Energy budget of the reconnection process

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[1] The relevance of magnetic reconnection in the frame of space plasmas is mainly due to the energy conversion taking place during this process. We address our investigations within this article to the energy budget of the reconnection process and focus our research on the conversion of magnetic energy into kinetic plasma energy and the spatial redistribution of the energy density. Using a time-dependent MHD reconnection model for an incompressible plasma, we derive the amount of released kinetic plasma energy and identify regions of enhanced a decreased magnetic field energy. The decrease of magnetic field energy in the wake of the outflowing plasma regions is compensated by a field energy enhancement above and below the outflow regions. This field energy is two times higher than the kinetic energy inside the plasma flow regions and gets removed from the reconnection site together with the plasma flow.


1. Introduction

[2] For the explanation of huge energy releases during solar flares or in the context of geomagnetic storms and substorms, magnetic reconnection represents the widely accepted plasma process being responsible for these phenomena. During the reconnection process, initially stored magnetic field energy gets converted into kinetic and thermal plasma energy, leading to the acceleration of heated plasma. Besides this energy conversion, reconnection leads to a topological reconfiguration of the magnetic field line structure, that is, initially different magnetic field lines get connected and are removed from the reconnection site together with the outstreaming plasma. Thus reconnection can be seen as initiator of a transport of mass, momentum, magnetic flux, current and energy. Sweet [1958] and Parker [1957] approximated the reconnection process as a two-dimensional steady state incompressible MHD problem, with the reconnection rate resulting from a boundary layer analysis. Since the reconnection rate arising due to this model was too small to explain the energy release rates in solar flares, Petschek [1964] presented an analytical investigation based on a smaller diffusion region and the implementation of shock waves. Since its establishment, the Petschek model has been extended to a more complex geometry, more general boundary conditions and a time-dependent reconnection rate [Semenov et al., 1983; Biernat et al., 1987]. Since reconnection has been understood as a multiscale process, investigations on several spatial and temporal scales are necessary. Reconnection influences the surrounding medium on the large scale via the generation of shocks, plasma outflow and disturbances in the magnetic field and plasma background. By excluding diffusion region processes, ideal MHD is a suitable theory for investigations on magnetic reconnection on the large scale and the disturbances created by the process. The disturbances on the macroscopic scale can be used to get information of the reconnection process itself [Semenov et al., 2005; Ivanova et al., 2007; Kiehas et al., 2008]. The modeled disturbances agree well with observations [Kiehas et al., 2009] and can also be found in simulations [Ugai and Zheng, 2006a, 2006b]. The reconnection process appears as fast reconnection, which is an important issue as pointed out by Ugai and Tsuda [1977]. Because of the conversion of magnetic field energy into kinetic and thermal plasma energy, a considerable amount of energy is transported from the reconnection site along the current sheet. Below we present an analysis of the energy conversion, taking place during reconnection and investigate the energy budget itself.

[3] As basis for these investigations, we use a time-dependent Petschek-type magnetic reconnection model [Semenov et al., 1983; Biernat et al., 1987]. This model works in the fast reconnection regime [Erkaev et al., 2001], shows strong plasma compression ahead of the OR for compressible solutions [Semenov et al., 1998a], and gives a variety of MHD waves and shocks [Heyn et al., 1988]. It can be extended for the case of compressible plasmas [Semenov et al., 2004a], asymmetric reconnection [Semenov et al., 1992] and can be applied to magnetopause [e.g., Biernat et al., 1998] and magnetotail [e.g., Semenov et al., 2005; Kiehas et al., 2009] reconnection. As initial configuration, two antiparallel magnetic fields embedded in two identical, uniform and incompressible plasmas, are separated by a current sheet, modeled as tangential discontinuity. Reconnection starts with the appearance of a locally and temporally restricted time-varying connection electric field in the center of the current sheet (Figure 1a). In the
steady state Petschek model, magnetic field lines from opposite sides of the current sheet are connected via standing shocks. Because of the unsteady behavior of the reconnection electric field in our model, the shocks form enclosed regions in the time-dependent extension of the Petschek model (Figure 1b). These regions correspond to the plasma outflow regions and grow in x and z direction as long as the reconnection electric field is active. After reconnection ceased, the outflow regions (OR) detach from the initial reconnection site and propagate in opposite directions along the current sheet, transporting the reconnected magnetic flux (Figure 1c). When reconnection ceased and the OR detach, no more reconnected flux is added to the system and the volume of the OR grows during their propagation due to the collection of plasma (see Figure 2).

