THREE-DIMENSIONAL MAGNETIC RECONNECTION IN ASTROPHYSICAL PLASMAS – KINETIC APPROACH

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Abstract. Reconnection is the most efficient way to release the energy accumulated in the tense astrophysical magnetoplasmas. As such it is a basic paradigm of energy conversion in the universe. Astrophysical reconnection is supposed to heat plasmas to high temperatures, it drives fast flows, winds and jets, it accelerates particles and leads to structure formation. Reconnection can take place only after a local breakdown of the plasma ideality, enabling a change of the magnetic connection between plasma elements. After Giovanelli first suggested magnetoplasma discharges in 1946, reconnection has usually been identified with vanishing magnetic field regions. However, for the last ten years a discussion has been going on about the structure of 3 D reconnection, e.g., whether in 3 D it is possible also without magnetic nulls or not. We first shortly review the relevant magnetostatic and kinematic fluid theory results to argue than that a kinetic approach is necessary to reveal the generic three-dimensional structure and dynamics of reconnection in collisionless astrophysical plasmas. We present results about the 3 D structure of kinetic reconnection in initially antiparallel magnetic fields. They were obtained by selfconsistently considering ion and electron inertia as well as dissipative wave-particle resonances. In this approach reconnection is a natural consequence of the instability of thin current sheets. We present the results of a nonlocal linear dispersion theory and describe the nonlinear evolution of the instability using numerical particle code simulations. The decay of thin current sheets directly leads to a configurational instability and three-dimensional dynamic reconnection. We report the resulting generic magnetic field structure. It contains pairs of magnetic nulls, connected by separating magnetic flux surfaces through which the plasma flows and along which reconnection induces large parallel electric fields. Our results are illustrated by virtual reality views and movies, both stored on the attached CD-ROM and also being available from the Internet.

1. Introduction

What we now call "reconnection" was originally suggested by Giovanelli (1946) as a possible mechanism to excite atoms at magnetic neutral points of sunspot magnetic fields. Now, decades later, we have learned that reconnection is a basic paradigm for the explanation of plasma energization, particle acceleration and structure formation in the universe. First, however, it was found to play an important role in stability considerations of magnetically confined laboratory and nuclear fusion plasmas (Kadomtsev, 1966). In magnetospheres reconnection has been identified to be the most important single physical process (Axford, 1999). At the sun it appeared to cause a much broader variety of phenomena than just the excitation of atoms at sunspots (cf., e.g., Priest, this volume). Generally reconnection was found to take place not only throughout the heliosphere but in the whole plasma universe (Tajima and Shibata, 1997). New evidences obtained by remote and *in situ* observations show that reconnection is a patchy, localized process, essentially three-dimensional and dynamic. It corresponds to a configurational instability rather than to a stationary process. All this does not fit into the classical reconnection models.

So, what models should be used to describe astrophysical reconnection? We argue that this question can be answered only by taking into account the direct particle interactions and not just fluid dynamical aspects. Also, it has appeared that reconnection is an essentially three-dimensional process. In this paper we will present first results about the structure and dynamics of kinetic reconnection in three dimensions. We start, in section 2, with a discussion of the achievements and limits of the existing reconnection models. In section 3 we review the constraints for 3 D reconnection due to magnetostatic and kinematic fluid considerations. In section 4 we argue why a kinetic approach is necessary to reveal the generic structure and dynamics of 3 D reconnection. In section 5 we present new results about the generic kinetic instability of thin current sheets. In section 6 we describe its direct consequence: a configurational instability which causes dynamic, essentially three-dimensional kinetic reconnection. Our results are summarized in section 7.

