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Some comments on transient and steady-state reconnection at the dayside magnetopause

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Abstract. Reconnection at the dayside magnetopause is the principal method by which energy is transferred from the solar wind into the magnetosphere-ionosphere system. There is still considerable uncertainty as to whether reconnection is transient or quasi-steady. Here we discuss some of the implications of assuming that reconnection occurring in regions where the magnetosheath flow is super-Alfvénic must be transient. We use a simple magnetospheric model to illustrate where on the magnetopause transient reconnection is most likely to occur, and show that the location of these regions is dependent critically upon the dipole tilt angle and the interplanetary magnetic field orientation. Although our idealised examples do not take into account temporal variations of the solar wind conditions, or the influence of the bow shock or magnetosheath, we believe that they demonstrate interesting features. For example, the results suggest that reconnection for northward IMF is almost always likely to be transient.

1. Introduction

The concept of reconnection on the dayside magnetopause, introduced by *Dungey* [1961], has proved to be one of the most significant steps forward in understanding how the solar wind energy enters the coupled magnetosphere-ionosphere system, and is thereafter distributed through it. Since 1961, much additional detail has been added to the initial concept. For example, *Siscoe and Huang* [1985] introduced the expanding and contracting polar cap model, more explicitly expressed by *Cowley and Lockwood* [1992]. Also there has been a plethora of observations of energetic particles and plasma velocity measurements (see *Smith and Lockwood* [1996], and *Ruohoniemi and Greenwald* [1996] for recent summaries) that are entirely consistent with the tenet of dayside reconnection.

Over the last two decades, there has been a debate as to whether dayside reconnection is quasi- steady state or transient (See *Newell and Sibeck* [1993]; *Lockwood et al.* [1994] and the references therein), although the simultaneous occurrence of quasi-steady state and transient reconnection is not uncommon [*Berchem and Russell*, 1984].

One approach to solving these outstanding and important questions is through modelling the reconnection process itself. In this paper, we adopt a different approach. Our tenet is that reconnection cannot be steady in regions where the magnetosheath flow is super-Alfvénic, a hypothesis that we justify in the next section of the paper. We then illustrate where transient reconnection on the dayside magnetopause is likely to occur using a simple model, and finally discuss some of the consequences of our findings in the context of recent observations.

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2. Background

In an active reconnection site, conservation of flux and energy must be satisfied. These conditions can only be achieved if the plasma motion is sub-Alfvénic in the rest frame of the active x-line [*La Belle-Hamer et al.*, 1995].Considering the dayside magnetopause, reconnection should occur primarily in the region where the magnetosheath flow is sub-Alfvénic. However reconnection can also occur where the plasma is super-Alfvénic, provided that the x-line is moving tailwards with speeds comparable to the magnetosheath flow. In other words, the plasma flow in the rest frame of the active x-line is sub-Alfvénic. However we suggest that this condition can never be quasi-steady as the reconnection site is drifting tailwards and thereby encountering very different plasma concentrations, velocity shears and magnetic field strengths [*La Belle-Hamer et al.*, 1995]. Therefore the conditions for reconnection to continue are unlikely to be satisfied for long, perhaps of the order of a few minutes. We conclude that reconnection in the super-Alfvénic regime must be transient.

In the idealised regime considered here, reconnection may be steady in regions where the plasma flow is sub-Alfvénic. Of course in practice, this may not be the case because the stability of the incoming solar wind and interplanetary magnetic field, as modified by the transfer functions of the bow shock and the magnetosheath will be continuing to change the conditions for reconnection. These variations are likely to mean than the reconnection rate within the sub-Alfvénic regime may be transient.

3. The model

We now investigate the locations on the magnetopause where the reconnection is likely to occur and determine where the magnetosheath flow speeds exceed the Alfvén speed using a comparatively simple model.

There are three main components to the model: magnetosheath draping, the conditions for reconnection to occur, and the magnetospheric magnetic field. For the sake of simplicity, we have used the perfect draping approximation: that is the magnetosheath field is everywhere tangential to the magnetopause. This form of draping preserves the clock angle of each field line. This is a good approximation on the dayside, becoming less realistic further towards the tail [*Crooker et al.*, 1985].

We adopt the antiparallel merging hypothesis: reconnection occurs on those regions where the magnetosheath

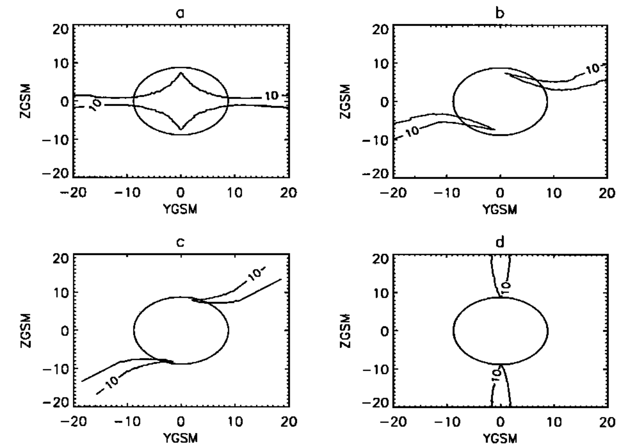

Figure 1. The irregular contours show the region where the anti-parallel reconnection condition is met - see text for details - for 1100 UT on 21 March for four clock angles of the IMF (a) 180° (purely southward), (b)135°, (c) 90°, and (d) 0°. The smooth ellipse represents the boundary between sub-Alfvénic (inside) and super-Alfvénic flow (outside).

and magnetosphere field are oppositely directed [*Crooker*, 1979]. We assume that reconnection occurs when the fields are < 10° of being antiparallel, the same condition as used by *Luhmann et al.* [1984]. We have tested our results to this assumption and found them to be insensitive to the precise angle chosen provided that it is within about ±20° of being anti-parallel.