Above and beneath the ORs, the magnetic field lines are compressed due to the appearance of the OR and field lines which are connected via the ORs as consequence of the reconnection process. In the following we present an analytical investigation of the conversion from magnetic energy into kinetic plasma energy. The result of this conversion is the appearance of ORs, which contain kinetic energy of the plasma and transport this energy along the current sheet. The amount of kinetic energy inside the ORs is compensated by a decrease in the magnetic energy inside these regions, which is shown in sections 2 and 3. Section 4 discusses the change in the magnetic energy inside the compression regions above and beneath the ORs. It is shown that these regions contain a huge amount of magnetic energy, which is two times bigger than the kinetic energy of the plasma inside the ORs. This interesting result is due to the redistribution of magnetic field energy as consequence of the reconnection process. In the wake of the ORs, the magnetic field density is decreased and this decrease is compensated by an increase in the magnetic field density above and beneath the ORs. Since these compression regions propagate together with the ORs, they can be seen as transporter of a huge amount of magnetic field energy. A discussion of this result is given in section 5.

The release of previously stored energy is one of the most important features of magnetic reconnection, both for solar and magnetospheric applications. For considerations on the energy release of the reconnection process, mainly kinetic and thermal energy of the plasma was taken into account, so far. During the course of substorms, reconnection-associated released energy is of big geoeffective importance, and therefore it is necessary to recognize that reconnection not only leads to a release of plasma energy but also to a transport

![Figure 1. Time-dependent Petschek reconnection. (a–c) Evolution of the plasma outflow regions/shock structures and the change in magnetic field topology. Reconnection is initiated at the origin of the sketched coordinate system. The light blue line denotes the current sheet, separating two antiparallel magnetic fields (blue arrows). Inside a locally confined region, a pulsative, time-varying reconnection electric field $E_r$ is established (Figure 1a), leading to the acceleration of plasma in opposite directions along the current sheet. Because of the temporally restricted activity of $E_r$, the plasma outflow is confined to closed outflow regions (gray areas, Figure 1b). These regions are bounded by shocks (red) and detach from the initial reconnection site after $E_r$ vanishes (Figure 1c). Since magnetic field lines from both sides of the current sheet are connected via the outflow regions, reconnected magnetic flux is transported, together with the plasma outflow regions. The dotted lines represent the separatrices [after Semenov et al., 2004b].](image)

![Figure 2. Reconnection electric field (red, modeled as $E = \sin^2(\pi t/T_0)$ and active during $0 < t \leq T_0$ with $T_0 = 1$), reconnected flux (black), and volume of the outflow region (per unit length of the reconnection line, blue).](image)
process with respect to magnetic field energy, which is two times bigger than the kinetic energy of the plasma.

2. Change of the Magnetic Energy Inside the OR

[6] We divide the system into two regions: The diffusion region, where dissipative processes have to be taken into account, and the convective region around the diffusion region, where ideal MHD is valid. Within this work, we investigate the large-scale energy transport and redistribution. Hence we restrict our analysis to the convective zone and take advantage of the ideal MHD equations. The convective region itself can be subdivided into the outflow region, i.e., the region of outflowing plasma, and the inflow region, i.e., the region around the outflow regions. Within the frame of the two-dimensional geometry, sketched in Figure 1, a one-dimensional tangential discontinuity separates two uniform and identical incompressible plasmas. The initial background magnetic field is represented by two antiparallel magnetic fields on either side of the discontinuity in the form \( \mathbf{B}_1 = -\mathbf{B}_2 = (B_0, 0) \), with \( B_0 \) as background magnetic field.