2. Existing reconnection models

The most prominent existing reconnection models are magneto-hydrodynamic (MHD). Already in their magnetostatic limit ($\partial \mathbf{B}/\partial t = 0$) they provide some general idea about possible reconnection geometries. Kinematic approaches ($\partial \mathbf{B}/\partial t \neq 0$) allow changes with respect to time. Since collisionless astrophysical plasmas are usually ideal at the scales of interest, they can be described almost everywhere by an Ohm's law with a vanishing r.h.s. ($\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$). This means that the magnetic flux is frozen into the plasma. In ideal plasmas magnetic flux and plasma always move together. An efficient plasma and particle energization needs a non-ideal plasma response which allows a change of the magnetic connection. The latter describes the essence of reconnection as the most efficient way to relax the magnetic tension to plasma heating and particle acceleration (Axford, 1967). Where could such regions of nonideal plasma response be expected? A good search criterion is to look for regions, where electric fields can rise to large values. This could happen, e.g., near singularities of the electric potential ϕ. In the static limit, where the electric field is potential, from the plasma ideality condition follows that ϕ must be constant along magnetic field lines, i.e. $\mathbf{B} \cdot \nabla\phi = 0$. In a kinematic approach there is also an inductive contribution to the electric field. In this case an ideal Ohm's law reveals $\mathbf{B} \cdot \nabla\phi = -\mathbf{B} \cdot \partial\mathbf{A}/\partial t$ ($\mathbf{A}$ is the vector potential; $\mathbf{B} = \nabla \times \mathbf{A}$). In both cases, however, the electric potential ϕ becomes singular, if the magnetic field vanishes, i.e. if $\mathbf{B}^2 \to 0$. Notice that at such magnetic nulls also the 'field line velocity' $\mathbf{v}_\perp = \mathbf{E} \times \mathbf{B}/\mathbf{B^2}$ piles up and becomes singular. A violation of the plasma ideality near magnetic field nulls would resolve the singularity problem by allowing a disconnection of the magnetic flux from the plasma flow. Over four decades the suggestion of Giovanelli (1946) that a discharge of the magnetic energy should be expected at magnetic nulls formed, therefore, a core hypothesis for most reconnection models. In two dimensions there is, indeed, no other way to magnetically disconnect plasma elements rather than through magnetic nulls. The strength of the perpendicular electric field through the null in the region of non-ideal plasma response has often been used as a measure of the efficiency of energy conversion (Cowley, 1976). Other authors emphasized the plasma flow speed through the nonideal-plasma region as an equivalent measure of efficiency of the energy conversion, the reconnection rate (Vasyliūnas, 1975). Concrete energy conversion rate and other characteristics of reconnection like the spectra of accelerated particles, the bulk plasma velocity, the plasma heating rate or structure formation depend, however, on the chosen model. In the Parker-Sweet model, for example, the efficiency of reconnection is strongly limited by the weak diffusive magnetic field erosion inside elongated current sheets (Parker, 1957). Since all plasma has to be pushed through a narrow outflow channel of the size of just the sheet width and since the outflow velocity is limited to the smaller Alfvén speed in the weaker outflow magnetic field, the reconnection rate remains small (Sweet, 1958). In his break-through work Petschek (1964) pointed out that a much higher efficiency of energy conversion can be achieved if the change of the magnetic connection takes place just in a small region near an X-point magnetic null. At the same time the plasma inflow can be collected from a broad region and expand into a broad outflow fan as well. In Petschek-type reconnection magnetic shock waves form in the plasma flow, since the local Alfvén speed drops considerably from inflow to outflow region. These shock waves provide most of the energy dissipation in Petschek of reconnection, much more than the magnetic diffusion inside the non-ideal plasma region near the X-point magnetic null (see Petschek, this volume). The Petschek-solution predicts a higher reconnection rate than the Parker-Sweet model. The maximum rate of stationary reconnection in two dimensions, however, is determined by the external flow boundary conditions (Priest and Forbes, 1986). In case of strong externally driven plasma flows even very fast steady reconnection is possible. Fast steady reconnection can take place, for example, at magnetopauses, the interfaces between fast flowing solar or stellar winds and magnetospheres.

Observations of energetic particles, plasma flows, heating and other consequences of reconnection have revealed, however that astrophysical reconnection is usually quite unsteady, bursty, even explosive as well as patchy and localized with an essentially three-dimensional structure. Further, it takes place, perhaps, rather as a configurational instability, relaxing a previously stable configuration to a state of lower energy, rather than as a stationary process (Axford, 1999). Astrophysical reconnection can, therefore, generally not be described by the existing stationary two-dimensional fluid models.

Unsteady, dynamic MHD simulations of reconnection usually start with some nonideal-plasma region, created by a locally added resistive term to the r.h.s. of the Ohm's law. Three-dimensional simulations have shown that reconnection immediately starts to reorganize the plasma flow and the magnetic field configuration into an essentially three dimensional pattern (cf. Otto, this volume). It seems that the plasma flows automatically adjust aiming at a state of most efficient energy conversion different from 2 D reconnection.

In section 4 we will argue that kinetic models will have to reveal the generic structure and dynamics of collisionless astrophysical reconnection. Such model so far exists only for thick current sheets, where an electron-resonant tearing mode instability was shown to cause reconnection due to dissipation by electron Landau damping (Coppi et al., 1966). The ion-resonant tearing mode instability, suggested for two-dimensional loop-like initial magnetic field configurations (Schindler, 1974), unfortunately, appeared to be stable (Galeev and Zelenyi, 1976). In three dimensions, however, a collisionless reconnection instability might be possible again even in 2 D magnetic fields with a finite cross-sheet magnetic field component B_n (Büchner, 1995). Before proceeding to kinetic reconnection in 3 D let us first shortly review in section 3 the general fluid constraints.

