DISTINGUISHING BETWEEN ANTI-PARALLEL AND COMPONENT RECONNECTION AT THE DAYSIDE MAGNETOPAUSE

K.J. Trattner(1), J. Mulcock(1), S.M. Petrinec(1) and S.A. Fuselier(1)

(1)Lockheed Martin ATC, 3251 Hanover Str. ADCS, B255, Palo Alto, CA 94304-1191, USA, Email: Trattner@spasci.com

ABSTRACT

Full 3D plasma observations in the cusp observed by the Cluster and Polar satellites in the northern and southern hemispheres are used to track the location of the reconnection line at the magnetopause during southward interplanetary magnetic field conditions. The low-velocity cutoffs in the flux measurements of the precipitating and the mirrored magnetosheath population on open cusp field lines are used to estimate the distance of the observing satellite from the reconnection line. The calculated distance is subsequently traced back along model magnetic field lines to the magnetopause where the shear angle between the geomagnetic field and the draped interplanetary magnetic field is calculated.
A series of cusp crossings during clock angles <200° revealed that magnetic reconnection favors anti-parallel reconnection within ±20° to 30° of the south direction. For smaller clock angles the reconnection site switches to a tilted X-line which crosses the component reconnection site in the sub-solar region.

1. INTRODUCTION

Understanding the processes of magnetic reconnection is of fundamental importance for solar atmospheric and heliospheric processes, solar wind-magnetosphere and magnetosphere-ionosphere coupling. In magnetic reconnection, magnetic fields from different topologies interconnect to create open magnetic field lines that allow energy and momentum to flow from the magnetosheath into the magnetosphere.

After decades of research there is incontrovertible evidence that magnetic reconnection occurs at the Earth's magnetopause both when the interplanetary magnetic field (IMF) is southward [e.g., 1, 2, 3] and when it is northward [e.g. 4, 5, 6].

A major outstanding question about magnetic reconnection is where reconnection will occur at the magnetopause for specific IMF conditions. There are two scenarios discussed in the literature: a) anti-parallel reconnection, which occurs where the magnetospheric field and the IMF are anti-parallel (shear angle of approximately 180°) and b) component reconnection, where shear angles between the magnetospheric field and the IMF as low as 50° [7] have been reported. Both scenarios have a profound impact on the character of the reconnection X-line and plasma transfer into the magnetosphere.

The anti-parallel reconnection sites for northward IMF conditions are relatively small regions poleward of the cusps at high latitudes. Recent studies during northward IMF conditions with particle detectors on Polar have revealed the existence of very long reconnection lines [8, 9] which led to the conclusion that both scenarios, anti-parallel and component reconnection, occur simultaneously.

The anti-parallel reconnection site for strictly southward IMF conditions covers the entire dayside magnetosphere along the magnetic equator. When a strong B_y component is present, the anti-parallel reconnection site splits, producing two separate reconnection lines in different hemispheres [e.g., 10]. Alternatively, the component reconnection tilted X-line model for southward IMF conditions predicts that a neutral line runs across the dayside magnetosphere through the sub-solar point, regardless of the magnitude of the B_y component [11]. The magnitude of the B_y component only determines the tilt of the X-line relative to the equatorial plane.

Reference [12] used observations by the IMAGE/FUV instrument to demonstrate that precipitating ions within a specific energy range on open magnetic field lines in the cusp will produce ionospheric emissions that are either associated with the anti-parallel or the component reconnection scenario. While there is a continuous ionospheric precipitation response at the magnetic foot points across the entire day side for the tilted X-line model, there is a gap in the ionospheric response across local noon for the anti-parallel reconnection model that can be used to determine which scenario is most appropriate.