[7] For the situation of weak reconnection, the reconnection electric field \( E_r \) is much smaller than the Alfvén electric field, \( E_A = 2v_A B_0 \), where \( v_A \) and \( B_0 \) denote the Alfvén velocity and the background magnetic field, respectively. Thus a small parameter \( \epsilon \) can be introduced,

\[
\epsilon = \frac{c E_r}{v_A B_0} \ll 1,
\]

and the outflow regions can be seen as thin boundary layer, that is, a perturbation analysis of the MHD equations can be performed, with \( \epsilon \) as small expansion parameter. Thus the magnetic field can be expanded in the form

\[
\mathbf{B} = \mathbf{B}^{(0)} + \epsilon \mathbf{B}^{(1)} + \epsilon^2 \mathbf{B}^{(2)} + \ldots
\]

(1)

where \( \mathbf{B}^{(0)} \) denotes undisturbed quantities and \( \mathbf{B}^{(1)} \) disturbances of the first order. An order of magnitude estimate shows that quantities tangential to the current sheet are of the order of \( \sim 1 \), whereas perpendicular components are of the order of \( \sim \epsilon \). Thus the outflow regions can be treated as thin boundary layers with tangential and normal components corresponding approximately to \( x \) and \( z \) components, respectively. The magnetic fields in the inflow and outflow regions appear in the general form as

\[
\mathbf{B} = \left( B_0 + B_x^{(1)}, B_z^{(1)} \right),
\]

(2)

\[
\mathbf{B}_x = \left( 0, B_x^{(1)} \right),
\]

(3)

where \( \mathbf{B} \) and \( \mathbf{B}_x \) represent the magnetic fields in the inflow and outflow regions, respectively.

[8] For the magnetic field and velocity components inside the OR, one finds in the normalized case as used throughout this work [Semenov et al., 2004b; Kiehas et al., 2009],

\[
\tilde{v}_x = \pm v_x,
\]

(4)

\[
\tilde{v}_z = 0,
\]

(5)

\[
\tilde{B}_x = 0,
\]

(6)

\[
\tilde{B}_z = \pm \frac{c}{v_A} E_r (t \mp x/v_A),
\]

(7)

where \( E_r (t \mp x/v_A) \) denotes the reconnection electric field and positive and negative signs denote leftward and rightward propagation, respectively. The reconnection electric field is modeled as

\[
E_r = \sin^2 \left( \pi/T_0 \right),
\]

being active during \( 0 < t \leq T_0 \) with \( T_0 = 1 \) in the normalized system (see Figure 2). With this, the reconnection electric field exhibits a time-dependent pulsative behavior. For the solutions the expansion (1) is disrupted after first-order terms \( \mathbf{B}^{(1)} \) and we neglect second-order terms \( \mathbf{B}^{(2)} \). With this, and under the assumption of homogeneous background plasma density distribution, the outflow velocity \( v_x \) corresponds exactly to the Alfvén velocity \( v_A \), which is equal to one in the normalized system. Taking into account also second-order terms, the outflow velocity deviates slightly from \( v_A \) and appears to be sub-Alfvénic [see study by Alexeev et al., 2000]. Using equations (4)–(7) and the equation for the shape of the OR [Biernat et al., 1987], defining the location of the OR in the \( x-z \) plane,

\[
z = f(x) = \pm \frac{c}{v_A B_0} x E_r (t \mp x/v_A),
\]

(8)

the perturbations outside the OR can be found from a linearized system of equations by taking into account the jump condition \( [B_z] = 0 \) for the field component normal to the shock [Semenov et al., 2004b; Kiehas et al., 2009].