3. Fluid theory constraints on 3D reconnection

General reconnection models have to describe the specifics of changing the magnetic connection between plasma elements through a region of a nonideal plasma response in three dimensions. In the past the nonideal Plasma regions were simply associated with magnetic field nulls. In two dimensions magnetic nulls can be only O- or X- points. Separatrices through the X-points divide regions of different magnetic topology, the line perpendicular to the magnetic field through the X-point is called a separator (Vasyliūnas, 1975). A direct transfer of the two-dimensional null point geometry to three dimensions would be structurally unstable (Greene, 1988), the the whole configuration would change qualitatively for the smallest modification of the system (Schindler et al., 1988). Magnetostatic considerations easily reveal possible structurally stable null points in three dimensions. One finds them by representing the local magnetic field near a null by a Taylor series expansion $\mathbf{B}_{r\to 0} \approx \delta\hat{\mathbf{B}} \cdot \mathbf{r}$, where the elements of the $\delta\hat{\mathbf{B}}$ matrix are $\delta B_{ij} = \partial B_i / \partial r_j$. Since $\nabla \cdot \mathbf{B} = 0$ the trace of $\delta\hat{\mathbf{B}}$ is zero. Hence, the current $\mathbf{j} = \nabla \times \mathbf{B}$ at the null can be expressed as $j_i = \epsilon_{ijk} \delta B_{kj}$. Only an asymmetric matrix $\delta\hat{\mathbf{B}}$ can give rise to a current. Depending on the properties of the three eigenvalues of $\delta\hat{\mathbf{B}}$ the following three categories of nulls are possible: (1) One of the eigenvalue vanishes. Then the other two can be either both real or complex conjugated. (2) All three eigenvalues are real. (3) One of the eigenvalue is real. Then the other two are complex conjugated. The first category corresponds to a X-point null (two real eigenvalues) or an O-point null (two complex conjugates). These are the well known 2 D nulls which are structurally unstable in 3 D. The second category provides two different (called A- and B-type) three-dimensional generalizations of a 2 D X-point (Cowley, 1973). The third category leads to two possible 3 D generalizations of an 0-point in 2 D. It corresponds to a field line either spiraling into or out of the plane, depending on the complex eigenvalues.

A kinematic fluid approach extends the investigation of 3 D reconnection configurations to changes with respect to time. Several different reconnection topologies are possible. If a nonideal plasma region is located along a spine magnetic field line, there might be a fan of field lines or a separator field line, connecting two three-dimensional nulls (Lau and Finn, 1990). Another possibility is the singular field line reconnection, proposed by Priest and Forbes (1989). The latter is due to an electric field component parallel to a magnetic field line which has a X-point topology in a perpendicular plane. This allows a hyperbolic plasma flow toward the singular field line as well as a hyperbolic outflow. Such 3 D reconnection has become mathematically well described in a covariant formulation of kinematic reconnection (Hornig, 1997). Three-dimensional reconnection through nulls is always associated, as reconnection in 2 D, with a discontinuous jump of the mapping of the field lines across the null region (Priest et al., 1997).

However, as Parker and others have suggested, in contrast to the two-dimensional case reconnection in 3 D nulls and separatrices might not be necessarily present. For example Schindler and co-workers suggested that 'finite-B-reconnection' should be possible without magnetic nulls at all. Based on the condition of a local breakdown of the 'frozen magnetic flux' theorem they derived a kinematic fluid scheme of 'general magnetic reconnection' (Schindler et al., 1988). According to them in 3 D one should call reconnection that a localized plasma non-ideality generates a finite line integral of the magnetic-field-parallel electric field ($\mathbf{E} \cdot \mathbf{B} \neq 0$) along a certain singular magnetic field line, even if the magnetic field does not vanish anywhere, i.e. without magnetic field nulls at all. Such reconnection would be quite different from the two-dimensional, stationary 'zero-B-reconnection', where magnetic nulls and $\mathbf{E} \cdot \mathbf{B} = 0$ are necessary conditions. As Schindler et al. (1988) proposed, the reconnection rate in 3 D would be determined by the line integral of the parallel electric field $E_{||}$ along a magnetic field line leading through a nonideal plasma domain. A finite value of this line integral is necessary, because otherwise 'finite-B-reconnection' would not have large scale consequences (Hesse and Schindler, 1988). Finite parallel electric field line integrals through nonideal plasma regions can be found, e.g., in collisionless shock waves and double layers, where the quasi-neutrality breaks at the Debye length scale. But, perhaps, this should not be called reconnection. On the other hand, Schindler et al. (1988) suggested 'finite-B-reconnection' in magnetotail-like loop fields in the presence of a finite magnetic shear fields. Another example could be reconnection on twisted magnetic field lines as in the braiding model (Parker, 1972) of solar coronal heating (Parker, 1994). In this model supposedly no separatrices form (cf., also, Parker, this volume). A possible 3 D reconnection without nulls could also be due to flipping through regions of steep gradients of the magnetic field linkage (Priest and Démoulin, 1995).

Anyway, there has still to be fulfilled the necessary condition of a non-ideal response of astrophysical plasmas for reconnection to take place. Greene (1988) argued that such breakdown of plasma ideality could be expected most probably in boundary layers, where structurally stable singularities of the ideal MHD can easily be found. This approach implies that singularities like magnetic nulls or closed loops should always be present in reconnecting magnetic fields.

