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The Alfvén edge in asymmetric reconnection

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Abstract. We show that in the case of magnetic reconnection where the Alfvén velocity is much higher in the plasma on one side of the current sheet than the other, an Alfvén edge is formed. This edge is located between the electron and ion edges on the high Alfvén velocity side of the current sheet. The Alfvén edge forms because the Alfvén wave generated near the X-line will propagate faster than the accelerated ions forming the ion edge. We discuss possible generation mechanism and the polarization of the Alfvén wave in the case when higher Alfvén speed is due to larger magnetic field and smaller plasma density, as in the case of magnetopause reconnection. The Alfvén wave can be generated due to Hall dynamics near the X-line. The Alfvén wave pulse has a unipolar electric field and the parallel current will be such that the outer current on the high magnetic field side is flowing away from the X-line. Understanding Alfvén edges is important for understanding the separatrix regions at the boundaries of reconnection jets. We present an example of Alfvén edge observed by the Cluster spacecraft at the magnetopause.

Keywords. Magnetospheric physics (Magnetopause, cusp, and boundary layers) – Space plasma physics (Magnetic reconnection)

1 Introduction

Magnetic reconnection is an important process in plasma physics commonly occurring in regions where narrow current sheets form separating regions with different plasmas (Priest and Forbes, 2000). Properties of magnetic reconnection strongly depend on the parameters of plasma in the opposing plasma regions. In the fluid description, when there is a large difference in the Alfvén speed V_A, there forms a rotational discontinuity RD on the side of the current sheet with the lower Alfvén speed and a slow expansion wave on the opposite side (Levy et al., 1964). An example where conditions for reconnection in most cases involve large differences in V_A is the Earth's magnetopause. Here the magnetosheath (solar wind plasma compressed behind the Earth's bow shock) is reconnecting with the magnetic field of the Earth magnetosphere. Usually V_A is about 5 times larger in the Earth magnetosphere plasma than in the magnetosheath plasma. In general, we can expect reconnection between plasmas with very different V_A in many locations in the plasma universe.

In real plasmas the fluid description of the boundaries formed by reconnection most often brakes down, particularly where ion and electron kinetic effects become important. Taking into account kinetic effects, well defined ion and electron edges should form during magnetic reconnection as suggested by Gosling et al. (1990). These boundaries have been identified in space data and have been studied in detail (e.g., Bogdanova et al., 2006).

In this paper we demonstrate that during magnetic reconnection there will be an additional boundary, we call it the Alfvén edge, that is located between the ion and electron edges on the side of the current sheet where the Alfvén velocity is highest. The Alfvén edge is associated with strong electric fields and parallel currents. This region corresponds to the region where a slow expansion wave is expected in the fluid description. In asymmetric reconnection, the Alfvén edge can be an important part of the structure of the separatrix region.

2 Alfvén edge

First we schematically explain the formation of the Alfvén edge. Figure 1 illustrates boundaries formed when reconnection occurs between two plasmas with different Alfvén velocity. Only the region to the right from the X-line is included. The Alfvén velocity V_A^{high} is higher than V_A^{low} due to

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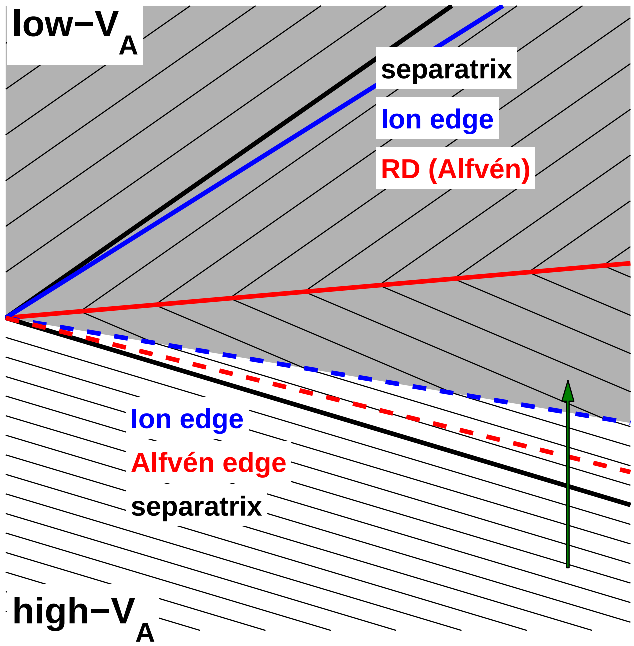