[9] Considering an area in space with the volume of the OR, the change of the magnetic energy inside this region before and after reconnection is

\[
\Delta W_{\text{OR}}^{\text{OR}} = \int_{\text{OR}} \left( \frac{B_z^{(1)}}{8 \pi} - \frac{B_0^2}{8 \pi} \right) dV,
\]

(9)

written in cgs units as used throughout this work.

[10] Since \( \left( B_z^{(1)} \right)^2 \) appears as second-order term, the magnetic energy inside the OR after the reconnection process can be neglected compared to the magnetic energy inside an area of the same volume as the OR before reconnection (see Figure 3). Hence the change of the magnetic energy inside the OR due to reconnection can be written as

\[
\Delta W_{\text{OR}}^{\text{OR}} = -\frac{B_0^2}{8 \pi} \int_{\text{OR}} dV.
\]

(10)
By integrating over the OR the change in the magnetic energy inside the OR can be calculated.

3. Volume of the OR

[11] In the following, the volume of the OR in the first quadrant (see Figure 1) is calculated per unit length of the reconnection line, which means that the extension in \( y \) direction is equal to 1.

[12] The OR can be defined by the shape of the OR in the first quadrant from equation (8),

\[
f(x) = \frac{c}{v_A B_0} x E_i(t - x/v_A).
\]  

[13] Since the OR is propagating with Alfvén speed, the leading front of it is located at \( x = v_A t \) (see Figure 4). The volume of the OR per unit length of the reconnection line can be found by integrating the function \( f \) over \( x \) with the boundaries from \( x = 0 \) to \( x = v_A t \), which gives for the first quadrant (Q1),

\[
V_{OR}^{Q1} = \frac{c v_A B_0}{v_A} \int_0^{v_A t} x E_i(t - x/v_A) \, dx.
\]  

We can define the functions \( F(t) = \int_0^t E_i(t) \, d\tau \) and \( G(t) = \int_0^t F(\tau) \, d\tau \) as the reconnected magnetic flux and the volume of the OR in dimensionless units, which are shown in Figure 2. The derivation of the volume of the OR in dimensional units is shown in the following. The reconnected magnetic flux \( F(t) \) is established during the active phase of the reconnection process and reaches its maximum level \( F_0 \) after reconnection ceased. Then, the OR grows linearly with time. From equation (12) one gets after changing the integration variable \( \tau = t - x/v_A \),

\[
V_{OR}^{Q1} = \frac{c v_A B_0}{v_A} \int_0^{v_A t} v_A^2(t - \tau) E_i(\tau) d\tau.
\]  

With this, we find for the volume of the OR in the first quadrant,

\[
V_{OR}^{Q1} = \frac{c v_A B_0}{v_A} G(t).
\]  

Because of mirror symmetry with respect to the \( x \) axis, the entire OR propagating into one direction exhibits a volume of

\[
V_{OR} = \frac{2 c v_A B_0}{v_A} G(t). \quad (13)
\]

With equations (10) and (13), the change of the magnetic energy inside an area corresponding to the OR is given by

\[
\Delta W_B^{OR} = - \frac{c v_A B_0}{4\pi} G(t) \quad (14)
\]

4. Kinetic Energy Inside the OR

[14] Since the plasma with density \( \rho \) is accelerated to Alfvén speed \( v_A \), the kinetic energy of this plasma, which is captured inside the OR is given as

\[
W_k = \frac{1}{2} \rho v_A^2 \int_{OR} dV.
\]

With \( \rho = \frac{1}{4\pi} \frac{B_0^2}{v_A^2} \) from the definition of the Alfvén velocity, \( v_A = \frac{B_0}{\sqrt{4\pi \rho}} \), and the integral over the OR from equation (13), this yields

\[
W_k^{OR} = \frac{c v_A B_0}{4\pi} G(t). \quad (15)
\]  

Figure 3. Magnetic field lines configuration in an area of the OR’s shape (left) before and (right) after reconnection.

