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# On the solar wind control of cusp aurora during northward IMF

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[1] The location of cusp aurora during northward interplanetary magnetic field (IMF) conditions and the solar wind control of that location are explored. The cusp aurora is imaged by the Imager for Magnetopause-to-Aurora Global Exploration's (IMAGE) Far Ultraviolet Instrument (FUV). Predicted locations of the cusp aurora were computed by assuming anti-parallel reconnection between the observed IMF orientation and the 1996 Tsyganenko model magnetopause magnetic field. While the majority of anti-parallel reconnection sites tailward of the cusp, when mapped to the ionosphere, coincide with the observed cusp aurora, the anti-parallel merging hypothesis cannot explain certain aspects of the observations, including its location dependence with IMF + By. *INDEX TERMS:* 2704 Magnetospheric Physics: Auroral phenomena (2407); 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions. **Citation:** Bobra, M. G., S. M. Petrinec, S. A. Fuselier, E. S. Claflin, and H. E. Spence (2004), On the solar wind control of cusp aurora during northward IMF, *Geophys. Res. Lett.*, *31*, L04805, doi:10.1029/2003GL018417.

## 1. Introduction

[2] IMAGE is the first satellite to produce continuous, three-dimensional, global images of the densities, energies and masses in the magnetosphere [*Burch*, 2000]. IMAGE's FUV Spectrographic Imager (SI12) visually captures how the solar wind affects the magnetosphere globally through changes in the Earth's aurora [*Mende et al.*, 2000]. One way that the solar wind directly affects the Earth's aurora on a localized scale is through a process known as magnetic reconnection. Magnetic reconnection at the magnetopause allows mass, momentum and energy to be transferred from the solar wind into the magnetosphere and ultimately into the ionosphere [c.f., *Smith and Lockwood*, 1996]. Localized dayside ionospheric emissions poleward of the auroral oval observed by the FUV SI12 instrument are thought to represent the precipitation of energetic solar wind protons which have undergone reconnection at the magnetopause, poleward of the cusp when the IMF is northward *Frey et al.*, 2002; *Fuselier et al.*, 2002; *Phan et al.*, 2003].

[3] In this study, auroral spot signatures observed routinely with IMAGE, along with magnetic field mapping, are used to investigate how reconnection between the IMF and the Earth's magnetic field depends on their relative orientation at the magnetopause. Numerous studies have suggested that reconnection occurs when these two magnetic fields are anti-parallel [*Crooker*, 1979]. Under northward IMF conditions, reconnection occurs poleward of the Earth's magnetospheric cusps. Alternately, reconnection may occur when the magnetic fields are not anti-parallel. Such component reconnection can occur poleward or equatorward of the cusps for northward IMF. In this paper, we specifically use observations and simple model predictions to test the anti-parallel reconnection hypothesis.

## 2. Methodology

[4] This study systematically explores the occurrence and location of cusp dayside emissions and their association with interplanetary conditions, particularly those controlling magnetic reconnection, such as the IMF orientation. Under northward IMF conditions, reconnection has been shown to produce a highly localized region of precipitation within the ionosphere that can be clearly distinguished through auroral imaging [*Frey et al.*, 2002; *Fuselier et al.*, 2002; *Phan et al.*, 2003] using the IMAGE SI12 instrument. Therefore our study concentrates on IMAGE-derived cusp locations during exclusively northward IMF conditions.

[5] An example of one such localized "spot" is shown in Figure 1. The left-hand panel of Figure 1 is an FUV SI12 image taken on 26 November 2000 at 16:24:51 UT. The false-color image is shown on a magnetic local time (MLT) and magnetic latitude (MLat) grid. The intensity scale of auroral brightness is logarithmic. Local noon is at the top; therefore, the upper half of the oval comprises the dayside aurora. The spot is located slightly poleward of the auroral oval near local noon.

[6] The control of spot location by the IMF orientation with respect to the Earth's magnetic field during reconnection was explored for events such as the one in Figure 1. Events satisfying solar wind criteria were selected using ACE solar wind parameters obtained from the Coordinated Data Analysis Web (CDAWeb) site. The conditions were: positive IMF $B_z$ component, solar wind velocity greater than 600 km/s, solar wind ion density greater than 10 $cm^{-3}$, and IMF clock angle that remained stable within $\pm 15^\circ$ for at least 10 minutes. These selection criteria yielded 997 ten-minute intervals from the IMAGE database spanning the period from 24 May 2000 to 16 December 2001. During consecutive ten-minute intervals in which the clock angle remained within $\pm 15^\circ$, the periods were combined to create one event. This further condition consolidated the 997 ten-minute intervals into 344 statistically independent events. For all 344 events, the average solar wind density, velocity, ram pressure, IMF $B_x$, $B_y$, $B_z$, and $B_x/B_z$ values during the interval were computed.