Fig. 1. Sketch of the main boundaries in reconnection when the Alfvén velocity within one of the reconnecting regions is higher than in the other. All the angles are magnified by about a factor of four to better illustrate the different boundaries. Plasma parameters are typical for reconnection at the Earth magnetopause. Electrons move much faster than ions and therefore their edges are very close to the separatrices and we do not show them explicitly. The green arrow illustrates how a spacecraft is crossing the boundaries in the observational example shown in Fig. 3. Plasma parameters are: $V_A^{high} = 5\,V_A^{low}$, $B^{high} = 2\,B^{low}$. Thermal velocity of ions on the high-V_A side is assumed to be $V_t^{high} = 10\,V_A^{low}$. The shaded area shows the region that is dominated by low-V_A side plasma.

higher magnetic field and lower plasma density in the high-V_A region. This is a typical situation for the Earth magnetopause. Inside the Earth magnetosphere the magnetic field is typically higher, the plasma density is lower. In such a situation in the fluid description a RD is expected to form in the low-V_A region plasma and the slow expansion wave on the high-V_A side of the current sheet (Levy et al., 1964). In the kinetic description we expect the formation of ion and electron edges on both sides of the current sheet (Gosling et al., 1990). Due to the large velocity of electrons, electron edge is located very close to the separatrix, and in Fig. 1 we indicate only separatrices (bold black lines).

When we follow one of the magnetic flux tubes, then the kink in RD will move with $\sim V_A^{low}$ away from the X-line. The low-V_A region plasma, when moving across RD, will be accelerated to a velocity that is $\sim 2\,V_A^{low}$ and form a plasma jet on the high-V_A side of the current sheet (RD). There will be an ion edge, dashed blue line in Fig. 1, where the fastest ions appear on the high-V_A side. There will be a similar ion edge also on the low-V_A side, solid blue line in Fig. 1. The location of ion edges depends on the thermal speed V_t of plasmas. In Fig. 1 we assume that $V_t^{low} < 2\,V_A^{low}$ and $V_t^{high} > 2\,V_A^{low}$ which is common at the Earth magnetopause. In this case the ion edge on the low-V_A side is located closer to the separatrix than on the high-V_A side.

For $V_A^{high} > 2\,V_A^{low}$ we will have a situation where the Alfvén wave in the high-V_A region propagates faster than accelerated ions from the low-V_A side forming the ion edge on the high-V_A side. Then there can form an Alfvén edge located between the ion and electron edges (separatrix) on the high-V_A side (normally V_A^{high} will be slower than the electron speed). This is illustrated in Fig. 1 where $V_A^{high} = 5\,V_A^{low}$ and the Alfvén edge has been marked by a red dashed line.

The Alfvén edge is located in a similar place as the slow expansion wave in the fluid picture. The difference is that the slow expansion wave takes care of matching boundary conditions between the outflow region and the high-V_A region, while the Alfvén edge can be an independent region where Alfvén waves generated at the X-line propagate away from the X-line. Note also, that any physical processes generating Alvén waves along the ion edge on the high-V_A side will create Alfvén waves that can propagate into the region between the Alfvén edge and the ion edge. Next we discuss one of possible mechanisms generating Alfvén waves near the X-line.