We want to find out, whether reconnection without magnetic nulls is possible and what the typical structure of 3 D reconnection is. Unfortunately fluid approaches can only verify the macroscopic consistency of possible three-dimensional reconnection models but not, whether it takes place with or without magnetic nulls. Fluid approaches cannot resolve the MHD singularities. Therefore, they cannot reveal the generic structure and dynamics of natural 3 D reconnection in collisionless astrophysical plasmas. To solve this problem flows and non-ideality should not be prescribed in form of a finite resistivity or else but, instead, they have to be determined selfconsistently including the interaction with the inertial particles. In the following section 4 we argue why the generic structure and dynamics of three-dimensional reconnection have to be looked for kinetically.

4. Reasons for a kinetic approach to 3 D reconnection

The first reason for applying a kinetic approach immediately follows from the necessity to break the frozen flux theorem. The latter generalizes the Kelvin-Helmholtz theorem by including the vorticity due to the gyro-motion of charged particles in magnetic fields (Axford, 1984). Hence, the frozen-flux-theorem has to be broken not just for the ions, which is easier, but also for the gyrating electrons. As a result one has to consider reconnection at the spatial and temporal scales of the electron motion.

A most probable route to reconnection is that of a configurational instability (Axford, 1999). Theoretical considerations and numerical investigations revealed, however, that the tearing mode of two-dimensional current sheets is stable in the presence of a finite magnetic field component B_n perpendicular to the sheet (Galeev and Zelenyi, 1976). This apparent stability could, however, be lost in 3 D allowing a modulation of the sheet in the current flow direction (Büchner, 1995). This modulation could also provide the scale of the 3 D structure of reconnection (Büchner, 1996). Hence one should look for a solution of the stability problem in the framework of a kinetic approach.

Fluid approaches do not selfconsistently describe the physical mechanism of the plasma non-ideality necessary for reconnection. Collisionless plasma non-ideality can be due to particle inertia, Landau damping or other phenomena causing off-diagonal in the magnetic field frame plasma pressure tensors. All these effects should be described kinetically to be completely understood before one can include them into more general models.

Last, but not least, in space plasmas under the pressure of external forces current sheets form, which thin down to particle scales (cf. Schindler, this volume). Such thin sheets were directly observed prior to reconnection in the Earth magnetotail. Their investigation needs a kinetic (particle) approach as well. Since thin current sheets are a probable starting point for a configurational instability leading to reconnection, we report in the following section 5 the latest results about instability threshold and other properties of the decay of thin current sheets.

5. Kinetic instability of thin current sheets

The formation of thin current sheets is a natural consequence of the action of external forces, stressing magnetized plasmas (cf., e.g., Schindler, this volume). In the course of rising magnetic field tension and the consequent sheet thinning the free energy increases, stored in field and currents. This enhances the probability of an unstable decay of the sheet. In the past the search for appropriate current instability modes was motivated mainly by looking for local modes which would be able to provide anomalous resistivity in collisionless plasmas. However, local instability analyses of electrostatic ion-acoustic modes showed that they are not relevant with regard to the parameters expected in typical reconnection regions (Coroniti and Eviatar, 1977). The strong plasma pressure gradients at the edge of current sheets could drive electrostatic lower hybrid drift wave instabilities. The high plasma-β inside current sheets, however, damps away these waves (Huba, 1980). Electromagnetic cross-field instabilities were looked for as well (Lui et al., 1991). While explaining electromagnetic wave outbursts (Kuznetsova and Nikutowski, 1994), they did not influence the reconnection dynamics of current sheets. However, all these theoretical investigations were based on local instability analyses. It is, therefore, not obvious that they apply in case of thin current sheets. Indeed, current particle code plasma simulations, which take into account non-local modes, have revealed quickly growing bulk modes of marginally thin current sheets (Büchner and Kuska, 1996), (Zhu and Winglee, 1996), (Pritchett et al., 1996). Years ago such instabilities have been predicted on the basis of analytical investigations of thick current sheets (Yamanaka, 1978). Currently we have obtained threshold, structure and linear growth rate of a nonlocal bulk instability of thin current sheets as well by using an appropriate system of base functions which allowed an analytical solution of the nonlocal wave equations (Büchner and Kuska, 1999). Our calculations have shown that the threshold of stability of thin current sheets is an ion gyro-radius wide sheet. The dispersion of the unstable mode is that of an unstable acoustic type ion-resonant mode. Mathematically the wave mode, which evolves after the sheet has thinned down to the threshold level, can be either symmetric or asymmetric about the current sheet midplane. For sufficiently large mass ratios we found a dominating symmetric mode (Büchner and Kuska, 1996), which reminded us the analogous ideal plasma sausage mode instability (Büchner and Kuska, 1999). An asymmetric about the sheet midplane mode has a similar dispersion, but its growth rate is larger than that of the kink mode only for artificially small mass ratios. Our conclusion is that a kink mode is typical for artificially low mass ratios (Zhu and Winglee, 1996), (Pritchett et al., 1996), while for higher mass ratios starting at least with