Finally, we use the Tsyganenko 96 magnetospheric field model [*Tysganenko*, 1995].

Our methodology is to specify the solar wind conditions (B_x, B_y, B_z, dynamical pressure), D_{st} and the epoch (year, day and UT). These are the input parameters required by the Tsyganenko 96 model. Then we discretise a region on the magnetopause from the sub-solar point to approximately 25 R_e tailward of Earth. The results shown in this paper use a grid of 10000 points. At each point on this grid, we calculate the angle between the magnetosheath and magnetospheric field. Where the reconnection criterion is fulfilled (i.e. within 10° of anti-parallel), we regard the grid point as within the reconnection region. For the examples presented later, we use two epochs: the March equinox at 1100 UT and the June solstice at 1700 UT. These seasons and times have been selected to be representative of the minimum and maximum dipole tilt. We shall see from the results section that the dipole tilt plays an important role in determining the extent of region likely to observe transient reconnection. We have chosen a dynamical pressure of 2.5 nPa and a D_{st} of -20 nT, typical values of these parameters.

The location of the Alfvénic boundary depends mainly upon the velocity of the solar wind. We have adapted the approach of *Cowley and Owen* [1989], who calculated that this boundary would lie at a distance of 6.8 R_e along the magnetopause from the subsolar point, based on a typical solar wind velocity of 500 kms^{-1}. Ignoring the curvature of the magnetopause between the subsolar point and the terminator, the x-coordinate x_a of the Alfvénic boundary in the GSM system is

$$x_a = r_s(1 - r_a/\sqrt{(r_s^2 + r_d^2)})$$

where r_s is the subsolar stand-off distance of the magnetopause, r_d is the radius of the dawn-dusk cross-section and r_a is the distance along the magnetopause between the subsolar point and the Alfvénic boundary. Our input parameters give $r_s = 10.3\ R_e$ and $r_d = 13.6\ R_e$. Using the Cowley & Owen value for r_a ($r_a = 6.8\ R_e$) gives $x_a = 6.2\ R_e$.

4. Results

Figure 1 shows four panels each for 1100 UT on 21 March for four different orientations of the IMF. They are (a) purely southward, (b) $B_y = -B_z$ (i.e. clock angle of 135° , (c) clock angle of 90° (i.e. purely zonal IMF), and (d) northward IMF. On each panel, there are two features shown. The smooth ellipse represents the boundary between sub-Alfvénic (inside) and super-Alfvénic flow (outside). The second contour shows the region where the anti-parallel reconnection condition, as defined above, is met.

For southward IMF conditions, (Figure 1a), the vast majority of the reconnection region lies within the sub-Alfvénic regime. There are two 'horns' in the super-Alfvénic regime that map to the flanks of the magnetopause (i.e. where Y GSM exceeds 8 R_e). It is within these horns that we expect transient reconnection will occur, whereas within the ellipse, quasi-steady state reconnection will occur, noting the caveat described at the end of section 2 concerning the time-dependence of the IMF and solar wind.

For the clock angle of 135° (Figure 1b), there are two discrete regions where the anti-parallel condition is satisfied. These regions are displaced from the sub-solar point, and about half their area is within the sub-Alfvénic region. Therefore the balance between quasi-steady state and transient reconnection has moved in the direction of the latter.

As the clock angle rotates further away from southward, the area where quasi-steady reconnection reduces in size and migrates to higher latitudes on the magnetopause as shown in Figure 1c for a clock angle of 90° . Here, only a small proportion of the reconnection region lies within the sub-Alfvénic regime, severely limiting the possibility of quasi-steady reconnection. For northward IMF (Figure 1d) virtually all the entire reconnection region lies outside the ellipse, implying that all reconnection for this IMF orientation will be transient.

Figure 2 shows the same set of clock angles as Figure 1, but for 1700 UT on 21 June when the dipole tilt is maximum. The main effect of the dipole tilt is to move all the reconnection regions southward. In the case of purely southward IMF (Figure 2a), the bulk of this antiparallel region is still within the sub-Alfvénic ellipse but displaced by 5 R_e from the equator. In Figure 2b & c (clock angles 135° and 90°), the reconnection sites on the dusk side are shifted down towards the equator, with significant areas lying within the sub-Alfvénic regime where quasi-steady reconnection can occur. By contrast, only transient reconnection can take place on the dawn side, as this entire reconnection region has been moved into the super-Alfvénic flow regime. For northward IMF, the northern reconnection site is moved partly within the sub-Alfvénic region, allowing the possibility of quasi-steady reconnection, while the southern merging site is displaced even further into the super-Alfvénic region, where only transient reconnection can take place. These effects will be in the opposite sense at the December solstice.