3 Alfvén wave generation

Possible way of generating the Alfvén wave can be seen when analyzing the region around the X-line (also called the diffusion region) in the two-fluid description where Hall effects appear. We limit ourself to antiparallel case and the mechanism is similar to the description of magnetic out-of-plane component generation in symmetric reconnection without guide-field (Mandt et al., 1994). The mechanism is illustrated in Fig. 2. Since the magnetic field is stronger on the high-V_A side, there will be a region on that side where the magnetic field amplitude decreases at least to values corresponding to V_A^{low} without significant changes in the direction. In this region there will be current in the out-of-plane direction as shown in Fig. 2. This current we expect to flow in a narrow layer, since numerical simulations indicate that currents near the X-line tend to flow in layer that is thinner than a typical ion scale. In such a thin layer ions are mainly unmagnetized and therefore the current will be carried by $\boldsymbol{E} \times \boldsymbol{B}$ drift of electrons. This requires the formation of an electric field normal to the current sheet, shown with green arrows in Fig. 2. The magnetic field lines entering this $\boldsymbol{E} \times \boldsymbol{B}$ drift region from the high-V_A side will move in the out-of-plane direction while the same field lines further away from the X-line are still undisturbed. This leads to the formation of the out-of-plane magnetic field component

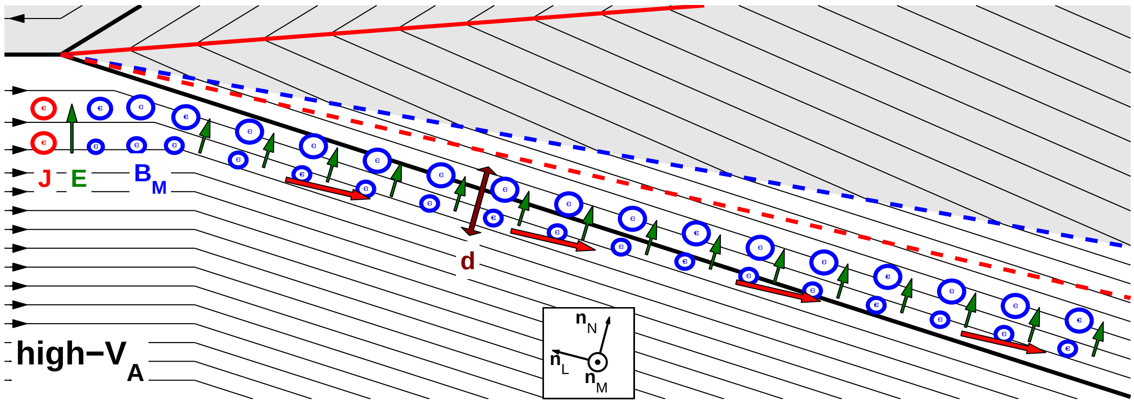

Fig. 2. Sketch showing the generation of an Alfvén wave. The mechanism is described in the text.

$\boldsymbol{B}_{\mathrm{M}}$ as shown in Fig. 2. The $\boldsymbol{B}_{\mathrm{M}}$ disturbance is in the direction of $\boldsymbol{n}_{\mathrm{N}} \times \boldsymbol{n}_{\mathrm{L}}$, where $\boldsymbol{n}_{\mathrm{N}}$ is normal to current sheet and $\boldsymbol{n}_{\mathrm{L}}$ points towards X-line as shown in Fig. 2. This is also consistent with Poynting flux $\boldsymbol{E}_{\mathrm{N}} \times \boldsymbol{B}_{\mathrm{M}}/\mu_{\circ}$ flowing away from the X-line. It is important to notice that the given polarization of $\boldsymbol{E}_{\mathrm{N}}$ and $\boldsymbol{B}_{\mathrm{M}}$ corresponds to the generation of an Alfvén wave propagating away from the X-line. Because the $\boldsymbol{E}_{\mathrm{N}}$ and $\boldsymbol{B}_{\mathrm{M}}$ are generated in a layer with perpendicular scale d smaller than the characteristic ion scale it will be a kinetic Alfvén wave. Therefore its damping and dispersion properties will strongly depend on plasma parameters. Associated to $\boldsymbol{B}_{\mathrm{M}}$ there will be also field-aligned currents such that the first current observed when going from high-V_{A} side towards low-V_{A} side will be flowing away from the X-line (Fig. 2), corresponding to electrons moving towards the X-line. The propagation at Alfvén velocity implies that the Alfvén wave will propagate along the direction parallel to the Alfvén edge (assuming zero perpendicular group velocity of the wave).