Figure 4. Volume of the outflow region per unit length of the reconnection line, which can be calculated by integrating over the OR, given by the function \( f \).
5. Magnetic Energy in the Inflow Region

Prior to a reconnection event, the magnetic energy density in the surrounding medium is given by \( B_0^2/8\pi \). Because of reconnection, the medium and hence the magnetic field gets disturbed, leading to a magnetic field \( B_1 \). The additional magnetic energy, which appears as a result of this disturbance in the medium, can be written as the difference of the magnetic energy after (related to \( B_1 \)) and before reconnection (related to \( B_0 \)),

\[
\Delta W_B = \int \left( \frac{B_1^2}{8\pi} - \frac{B_0^2}{8\pi} \right) dV. \tag{19}
\]

Inserting for \( B_1 \) from equation (2) and neglecting terms of \( O(1) \) and the change in the magnetic field from equation (21), the change in the magnetic energy can be obtained by equations (22) and (23). By measuring the magnetic field disturbances at level \( z = 0 \), the amount of magnetic energy in the area filled out by the outflow region, is completely generated out of magnetic energy. The loss of magnetic energy in the column above the outflow region can be expressed via \( 1/\pi \), since any error occurring out of this assumption is of the second order. Since the magnetic potential \( A \) is defined to be zero at infinity, this leads to

\[
\Delta W_B = \frac{B_0}{4\pi} \int \int B_1(1) dxdz. \tag{20}
\]

By introducing a vector potential \( A = (0, A, 0) \) of the form \( B = \nabla \times A \), the components of the magnetic field can be written in terms of \( A \),

\[
B_z^{(1)} = -\frac{\partial A}{\partial z}, \quad B_z^{(1)} = \frac{\partial A}{\partial x}. \tag{21}
\]

With this, the change in the magnetic energy can be displayed by the integral over a vector potential,

\[
\Delta W_B = -\frac{B_0}{4\pi} \int \int \frac{\partial A}{\partial z} dxdz, \quad \Delta W_B = \frac{B_0}{4\pi} \int \left( A|_{z=-\infty} - A|_{z=0} \right) dx.
\]

Within the frame of a thin boundary layer analysis, we can assume \( z_0 = 0 \), since any error occurring out of this assumption is of the second order. Since the magnetic potential \( A \) is defined to be zero at infinity, this leads to [see also study by Semenov et al., 1998b],

\[
\Delta W_B = \frac{B_0}{4\pi} \int A|_{z_0} dx, \tag{22}
\]

where \( A|_{z_0} \) can be expressed via \( B_z^{(1)}|_{z_0} \) from equation (21),

\[
A|_{z_0} = \int B_z^{(1)}|_{z_0} dx. \tag{23}
\]

Hence the disturbances \( B_z^{(1)} \), measured at the level \( z_0 \), give the change in the magnetic energy in a column \( z > z_0 \) by double integration of \( B_z^{(1)} \) and the change in the magnetic energy in the entire column can be calculated (see Figure 5).

5.1. Magnetic Potential

The result of the calculations for the change in the magnetic field energy inside the column above the outflow region depends on the level \( z \) from where the calculations start. To get the entire energy, it is necessary to choose \( z = z_0 \), where the level \( z_0 \) represents the boundary between the surrounding medium and the outflow region, defined by the shocks. Therefore we work with the boundary conditions appearing at the shock. For the magnetic field, this boundary condition in the unnormalized case in the first quadrant is given by [Semenov et al., 2004b; Kiehas et al., 2009].

\[
B_z^{(1)}|_{z_0} = \frac{c}{v_d} \left( 2E_r \left( t - \frac{x}{v_d} \right) - \frac{x}{v_d} E'_r \left( t - \frac{x}{v_d} \right) \right). \tag{24}
\]