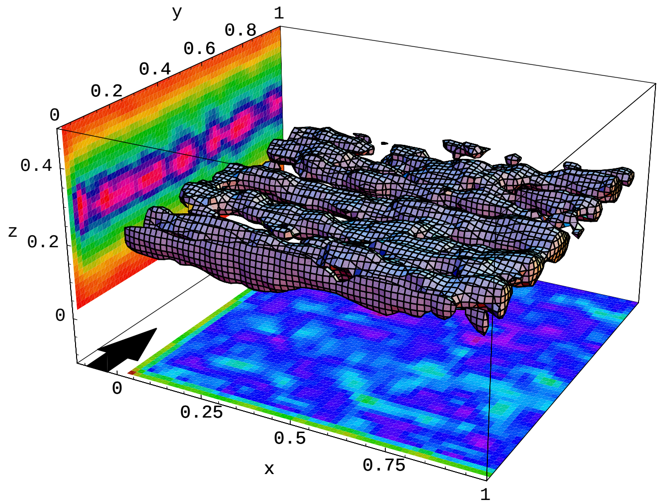

Figure 1. Densitiy modulation due to a the bulk instability of thin current sheets (Büchner and Kuska, 1999)

$m_e : M_i = 1 : 64$, the sausage symmetry prevails.

Let us illustrate structure and dynamics of the sausage mode bulk instability of thin current sheets by showing the spatial distribution of the resulting plasma density modulation. Figure 1 depicts an isosurface of constant plasma density at a $\frac{2}{3}$ of the maximum level. It was obtained by means of particle-in-cell (PIC) code simulations using the three-dimensional, fully kinetic electromagnetic code GISMO (Büchner and Kuska, 1996). The simulations started with a thin Harris-type equilibrium current sheet. In accordance with the analytically derived marginal stability criterion the initial sheet half-width L_z was chosen to be about one ion gyroradius in the external magnetic field. As usual for particle simulations an artificial mass ratio had to be used. Figure 1 corresponds to simulations with a mass ratio $m_e : M_i = 1 : 64$, which allows a quite good separation of electron and ion effects. The sausage mode symmetric density perturbations can be seen in the Figure. Side and bottom planes of the simulation box depict contour plots of the plasma density in two planes cutting the box through the central planes parallel to the box sides, at which they are projected. The structure in Figure 1 corresponds to a developed stage of the instability, close to its saturation. More details about the nonlocal bulk instability of thin currents sheets can be found in (Büchner and Kuska, 1999). A color version of Figure 1 as well as a movie, which depicts the evolution of the instability the propagation of the resulting wave in the current direction (the arrow in the lower left corner of the box) can be watched with a PC using the attached CD-ROM. For comparison the attached CD-ROM contains also the results of simulations of a $m_e : M_i = 1 : 1$ plasma. Equal masses correspond to a longer wavelength and an asymmetric kink-mode displacement of the density maxima. Those who do not possess the CD-ROM can access the necessary data files also in the WorldWideWeb, through the author's homepage at URL *http://www.mpae.gwdg.de/~buechner*. If an *avi* viewer is installed on the computer, the animation starts immediately after opening the frontpage related to this paper by an appropriate HTML-viewer or net browser. There are also *wrl* files on the CD-ROM as well as on the net site. With their help and a virtual reality viewer plugin to the net browser, like, e.g. the Cosmo Player (version 2.0 or higher), available, e.g., at URL *http://cosmosoftware.com/products/player/*, one can watch the density structure from different viewpoints. With the installed plugin and a browser the virtual reality files open automatically after clicking the corresponding button on the frontpage of the paper.

The most unstable current sheet decay mode generates electric field oscillations in the direction of wave propagation and current flow. This oscillating electric field accelerates the electrons. Their thermalization on non-adiabatic and chaotic orbits it heats the electrons as well. While the resonant ion interaction drives the mode the electron energization is the major way to dissipate the energy of the growing wave. Meanwhile the heated, non-adiabatic electrons allow a change of the magnetic connection. A configurational instability of the whole system becomes possible and, therefore, reconnection. In the following section 6 we describe the consequences of this process for the magnetic topology of 3 D kinetic reconnection.

6. Magnetic topology of 3 D kinetic reconnection

In the previous section we discussed that thinning current sheets unstably decay after reaching a sheet width comparable with the ion gyroradius. A bulk plasma wave grows which receives current energy by inverse resonant Landau damping on the drifting ions. The wave field heats the electrons and destroys the electron adiabaticity. The electrons become quasi-adiabatic and chaotic as the ions already are (Büchner and Zelenyi, 1989). This de-magnetization of the electrons is equivalent to de-freezing the magnetic flux from the plasma in the magnetofluid approach. The electron demagnetization allows a change of magnetic connection and, therefore, reconnection. The preexisting fluctuation-level Debye-scale microscopic magnetic regions merge and form large scale reconnection islands (Büchner, 1999). This 3 D merging process can be compared with the plasmoid formation process in two-dimensional reconnection. Since electrons and ions are electrically coupled, the plasma stays quasi-neutral. The consequent necessity to accelerate the ions in the reconnection induced electric fields limits the growth of the configurational instability (Büchner, 1998). The resulting linear growth rate of the reconnecting configurational instability in 3 D appeared to be, nevertheless, much faster than the growth of a two-dimensional collisionless tearing mode instability (Coppi et al., 1966). The further non-linear growth of the three-dimensional reconnection instability corresponds to a magnetic field and plasma flow pattern, which considerably differs from two-dimensional reconnection.