Reference [13] used a double-cusp signature observed by the Cluster satellites to determine the location of the reconnection sites. 3D ion observations were used to calculate the distance to the reconnection line for two ion-energy dispersions observed during a Cluster cusp crossing, which were subsequently traced back to the magnetopause along geomagnetic field lines. Two separate reconnection sites in different hemispheres, in agreement with the anti-parallel reconnection model,

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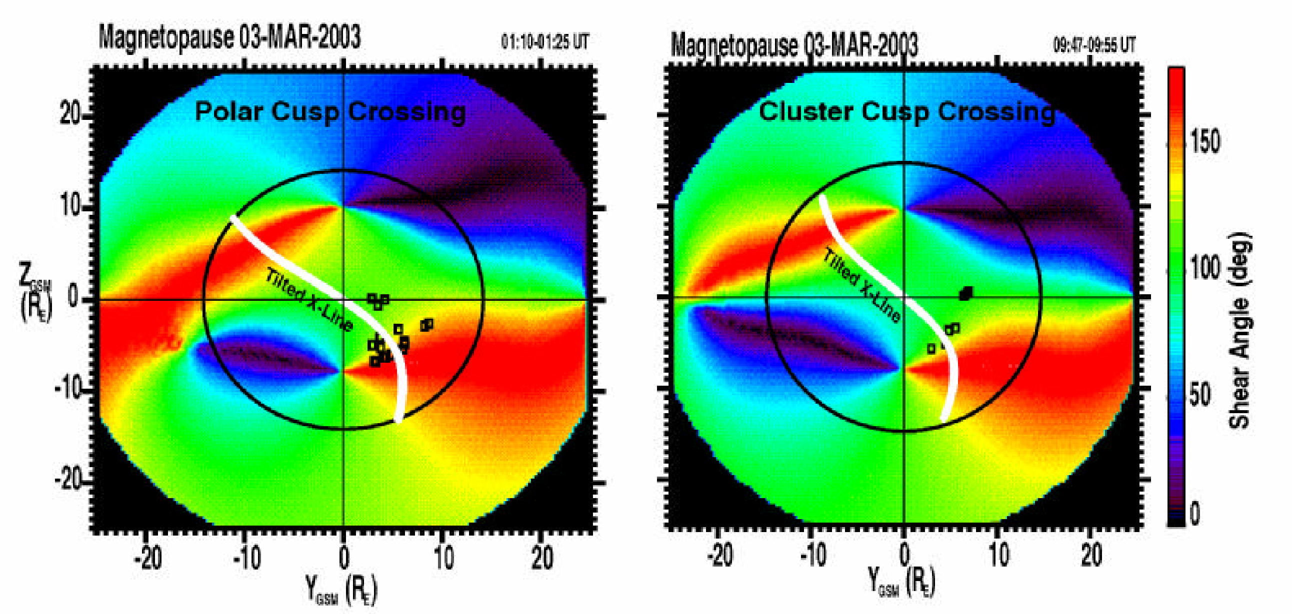

Figure 1: The magnetic field shear angle at the magnetopause as seen from the Sun, calculated from the magnetic field direction of the T96 model and the draped IMF conditions [17] during a southern Polar (left) and northern Cluster (right) cusp crossings on March 3, 2003. Square symbols represent the locations of the reconnection line at the magnetopause. The locations were determined by tracing the calculated distances to the reconnection line back to the magnetopause, along the geomagnetic field line in the T96 model, starting at the position of the satellites in the magnetosphere.

were determined for the two cusp structures observed by Cluster.

By using observations of the ion composition instruments on-board the Cluster and Polar satellites in conjunction with observations by the IMAGE/FUV instrument, we are in the unique position to systematically map out the location of the reconnection line for various solar wind and IMF conditions [e.g., 12, 13].

It is the goal of this study to distinguish between anti-parallel and component reconnection for southward IMF conditions, and thereby making a critical step in understanding the fundamental properties of reconnection.

