) reconnection between loops. The Keplerian shear leads to a rapid stretching of the loops in the toroidal direction. Correspondingly, the disk motions perform work against magnetic forces, which means that magnetic energy is pumped into the corona. The coronal flux loops inflate due to the increased magnetic pressure and the characteristic magnetic scale-height increases. If there were no reconnection, this process would go on until the flux tubes grew to a height of order the disk radius $R$, after which the expansion would accelerate and the field would effectively open up. Essentially, one would get a dense forest of field lines going up and down.

The main role of reconnection is that it controls the magnetic energy scale height of the magnetized corona (e.g., Uzdensky & Goodman 2006) and acts as a mechanism for converting the magnetic energy pumped into the corona into the particle energy of hot coronal gas resulting in X-ray emission. Another important role of reconnection is that it may lead to a magnetic “inverse cascade” in the corona, i.e., to the production of a significant population

Fig. 6.— Magnetic loops in the corona of a turbulent accretion disk.
of loops with large radial \(^5\) footpoint separations (see Tout & Pringle 1996; Uzdensky & Goodman 2006), which may result in an enhanced transport of angular momentum.

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A. Solar Coronal Heating as a Self-Regulated Process

[The material in this Appendix was not presented at the Meeting. It has been added only afterwards.]

In this Appendix I discuss the implications of equations (5) and (9) for plasma heating in the solar corona.

I propose that coronal heating is a self-regulating process working to keep the corona marginally collisionless in the sense of equations (3), (5), and (9).

As long as the twisting of coronal loops by photospheric footpoint motions and flux emergence events keep producing current sheets in the corona, magnetic dissipation in these current sheets leads to continuous coronal heating. This heating of course is not uniformly distributed but instead is localized in both space in time (Rosner et al. 1978), as in Parker’s nano-flare picture (Parker 1988). The overall, integrated heating density, i.e., the rate of magnetic dissipation per unit volume, depends on the reconnection rate in these sheets, e.g., on whether reconnection is fast (e.g., Petschek) or slow (Sweet–Parker). This is actually a somewhat subtle point. Indeed, in a steady state, the energy dissipated in the corona per unit time should be equal to the power pumped into the corona magnetically from the solar surface. And it is not obvious why and how the energy-pumping rate depends on what is happening in the corona. For example, if the corona were enclosed in a fixed volume,

\(^5\)Loops with large toroidal footpoint separations are easily produced by the Keplarian shear alone.
then the energy dissipation per unit volume would be fixed (as in driven MHD turbulence in a box). However, it is important to recognize that the volume of the corona is not fixed! If, for example, reconnection were to suddenly slow down, then more energy would be pumped in than the corona could dissipate; then, in order to accommodate this additional free magnetic energy, the corona would respond by just increasing its scale-height. That is, coronal magnetic structures would grow in height until, finally, the total dissipation in the corona became equal to the total input from the photosphere. Because of the increased volume, the magnetic dissipation per unit volume is decreased.

[Note that there is an additional effect: as coronal magnetic structures grow in height, the amount of energy pumped into the corona by the footpoint motions may go down. This is because the work done by footpoint motions is proportional to $v_{fp} \cdot B_{\text{hor}} B_z / 4\pi$. As the coronal structures grow in height without increasing their lateral size, the horizontal field, $B_{\text{hor}}$, decreases, whereas the vertical field component, $B_z$, does not change. Correspondingly, the overall power pumped from the photosphere into the corona goes down.]

As follows from equation (5) or equation (9), the regime of reconnection is determined by the global scale $L$ of the reconnection layer and by the basic physical parameters characterizing the plasma in the layer (i.e., $n_e$, $T_e$, and $B_0$). The typical values of $L$ and $B_0$ are determined by the scale and strength of the magnetic structures emerging from the Sun and by the scale of footpoint motions (e.g., the meso-granular scale). Therefore, for the purposes of the present discussion, let us regard $L$ and $B_0$ as fixed and ask what determines the electron density and temperature in the corona.

Following this line of reasoning, let us invert equation (9) and view it as the condition for the plasma density. That is, let us introduce a scale-dependent critical density, $n_c$, below which the reconnection process transitions from the slow collisional Sweet–Parker regime to a fast collisionless regime:

$$n_c \sim 2 \cdot 10^{10} \text{ cm}^{-3}  B_0^{4/3} L_9^{-1/3},$$  \hspace{1cm} (A1)

where $L_9$ is the global reconnection layer length expressed in units of $10^4$ km.

Next, an important link in the chain is the existence of a positive feedback between the coronal heating and the density in the corona. This feedback is due to the fact that the gas high in the corona comes from evaporation from the surface along the field lines that just underwent reconnection.

Let us consider an example of how this works.

Let us suppose that due to field-line twisting, a reconnecting structure is set up in the corona with the current sheet length $L$ and the reconnecting field component $B_0$. Let us further suppose that, initially, the density of the background plasma is higher than $n_c$,
so that the reconnection layer is collisional and reconnection proceeds very slowly, in the
Sweet–Parker regime. That is, there is almost no reconnection at all. Coronal heating
is then inefficient, the surrounding plasma gradually cools and the pressure scale height
gradually goes down. The gas gradually precipitates. Then the density of the plasma
entering the layer decreases and at some point becomes lower than the critical density. The
reconnection process then suddenly switches to the collisionless regime. Petschek-like fast
reconnection ensues, and the rate of magnetic energy dissipation greatly increases. A flare
commences. Some fraction of the energy released by reconnection is transported by the
electron conduction along the reconnected field lines down to the base, where it is deposited
in the dense photospheric plasma. This in turn leads to a massive evaporation along the same
field lines. As a result, the newly-reconnected loops are now populated with relatively dense
and hot plasma. They cool down only slowly via radiation losses, keeping their relatively
high density for an appreciable length of time. If, during this time, these loops become
twisted or somehow get in contact with other loops, they are now not likely to reconnect
rapidly, since their plasma density is above critical. This inhibits further coronal heating in
the given region. In fact, we can speculate that for any further outbursts of coronal activity
in the given region to occur, one has to wait for the gas in post-reconnective loops to cool
down significantly, which occurs on a longer, radiative timescale.

Thus we see that, although highly intermittent and inhomogeneous, the corona is work-
ing to keep itself roughly at about the height-dependent critical density given by equa-
tion (A1). Correspondingly, the background coronal temperature should be such that results
in a density scale-height that is just large enough to populate the corona up to the critical
density level at a given height. In this sense, coronal heating regulates itself.

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