One difference between 2 D and 3 D reconnection is that in three dimensions plasma outflow is possible also in the third, the original current direction.

Further, our simulations revealed regions of vanishing magnetic fields, although in their specific 3 D form. Let us illustrate the generic structure of the resulting three-dimensional reconnection by showing some typical magnetic field topologies. As in section 5 we use the results of kinetic plasma simulations with the PIC code GISMO. The initial configuration is the same as discussed in section 5. The difference is that we now show results obtained for a mass ratio $m_e : M_i = 1 : 25$ and for an even thinner sheet, which reconnects faster.

The general picture of 3D reconnection can be seen in Figure 2. The figure combines density and magnetic field information of the developed nonlinear configurational instability in one plot. The density modulation, caused by the bulk current instability, reveals regions of enhanced and lower density. The higher density regions correspond to darker regions at the side planes of the box (in the color version on the CD-ROM: blue). The side planes depict density contour plots through central cutting planes of the box in Figure 2. As one can see in the Figure, and, even better, by rotating the structure using the corresponding virtual-reality-files on the attached CD-ROM (click the Figure), the field reminds the pattern of Petschek reconnection only near the density maxima. The rest of the 3 D magnetic field structure strongly deviates from 2 D. One important effect is field aligned Hall-currents. Hall currents due to the different mobility of ions and electrons cause a specific δB_y- magnetic field perturbation also in 2 D (Teresawa, 1983), but a quite different one in 3 D (Büchner et al., 1998). Due to the density modulation along the original current direction Y the strength of the Hall currents varies along Y and so does the magnetic field perturbation δB_y. Starting from a magnetic null position near the density maxima the magnetic field lines either spiral or diverge out due to $\delta B_y(Y) \neq 0$ or converge into the nulls.

The field topology near the null regions and their magnetic connection can better be seen in Figures 3-5. The Figures show selected magnetic field lines from a viewpoint in the positive Y-direction, i.e. from the back of Figure 2. The field lines are integrated only in one direction from starting

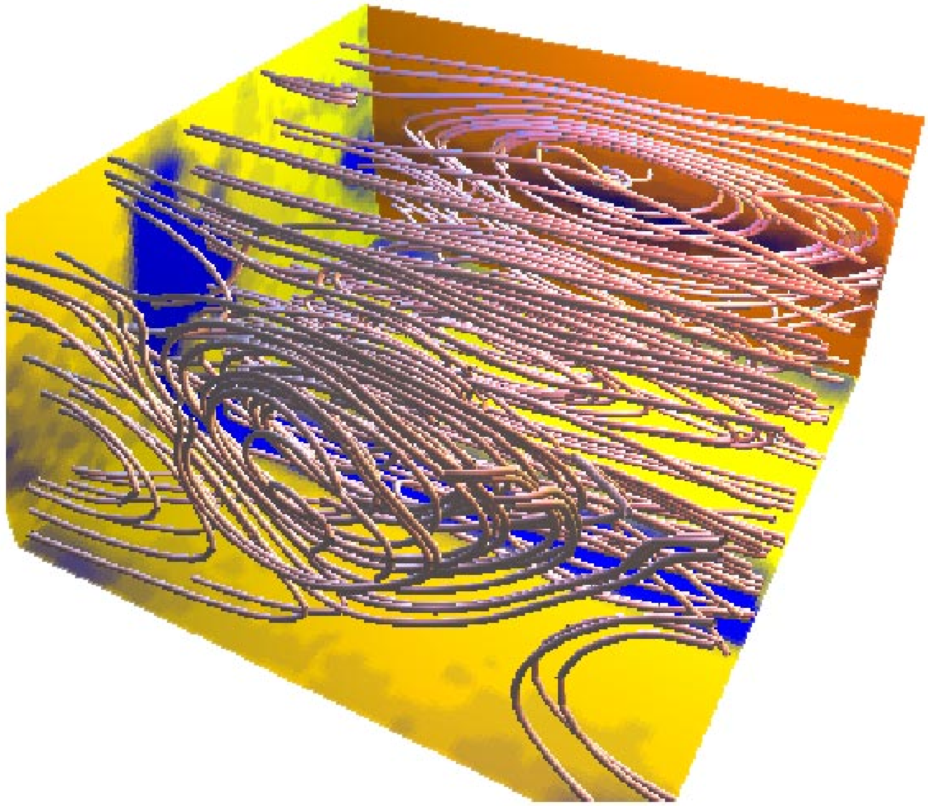

Figure 2. Overall magnetic field structure and density of 3 D kinetic reconnection through thin current sheets

points located along a line (Figure 3) and near a point (Figures 4-5) at an upper right position in the box. Figure 3 depicts a pair of two magnetic nulls in developed 3 D reconnection through thin current sheets embedded in initially antiparallel magnetic fields ($B_{yo} = 0$). Both nulls are located inside the maximum density region of the bulk current instability. One of them is spiraling, the other one mainly diverging. These two nulls are not only connected with each other but also with a second pair of nulls (not shown in Figure 3) located in the neighboring density maximum of the current instability.