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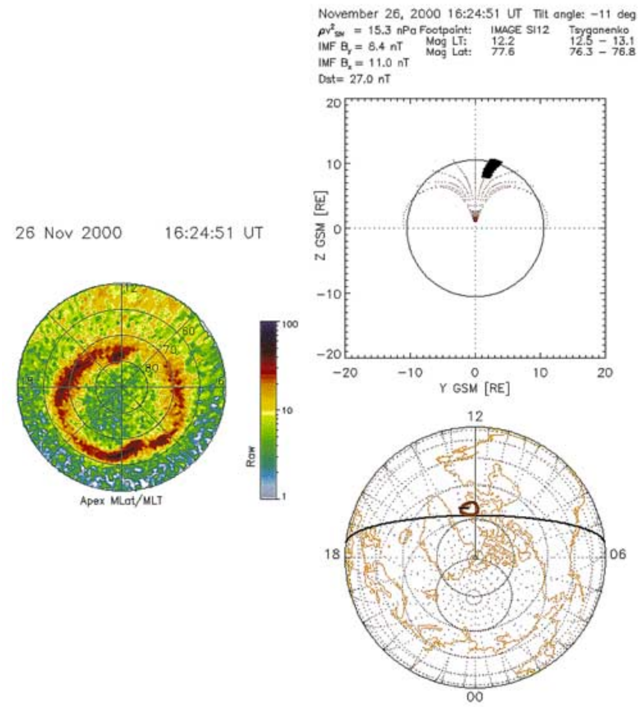


**Figure 1.** Composite images from 26 November 2000, showing: FUV SI12 image of auroral oval (left); region of anti-parallel magnetic field geometry between measured IMF and model magnetic field (top right); and, location of auroral "spot" (red circle), projection of anti-parallel merging sites into the ionosphere along model field lines, and the day-night terminator (curved solid black line).

[7] In order to minimize timing uncertainties stemming from the propagation of solar wind conditions at the ACE spacecraft to IMAGE, particularly the subtle details of the solar wind's passage across the bow shock, through the magnetosheath, and into the magnetosphere, the center time of each ten-minute interval event was chosen as the representative time. Upon examination of the SI12 images at that given time, the existence of a spot and its properties were recorded. If a spot was observed, an automated routine was used to evaluate its size. The spot size was determined as follows. The approximate center was first specified manually and then a computer routine pinpointed its maximum intensity. The location of the maximum intensity became the center of an $81 \times 81$ pixel region (typical pixel size is 50–100 $km^2$) used for measuring the spot size. Image intensities were interpolated to make a rotated $81 \times 81$ pixel region having the same center, but aligned along the magnetic longitude line passing through the center. A median was calculated for the 41 pixels starting at the central maximum and going to the edge in each of the four Cartesian coordinate directions of the rotated image. The edge of the spot was defined at the location where the measured intensity is less than or equal to the halfway value between the peak and the median. This objective technique robustly isolated the spot. Total spot area was computed by connecting the edge locations with piecewise continuous ellipse segments. The lower right panel of Figure 1 illustrates the results of this procedure; the red ovoid delineates the computer calculated spot outline.

[8] Although there is some user judgment in selecting the initial spot location, human bias is minimized by the consistent algorithmic selection of spot maximum and median intensities. Spots chosen were always localized and situated poleward of the dayside auroral oval. Furthermore, in order to minimize bias, spots were chosen without any *a priori* knowledge of specific upstream conditions (aside from the IMF being northward, of steady clock angle, and the solar wind of high density and velocity).

[9] Each observed spot location was compared to the predicted ionospheric locations of anti-parallel merging. These predictions were obtained from the recorded IMF orientation superposed on the 1996 Tsyganenko model [*Tsyganenko*, 1995] (to determine the anti-parallel merging sites) and a magnetic mapping to the ionosphere. The T96 model was driven with the appropriate input parameters for the observation time, including eventual sorting parameters of interest, such as the dipole tilt angle. For specifying the magnetosheath magnetic field, the upstream IMF clock angle was used without incorporating the effects of draping. While IMF draping may be important in some locations, the events in this study are generally located close to the noon-midnight meridian where draping is not as critical as it is near the flanks.