2. OBSERVATIONS

It is possible to estimate the distance to the reconnection line by using the low-velocity cutoffs of the precipitating and mirrored magnetosheath populations in the cusp together with a time-of-flight model [e.g., 14] and the Tsyganenko 1996 (T96) semi-empirical magnetospheric field model [15]. The distance to the reconnection line X_r is defined by:

$$X_r / X_m = 2 V_e / (V_m - V_e)$$

Where X_m is the distance to the ionospheric mirror point, V_e is the cutoff velocity of the precipitating (earthward propagating) ions, and V_m is the cutoff velocity of the mirrored distribution. X_m is determined by using the position of the satellite in the cusp and tracing the geomagnetic field line at this position down to the ionosphere by using the T96 model. The resulting distance is subsequently traced back to the magnetopause using again the T96 model.

An example of such a trace is shown in Figure 1. Plotted are the magnetopause shear angles for the March 3, 2003 cusp crossings by the Polar (left) and the Cluster (right) spacecraft, as seen from the Sun. Square symbols in the shear-angle plots show the location of a section of the reconnection line at the magnetopause. The black circle represents the location were the terminator plane crosses the magnetopause with the dayside magnetopause inside the circle and the tailside magnetopause outside the circle.

The magnetopause shear angle is calculated from the magnetospheric field directions and the IMF field directions at the magnetopause. The magnetospheric field directions across the magnetopause were determined using the T96 magnetic field model at the magnetopause location by [16] for the solar wind conditions observed during the cusp crossings. The IMF used to calculate the magnetopause shear angle was

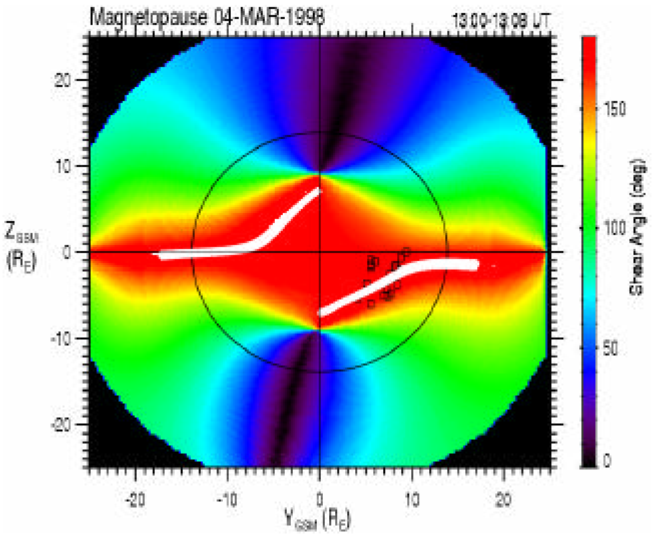

Figure 2: The magnetopause shear angle for the March 4, 1998, cusp crossing as seen from the sun. The locations of the field line traces indicate an anti-parallel reconnection event.

draped around the magnetopause using the analytical model by [17] that is based on the model by [18].

Red regions represent anti-parallel magnetic field regions at the magnetopause while black regions represent parallel magnetic field conditions. The Polar and Cluster cusp crossings are more than eight hours apart in time and occurred in different hemispheres with Polar in the southern cusp and Cluster in the northern cusp. However, both cusp crossings occurred during similar IMF clock angles (about 255°), which results in almost identical shear angle plots.

The location of the reconnection line derived from the Polar crossing of the southern cusp is in the southern hemisphere close to the anti-parallel reconnection region. The location of the reconnection line derived from the Cluster crossing of the northern cusp is also in the southern hemisphere at about the same location as the Polar trace result. That demonstrates the accuracy of the low-velocity cutoff method to deliver consistent results in revealing the location of the reconnection line at the magnetopause.

Despite the proximity to the anti-parallel reconnection region, the location of the trace points on the magnetopause with an extension towards the equatorial region lead to the conclusion that these events are in agreement with a tilted X-line [11] which is also shown in Figure 1 as a white line [19].

Figure 2 shows the magnetopause shear angle for a Polar cusp crossing over the northern hemisphere on March 4, 1998. The IMF clock angle observed by the Wind satellite upstream of the bow shock during the time of interest was with 191°, i.e., almost directly southward. This condition causes the anti-parallel reconnection region (red area) to cover almost the entire dayside and extending into the equatorial regions at the flanks.