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change in the magnetic energy in the area region $0 < x < x_i|\alpha=0$ is negative and in the region $x_i|\alpha=0 < x < 2$ positive for the same amount. Thus, for $t \gg T_0$, the amount of additional magnetic energy, i.e., the amount of magnetic energy redistribution in the region above the OR, is given by,

$$\Delta W_B^{\text{above OR}} = -\frac{c v_A B_0}{4\pi} x F(t - \frac{x}{v_A}).$$

If we compare the kinetic energy of the plasma inside the OR in the first quadrant (equation (17)) with the additional magnetic energy above it (equation (27)), we find

$$\frac{\Delta W_B^{\text{above OR}}}{W_k^{\text{OR Q1}}} = \frac{c v_A B_0}{4\pi} t F_0, \quad \frac{\Delta W_B^{\text{above OR}}}{W_k^{\text{OR Q1}}} = 2 W_k^{\text{OR Q1}}.$$  

The same is true for the other quadrants due to mirror symmetry with respect to the $x$ and $z$ axes (see Figure 8). This means that the reconnection process leads not only to a conversion of magnetic energy into kinetic plasma energy inside the OR, but also to a redistribution of magnetic energy in support of the region above and consequently also below the OR.

Inserting the potential at $z = z_0$ from equation (25) in equation (22), we find the change in the magnetic energy inside the inflow region as,

$$\Delta W_B^{\text{inside OR}} = -\frac{c B_0}{4\pi} x F\left(t - \frac{x}{v_A}\right).$$

shown in Figure 6c. It can be seen that the function decreases for $0 < x < x_i|\alpha=0$ and increases for $x_i|\alpha=0 < x < 2$. Since the increase compensates the decrease totally, the additional magnetic energy above it (equation (27)), we find

5.2. Magnetic Energy

Inserting this boundary condition in equation (23), the potential can be calculated at $z = z_0$,

$$A_{\text{inflow}} = c \left( \int 2E_x \left(t - \frac{x}{v_A}\right) dx - \int \frac{x}{v_A} E_z \left(t - \frac{x}{v_A}\right) dx \right).$$

With $E'_x(t - \frac{x}{v_A}) = \frac{\partial}{\partial x} (-v_A E_x(t - \frac{x}{v_A}))$, this reads

$$A_{\text{inflow}} = c \left( \int E_x \left(t - \frac{x}{v_A}\right) dx + x E_z \left(t - \frac{x}{v_A}\right) \right),$$

which gives, with $\int E_x \left(t - \frac{x}{v_A}\right) dx = -v_A F(t - x/v_A)$ from the definition of the reconnected flux,

$$A_{\text{inflow}} = c \left(-v_A F\left(t - \frac{x}{v_A}\right) + x E_z \left(t - \frac{x}{v_A}\right) \right).$$

5.2. Magnetic Energy

Inserting the potential at $z = z_0$ from equation (25) in equation (22), we find the change in the magnetic energy inside the inflow region as,

6. Summary and Conclusions

During the active phase of reconnection, the amount of reconnected flux increases rapidly with time and the outflow regions grow in both, $x$ and $z$ direction, leading to an increase of their volume. During this active phase of reconnection magnetic energy, which was stored in the current layer, gets converted into kinetic plasma energy, evident by the evolution of the outflow regions. Eventually,

Figure 6. (b) Calculations for the vector potential and (c) change of the magnetic energy in the inflow region for the boundary condition $B_z$ of the magnetic field at $z = 0$, shown in Figure 6a, together with the shape of the shock at time $t = 2$. The vertical dashed lines represent the onset and the end of the disturbance in $B_z$. 