[10] The upper right panel in Figure 1 illustrates a view from the Sun toward the Earth. The circle is the boundary of the magnetopause at the terminator. Red lines show the projection of model magnetic field over the Y-Z GSM plane. The shaded area in the upper right quadrant shows the predicted location where the IMF field lines are anti-parallel (shear angle >170°) to the model magnetospheric field lines. When this shaded area is mapped magnetically to the ionosphere (lower right panel), it appears as a short black line just slightly post-noon MLT and at about 76° MLat. (The solid curved black line is the terminator.) This panel demonstrates that the ionospheric projection of the predicted anti-parallel region is at essentially the same location as the observed spot.

## 3. Data Analysis

[11] Evaluation of the 344 events between 24 May 2000 and 16 December 2001 revealed only 56 concurrent bright spots. Therefore, approximately only one in every seven events yielded an observed spot. No statistically significant seasonal occurrence rate was evident; the probability of observing a spot was the same during winter (November–January) as during summer (May–July).

[12] Previously, it was determined that dynamic pressure plays an important role in observing a spot with the IMAGE SI12 imager. Specifically, it was reported that high dynamic pressure is a necessary condition for observing a spot [*Frey et al.*, 2002]. To explore this dependence, the events in this study were sorted by solar wind dynamic pressure. The average dynamic pressure for events with observed spots was 9.3 nPa ± 5.8 nPa. This is significantly higher than the ~1.5 nPa dynamic pressure for average solar wind conditions. In order to determine if other solar wind factors control the appearance of a spot,

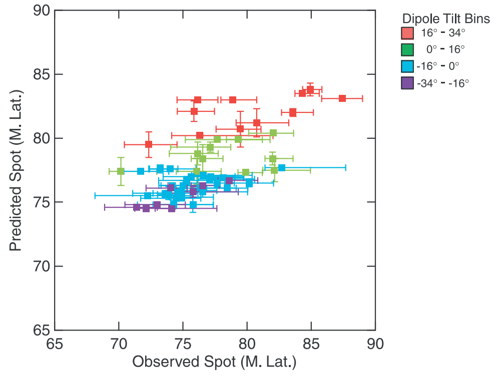


**Figure 2.** Observed versus predicted spot latitude as a function of dipole tilt (color coded). A clear trend of increasing spot location with latitude is consistent with previous studies of cusp location with dipole tilt.

a separate data set of events with dynamic pressures greater than one standard deviation from the average conditions (3.7 nPa) for the events with observed spots was constructed. It was used to investigate possible magnetic field orientation control on the occurrence and location of a spot.

[13] One possible parameter that may control the occurrence of a spot's projected location in the ionosphere is the IMF $B_x$ component. Consequently, spot occurrence frequency was explored as a function of the ratio of IMF $B_x$ to $B_z$. For the Fall/Winter months (September–March), and for dynamic pressures >3.7 nPa, there is no statistically significant trend of spot occurrence with $B_x/B_z$.

[14] The location of the spot may be strongly controlled by the Earth's dipole tilt angle. Past studies have shown that the greater the dipole tilt, the higher the cusp's magnetic latitude. Figure 2 shows the observed magnetic latitude of the spot versus the latitude predicted by mapping the model anti-parallel reconnection region to the ionosphere for all 56 events. The points in Figure 2 are color-coded by dipole tilt angle in four bins of approximately equal size. Although the observed spots often had considerable latitudinal range (shown here as a bar about the spot's center), their latitudinal location typically included the predicted location (which had much smaller latitudinal range as demonstrated in Figure 1). Figure 2 reveals the strong, clear trend anticipated in spot location with dipole tilt. For negative dipole tilts, the spot is located at lower magnetic latitude than for positive dipole tilt. The dipole tilt dependence of the magnetic cusp location is a known feature of the T96 model. Figure 2 reaffirms this dependence using an independent auroral emission definition of the cusp.

[15] Several earlier studies have investigated the IMF $B_y$ control of cusp location using *in situ* single spacecraft observations, typically at low altitudes [c.f., *Newell and Meng*, 1989]. That same dependence is explored here in Figure 3 which plots the observed spot location against the predicted anti-parallel ionospheric mappings in magnetic local time. In this case, there is a less clear dependence revealed with IMF $B_y$. For negative IMF $B_y$ values, the observed and predicted cusp locations cluster as expected on the dawn side of local noon. For positive IMF $B_y$ values, the observed cusp location showed no strong preference for either side of local noon, while the predicted locations, as expected, favored the afternoon sector.