5. Discussion

When the IMF is southward both transient reconnection and quasi-steady is expected (Figure 1a), the former occurring on the flanks of the magnetosphere and the latter seen near the sub-solar point. As the clock angle rotates away from 180° , the ratio of transient to quasi-steady reconnection increases. Typically the IMF has a y-component of ±3 nT (see *Leonard et al.* [1995], for example), and the total field strength is about 5 nT, thus the clock angle is usually well away from 180°. Therefore a significant proportion of the area where the reconnection condition is satisfied will be in the super-Alfvénic region. Thus we might expect that there is almost always going to be a contribution to the total reconnection electric field from transient reconnection. Radar observations of the ionospheric effects of reconnection support this view, in that they often show quasi-steady flow across the open-closed field line boundary of several hundred ms^{-1}, with short-lived increases rising to twice the 'DC' flow [e.g. *Baker et al.*, 1997; *Pinnock et al.*, 1999].

For low values of dipole tilt angle there is a high degree of symmetry between the reconnection sites in both hemispheres but, when the dipole tilt is large, significant differences between northern and southern reconnection sites may be present (e.g figures 2b & c).

The most comprehensive analysis of the occurrence of transient reconnection (flux transfer events, FTEs) near the magnetopause has been carried out by *Kawano and Russell*, [1996, 1997 *a&b*]. They confirmed the results of *Berchem and Russell* [1984] that FTEs are almost equally likely to occur at any magnetic local time dependence from 0400 to 2000 MLT. These authors detail the occurrence of FTEs as a function of B_z, and their motion as function of IMF B_y. However our results suggest that the occurrence of FTEs will be dependent on both B_y and B_z simultaneously. Consequently their analysis needs to be extended to test the hypotheses put forward in this paper by re-ordering the FTE occurrence as a function both of clock angle and dipole tilt. *Berchem and Russell* [1984] find that there is a minimum in occurrence of FTEs in the sub-solar region which is consistent with our hypothesis. However such a conclusion must be treated with considerable caution because the sampling of the magnetopause was normally within a few R_e of the equator and only between June and December, and hence may be biased.

As the ionospheric image of FTEs is now reasonably well described and understood [e.g., *Pinnock et al.*, 1993; 1995; *Proven et al.*, 1998], and because the SuperDARN radars [*Greenwald et al.*, 1995] have good global coverage and large fields of view, it should be possible to use their data to test the ideas put forward here. For example contrasting the FTE occurrence in the morning and afternoon simultaneously for the IMF and dipole tilt conditions shown in figure 2b&c would be most revealing. Such a study would have to take account of the dependence of the location of ionospheric signatures upon IMF B_y [*Cowley et al.*, 1991], and of the fact that a small displacement in the ionosphere can map to a large displacement on the magnetopause flanks. Hence it may be difficult to determine whether the ionospheric region maps to the sub- or super- Alfvénic region on the magnetopause (see *Crooker and Siscoe* [1990], for example). Finally the transfer functions of the bow shock and the magnetosheath are not known accurately, and this limits accurate modelling of the IMF impinging upon the magnetopause.

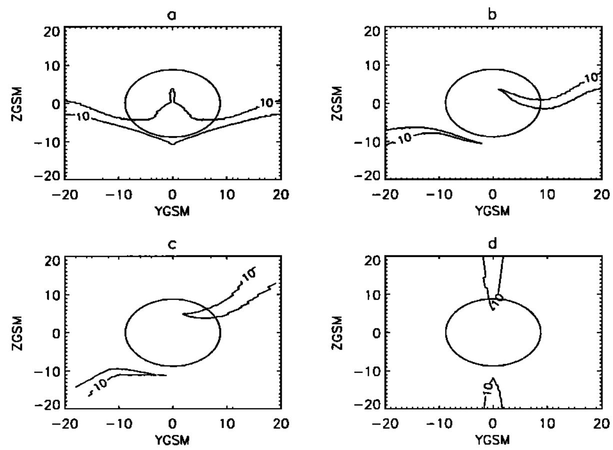

Figure 2. Same as figure 1, but for 1700 UT on 21 June when the dipole tilt is at a maximum.

In this paper, we have assumed several idealised conditions. For example, perfect draping, and steady IMF and solar wind plasma pressure. Neither occurs in practice, except perhaps during the passage of some parts of a solar wind magnetic cloud. Temporal variations in the solar wind, and IMF will contribute to the occurrence of transient reconnection events, indeed even internal magnetospheric process may contribute to transient reconnection [*Rodger*, 1998]. Also we have not considered over-draped open field lines [e.g., *Crooker et al.*, 1998]. Therefore in practice, the balance between quasi-steady state and transient reconnection will be dependent upon the tenet of this paper convolved with the detailed temporal variations of the IMF, the solar wind, motion of reconnected flux tubes and internal magnetospheric processes.

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