With $E'_x(t - \frac{x}{v_A}) = \frac{\partial}{\partial x} (-v_A E_x(t - \frac{x}{v_A}))$, this reads

$$A_{\text{inflow}} = c \left( \int E_x \left(t - \frac{x}{v_A}\right) dx + x E_z \left(t - \frac{x}{v_A}\right) \right),$$

which gives, with $\int E_x \left(t - \frac{x}{v_A}\right) dx = -v_A F(t - x/v_A)$ from the definition of the reconnected flux,

$$A_{\text{inflow}} = c \left(-v_A F\left(t - \frac{x}{v_A}\right) + x E_z \left(t - \frac{x}{v_A}\right) \right).$$

5.2. Magnetic Energy

Inserting the potential at $z = z_0$ from equation (25) in equation (22), we find the change in the magnetic energy inside the inflow region as,

$$\Delta W_B^{\text{inside OR}} = -\frac{c B_0}{4\pi} x F\left(t - \frac{x}{v_A}\right).$$

shown in Figure 6c. It can be seen that the function decreases for $0 < x < x_i|\alpha=0$ and increases for $x_i|\alpha=0 < x < 2$. Since the increase compensates the decrease totally, the
the reconnection electric field ceases and the outflow regions detach from the initial reconnection site. In the course of the outflow regions propagation, the OR collects plasma, which is highly accelerated via the shocks and captured inside the OR. Hence the conversion of magnetic energy into kinetic plasma energy continues at the shocks after reconnection ceased and the outflow regions grow in \( z \) direction with the accumulation of plasma inside. The magnetic energy density inside the OR is decreased, and the kinetic energy of the plasma is increased for the same amount as the magnetic energy is reduced, as equation (18) shows. Thus the conversion of magnetic energy into kinetic energy of the plasma is evident.

[23] For the region outside the OR we find the following situation: Because of the reconfiguration of magnetic field lines, the magnetic field density in the wake of the outflow region is depleted, since magnetic field lines of this area are now connected via the shocks with field lines from the opposite side of the initial current sheet. By the propagation of the OR, these field lines are removed from the initial scenery in form of reconnected flux tubes. This rarefaction of the magnetic field density in the wake of the outflow region is reflected in the decrease of the magnetic field energy in Figure 6c for the area \( 0 < x < 1 \), corresponding to the wake of the OR. The magnetic energy further decreases until the point \( x_{j=0} \). In the region above the OR, the magnetic field density is increased, since the appearance of the outflow region leads to a compression of the magnetic field lines above the outflow region and reconnected field lines entering and leaving the OR are present. This situation is expressed by an increase in the magnetic field energy in Figure 6c for the area \( x_{j=0} < x < 2 \), corresponding to an area inside the TCR. It can be clearly seen that the decrease of the magnetic field energy in the wake and the increase of the magnetic field energy above the OR are evident.

**Figure 7.** Energy redistribution as a result of the reconnection process. In the wake, a reduction of the magnetic energy of the value of \( 2W_k \) appears. This decrease is compensated by an enhancement of the magnetic field energy above the OR. Inside the OR, the amount of kinetic energy corresponds to the amount of magnetic energy, which was present in an area of the OR’s size before the outflow region appeared.

**Figure 8.** Illustration of the magnetic field lines configuration due to reconnection. In the wake of the shocks, a rarefaction of the magnetic field lines appears. Above the shock, they are compressed, and inside the OR, the magnetic field lines density is reduced. The background color symbolizes the magnetic field strength. The field lines direction correspond to those in the Earth’s magnetotail.
magnetic energy above the OR compensate each other. With this, we can propose the following picture: The rarefaction of magnetic field lines in the wake of the OR, corresponding to a loss of magnetic energy, is compensated by a compression of field lines, i.e., an increase of magnetic energy, above the outflow region (see Figure 7). With the propagation of the outflow region this compression region of enhanced magnetic field energy above the OR also travels along the current sheet. In magnetotail observations, these regions are commonly denoted as “traveling compression regions”, or “TCRs” (see Figure 8). Hence we propose that TCRs act as transporter of magnetic energy, and the amount of this magnetic field energy is two times higher than the amount of kinetic plasma energy inside the plasma “bubble” beneath it, as reflected by equation (28).

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