To our knowledge there is no direct identification of the Alfvén edge in numerical simulations. However, taking a look on the existing publications of numerical simulations we can identify regions reminiscent of the Alfén edge. For example, in a simulation of asymmetric reconnection by Pritchett (2008) magnetic fields, electric fields and currents on the high-V_{A} side are similar to the ones described here. However, the size of the simulation box was too small to identify the behaviour of this wave further away from the X-line, so that the ion, Alfvén and electron edges can be clearly separated. Similar results were found in the simulation by Tanaka et al. (2008). More simulations are necessary to clearly identify the Alfvén edge.

4 In situ example

To our knowledge, the Alfvén edge has not been identified in in situ measurements, even though it has been shown that drift-kinetic Alfvén waves are propagating away from the X-line (Chaston et al., 2005). Here we present one example where the data indicate the presence of an Alfvén edge. The example shown in Fig. 3 is from a reconnection event close to the subsolar point in the Earth magnetosphere, observed by the Cluster spacecraft (Escoubet et al., 1997). The effect by cold (eV) plasma on reconnection during this event is studied by André et al. (2010). Cluster spacecraft C3 and C4 are located 30 km away from each other. During the crossing of the boundaries on the magnetospheric side, Fig. 2, the local normal to such boundaries is estimated by using the minimum variance analysis and the velocity in the normal direction is estimated by using the timing of magnetic field structure passing both C3 and C4. In this way the spatial scale of the boundaries, marked on the top in Fig. 3, can be estimated. Figure 3a shows the magnetic field, Fig. 3b the measurements of $\boldsymbol{E}_{\mathrm{N}}$ on C4. Note that before ∼23:12:15 UT the electric field measurements are contaminated by cold ion wakes. However, $\boldsymbol{E}_{\mathrm{N}}$ derived as $-\boldsymbol{v} \times \boldsymbol{B}$ is close to zero (dots), where $\boldsymbol{v}$ is the plasma velocity. The current in Fig. 3c is estimated based on the single spacecraft technique. For this event, the current flowing parallel to the ambient magnetic field is flowing away from the X-line. The plasma density is estimated from the satellite potential (Pedersen et al., 2001). Finally, Fig. 3e, f show the electron spectrograms for the instrument sectors closest to the directions away and towards the X-line along the ambient magnetic field. Red dots indicate time intervals when the measuring instrument sectors are aligned with the magnetic field.

During this event the spacecraft cross the three boundaries on the high-V_{A} side (magnetospheric side) of the current sheet in this order: separatrix, Alfvén edge and ion edge. The approximate location of the boundaries is marked by shaded intervals (gray – separatrix, pink – Alfvén edge, blue – ion edge). We have identified the separatrix as the boundary where high energy electrons (electrons of high-V_{A} side with energies more than 1 keV) moving away from the X-line disappear, as seen in Fig. 3e (Khotyaintsev et al., 2006).