Figure 4 zooms out details of the spiraling out type null to the right of Figure 3 and Figure 5 enhances the field structure near the diverging null to the left of Figure 3. All field lines shown in Figures 4 and 5 start from almost the same initial position to the right of the Figures. In Figure 4 one sees also diverging field lines near the spiraling null. Near null

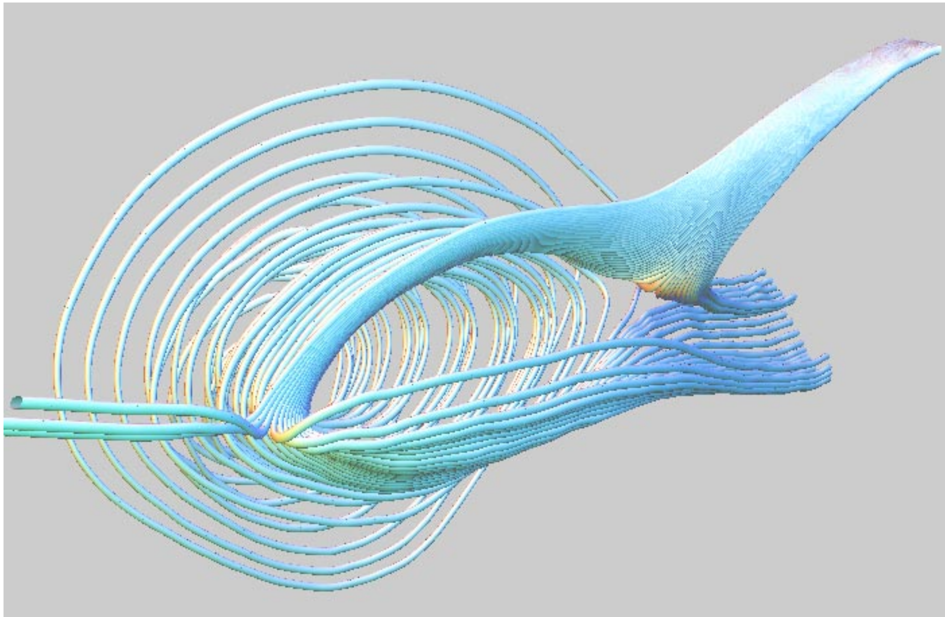

Figure 3. Magnetic field structure between two 3 D nulls

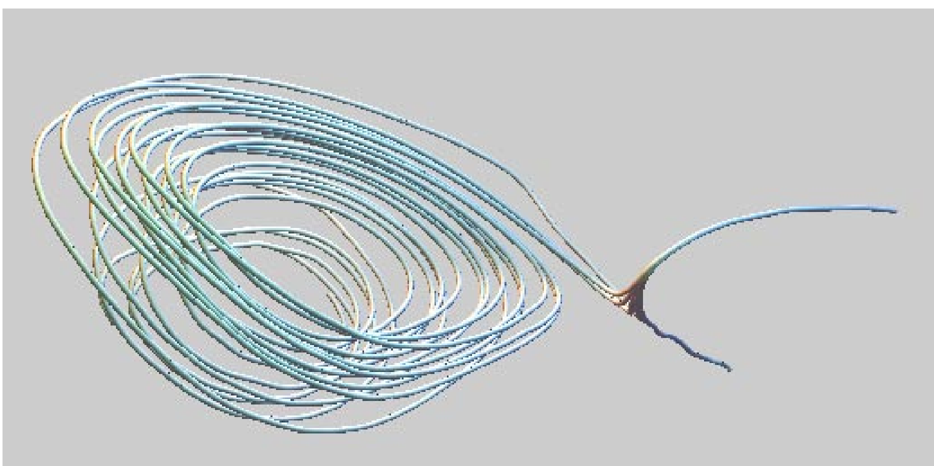

Figure 4. Magnetic field structure of a converging 3 D null

points the magnetic field strength becomes minimum. However, it does not vanish completely. This indicates, that although one has reached a region of vanishing magnetic field one has not directly hit the singular null point. The principal difficulty to reach a singularity also technically complicates

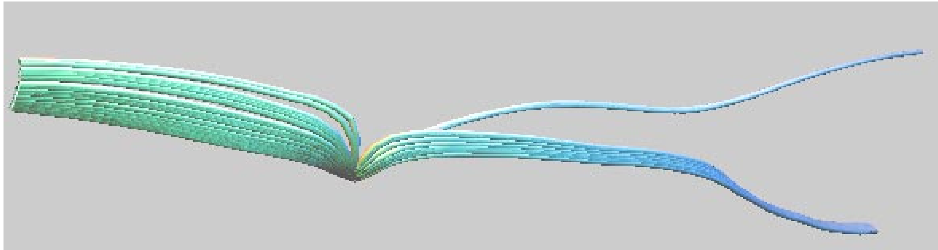

Figure 5. Magnetic field structure of a diverging 3 D null

the calculation of the eigenvalues of the magnetic field near the null, and, therefore, of the determination of the direction of the central spine as well as of its perpendicular plane (Parnell et al., 1996).