As shown in Figure 1, the black square symbols depicted in Figure 2 represent the end points of the magnetic field line traces to the magnetopause. 3D ion distributions between 13:00 UT to 13:08 UT have been used to calculate the distance of the satellite from the reconnection site used in these field line traces.

All trace points are located in the dusk sector of the southern hemisphere, surrounding the white line which marks the magnetopause location where the geomagnetic field and the draped IMF are exactly anti-parallel. For southward IMF conditions the entire dayside of the magnetopause has favorable (high shear angle) conditions to initiate reconnection. The results of the cutoff method indicate that even under such favorable conditions the reconnection site will not be simply located at the equatorial region but can extend to high latitudes where reconnecting field lines are almost exactly anti-parallel.

Figure 3 shows the magnetopause shear angle for a cusp crossing over the northern hemisphere on March 7, 1997. This cusp pass was characterized by a substantial IMF component in the B_Y direction observed by the Wind satellite upstream of the bow shock which led to an IMF clock angle of 142°. The day-side anti-parallel reconnection regions for this condition are at high latitudes on the northern dusk sector and the southern dawn sector.

The black square symbols from the magnetic field line traces are located in the dusk sector of the northern hemisphere but do not follow the anti-parallel reconnection region there. The location of the symbols stretches out towards the sub-solar region and along the location of the tilted X-line [11]. Based on the similarity with the tilted X-line this cusp crossing was interpreted as a typical case of component reconnection.

3. CONCLUSION

A systematic investigation of the location of the reconnection lines for clock angles <200° revealed a fundamental change in the reconnection location as a function of the clock angle.

For southward IMF conditions with clock angles around 180° the reconnection lines are in the anti-parallel reconnection region. Within IMF directions of 20° to 30° around the southward direction, the reconnection line follows exclusively the region where the geomagnetic field and the draped IMF are most anti-

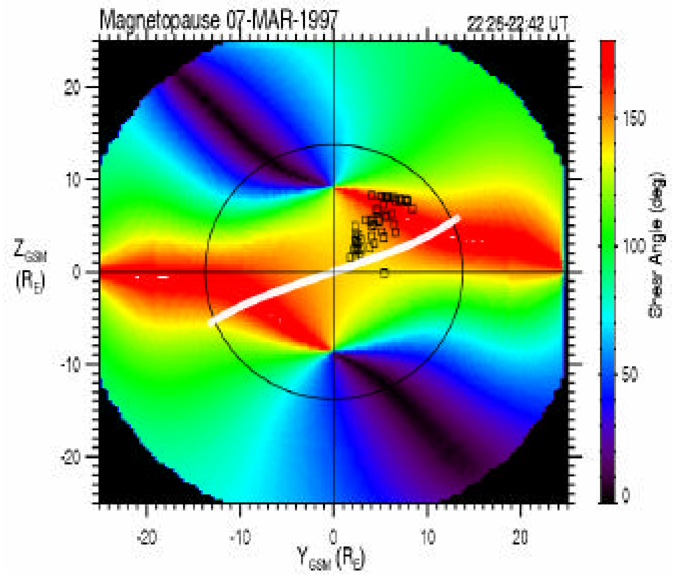

Figure 3: The magnetopause shear angle for the March 7, 1997, cusp crossing as seen from the sun. The locations of the field line traces indicate a component reconnection event which follows a tilted X-line.

parallel. This includes switching hemispheres if the IMF B_Y component changes sign.

With an increasing IMF B_Y component the reconnection location abandons the anti-parallel reconnection region and forms a reconnection line across the dayside, close to or crossing the sub-solar point. This is in agreement with predictions by [11] who suggested a reconnection line across the sub-solar point for IMF conditions with large B_Y components.

The traced locations of the reconnection line also revealed that some observed tilted X-lines cross the day side but would not necessarily cross the sub-solar region. Depending on the IMF B_X component such an X-line might cross the day side further north as the symbols in Figure 3 indicate or further south of the sub-solar point. A modification of the tilted X-line model might be required to accommodate these results.

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