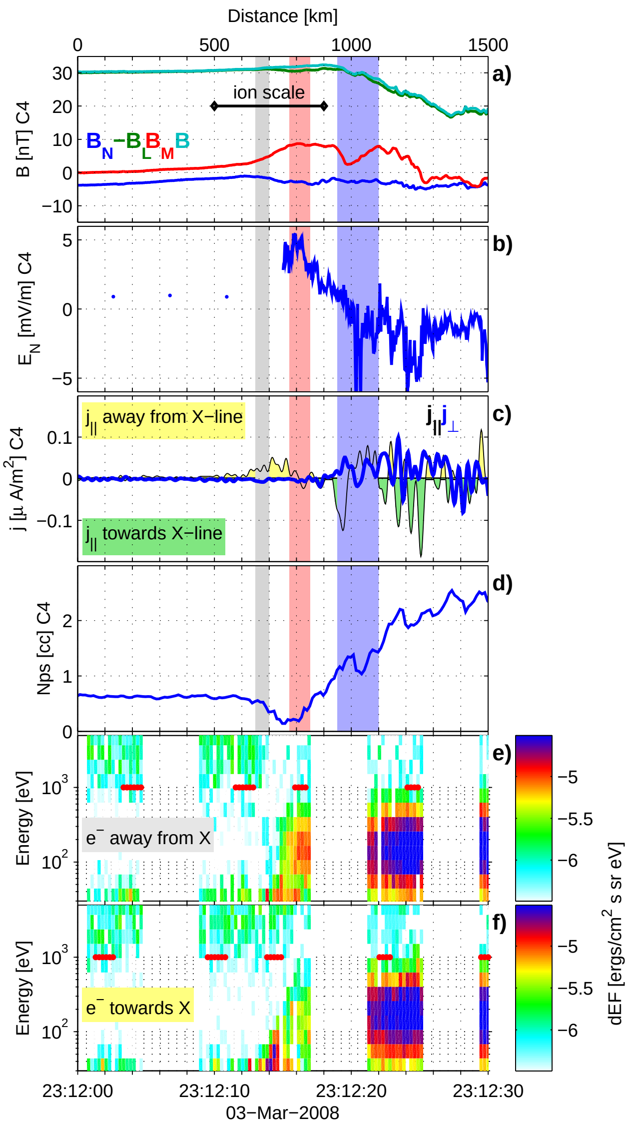

Fig. 3. Cluster C4 observations of a crossing of boundaries on the magnetospheric side during reconnection at the magnetopause. Boundaries are color marked as separatrix (gray), Alfvén edge (pink) and ion edge (blue). Panels show: **(a)** magnetic field, **(b)** electric field, before 23:12:14 UT the electric field is contaminated due to the presence of cold magnetospheric ions, but electric field values shown (dots) are the ones inferred from ion velocity, **(c)** parallel and perpendicular currents, **(d)** plasma density derived from the satellite potential, **(e)** electron energy spectrogram of electrons moving parallel to magnetic field (away from X-line), **(f)** electron energy spectrogram of electrons moving antiparallel to the magnetic field. On magnetospheric side ion inertial length is ∼360 km and gyroradius of hot 10 keV ions is ∼480 km. On the magnetosheath side of boundaries the inertial length is ∼130 km and gyroradius for magnetosheath ∼1 keV ions is ∼230 km.

On these field lines there are still high energy electrons moving towards the X-line, Fig. 3f, and therefore the spacecraft are crossing the first open field lines. At the separatrix, the first magnetosheath (low-V_A side) electrons having energies around a few hundred eV and moving away from the X-line also appear, see Fig. 3e. We identify the Alfvén edge as the region with the strongest $\boldsymbol{E}_N$ and $\boldsymbol{B}_M$ disturbance. $\boldsymbol{E}_N$ and $\boldsymbol{B}_M$ disturbance directions are consistent with the sketch in Fig. 2. The ratio $\boldsymbol{E}_N/\boldsymbol{B}_M \sim 600$ km/s which is close to $V_A^{high} \sim 1000$ km/s. Also the parallel current that is first observed is in the direction away from the X-line, consistent with the sketch in Fig. 2. It is difficult to estimate the exact perpendicular size of the Alfvén wave from the data, but approximately it is of the order of a few hundred km, which is less than the ion inertial length and the gyroradius of the hot magnetospheric (high-V_A side) ion population. The parallel current flowing away from the X-line in this case seems to be carried by cold ionospheric electrons that have been accelerated towards the X-line, as one can see in Fig. 3f at energies below 100 eV during the time of the peak of the parallel current. There are no ion measurements shown in Fig. 3, but the presence of the ion edge can be identified as the increase in plasma density which is due to the appearance of low-V_A side (magnetosheath) ions. When the density increase is significant it implies that the bulk of accelerated magnetosheath ions have reached the spacecraft and we can identify it as the ion edge. The appearance of magnetosheath ions leads to increased plasma thermal pressure and therefore the magnetic field amplitude is decreasing to keep the total pressure constant. In summary, we show that our observations are consistent with the sketch presented in Fig. 2 and that the Alfvén edge may be identified in the data.

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