The same is true for the diverging null region to the left of Figure 3 whose enhancement is shown in Figure 5. Figure 5 depicts a fan of outgoing field lines which all stem from almost the same near-spine field line, which starts to the right of the Figure. As in the case of Figure 4, all field lines start from only slightly varying initial coordinates. They are located so close to each other that they even do not appear separated before until they start to diverge in the null region.

Notice that the kinetic simulation results reported here in this paper provide the generic structure of 3 D reconnection through thin current sheets, embedded in maximum sheared (180^o), i.e. antiparallel magnetic fields ($B_{yo} = 0$). We found that the resulting 3 D reconnection is characterized by multiple pairs of magnetic null regions. In contrast to separator lines out of a 2 D X-point magnetic nulls in 3 D nulls are connected by flux surfaces separating regions of different magnetic field topology in 3 D. More pairs of magnetic nulls are located along the original current direction (not shown here). There the separating flux surfaces from the null regions, shown in Figures 3- 5) head for. In 3 D kinetic reconnection these two-dimensional separator surfaces connect null regions of opposite type. The plasma flows are deflected around the magnetic nulls and through the separators forming a typical 3 D flow pattern. Parallel to the corresponding magnetic flux surfaces 3 D reconnection induces the maximum parallel electric fields. Only in planes $Y = const.$ near the density maxima, i.e. inside the sausages of Figure 1 the plasma flow pattern of 3 D reconnection reminds the one of two-dimensional Petschek reconnection. In 3 D important plasma flows take place pointing in the original current direction. Therefore, due to the three-dimensionality, in thin sheets, enforced by a bulk current instability, the plasma can escape from regions of enhanced density also in the third dimension.

Notice that, as for the bulk current instability in section 5, the color-version of Figures 3- 5 as well as their virtual reality files, allowing to watch them from different viewpoints, are stored on the attached CD-ROM. They can also be obtained from the homepage of the author (for technical details, see section 5).

7. Summary

Since observations indicate that astrophysical reconnection is non-stationary, essentially three-dimensional and patchy, there is a need to derive models beyond the existing and well developed two-dimensional and stationary ones. Our point is that, before one can turn back to develop appropriate large scale fluid models, it is necessary to consider reconnection kinetically to find its generic 3 D structural and dynamical properties. We reviewed the state of model formation and presented new theoretical results about the stability of thin current sheets. We also presented results of appropriate numerical PIC (particle-in-cell) code simulations of the nonlinear evolution of the current sheet instability, its transition to a configurational instability and, finally, to reconnection. We focused on the case of antiparallel magnetic fields (180^o shear angle). The main stumbling block for reconnection is to release the electrons from the magnetic field. This is the kinetic equivalent of breaking the frozen flux theorem of ideal MHD. The electron magnetization was found to be overcome in thin current sheets by a kinetic bulk current instability mode which heats the electrons beyond adiabaticity. This allows a configurational instability and essentially 3 D reconnection. The resulting rate of reconnection is determined by the more inertial ions, which also have to be accelerated in the induced electric field. The characteristic time scale of the instability is the ion gyroperiod. This is much faster than that of the two-dimensional tearing mode instability. Also, the 3 D reconnection rate is higher than the 2 D Petschek limit. The reason is that in 3 D plasma outflows are possible also in the third dimension, the original current flow direction. The characteristic length scale in the third direction is the wavelength of the most unstable bulk current mode. The magnetic field structure of 3 D reconnection is determined by the location of the most efficient resonant interaction between particles and growing wave fields as well as by Hall currents due to the different mobility of electrons and ions. The currents are most intense in the higher plasma density regions where pairs of magnetic nulls form. The magnetic field topology near 3 D nulls leads to either converging, spiraling together, diverging or expanding magnetic flux tubes. Any of the pairs of null regions is connected with a neighboring, located a wavelength of the bulk instability mode away. They are connected by magnetic flux surfaces along which strong electric fields are induced. The connecting flux surfaces separate regions of topologically different magnetization similar to separator lines in 2 D reconnection.

Notice that these results were obtained for initially antiparallel magnetic fields. Initial shear angles unequal to 180^o change the properties of reconnection as discussed in a separate paper (Büchner et al., 1999).

8. Acknowledgements

The author cordially thanks Sir I. Axford, K. Schindler and V. Vaselikeūlnas for their support of this study and for stimulating discussions, J.-P. Kuska for programming GISMO and the Deutsche Forschungsgemeinschaft for funding research project BU 777 / 2-3.

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