## 4. Discussion

[16] Before discussing specific results of our analysis, it is valuable to place this study in the context of closely related efforts. *Frey et al.* [2002] explored the MLT location of cusp aurora using IMAGE data and its control by the IMF and solar wind. They reported a linear relationship between the MLT location of the cusp aurora and the IMF By which was interpreted as evidence for anti-parallel merging. It is important to underscore that their methodology was different than the one used here in two important ways. First, *Frey et al.* [2002] identified auroral spots and then explored spot location as a function of the coincident IMF orientation and solar wind conditions. This study identified IMF conditions first and then searched the IMAGE data for spot occurrence.

[17] Second, Frey et al. suggest that the solar wind ram pressure is more important than number density in determining the occurrence of cusp aurora detected by SI12. As described in Section 2, this study used a number density threshold for event selection and this difference warrants discussion. Ram pressure and number density in the solar wind tend to track one another because density and speed are anti-correlated, however the range of density variation is much greater than that of speed. There are many instances in the solar wind when the speed is average (400 km/s) but the density is high, but few cases when the speed is high (>600 km/s) and the density is also high. Consequently, high speed intervals are mostly nominal pressure intervals. So, using solar wind number density for initial event selection and considering dynamic pressure later is roughly equivalent to the *Frey et al.* [2002] study that started with dynamic pressure. Finally, despite the contention that the ram pressure is the controlling factor, Frey et al. show many events with dynamic pressure below 5 nPa (i.e., see their Figure 13a).

[18] Owing to these differences in selection criteria, their study had 2/3 fewer independent events (we had 54 events as opposed to their 18). As a result of poorer statistics, the spread of their data around the reported best fit line is quite large. Nevertheless, despite their comparatively smaller data

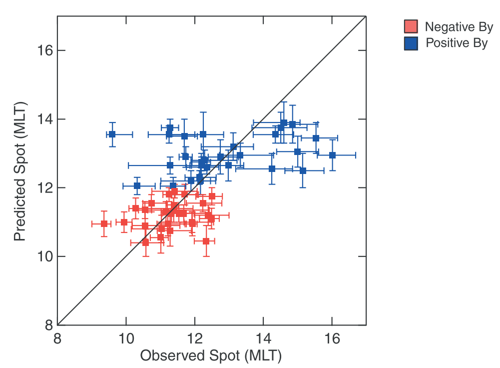


**Figure 3.** Observed versus predicted spot MLT as a function of IMF By (color coded). See text for discussion.

set and different selection criteria, there are similarities between their findings and ours. For example, comparison between their Figure 12b and the equivalent from this study (Figure 3) reveals that both studies find numerous cases when IMF By was negative but where the spot was located on the dusk side.

[19] The analysis here shows that while some trends of solar wind-, magnetospheric configuration-, and IMF-control of spot occurrence and location are as anticipated (namely, dynamic pressure, dipole tilt, and negative IMF $B_y$), others are absent ($B_x$) or unexpected (positive IMF $B_y$). The most significant issue to explore is the confounding behavior of spot position with IMF $B_y$.

[20] Several factors probably influence this behavior. One factor is the assumption that the reconnection is strictly anti-parallel. To explore the degree to which the magnetic shear angle influences the predicted locations, the analysis was repeated for several events but for which the precisely anti-parallel condition was relaxed. Looser tolerances in magnetic shears (>170 degrees → >140 degrees) produced increasing zones on the magnetopause and thus, commensurately, larger predicted areas projected in the ionosphere. However, the magnetic mapping yields an asymmetric stretch of projected features at ionospheric altitudes with magnetic local time. The MLT of the ionospheric footpoint increases faster in the dawn direction for IMF $-B_y$ with incremental steps away from a pre-noon magnetopause position. This is a geometrical effect owing to the fact that high-latitude magnetic fields are more deformed out of the meridional plane the further their distance from the symmetry plane at noon. Of course, the opposite trend would account for a duskward spread away from noon in the afternoon hours for IMF $+B_y$ conditions. This mapping effect may well explain the significant spread seen between the observed and predicted spot locations with MLT.

[21] While the former effect can account for much of the MLT discrepancy in the pre-noon sector during IMF $-B_y$ conditions, it cannot be important for the more surprising discrepancy found for IMF $+B_y$ conditions. For these conditions, the predicted and observed locations often do not even lie in the same quadrant. Therefore, if anti-parallel reconnection is responsible for cusp location, then some other effect is operating to influence these results.

[22] A possible clue and interpretation comes from the earlier work of *Newell et al.* [1989]. Their Figure 3 reveals the same effect shown here in Figure 3, yet using a completely different technique (direct measurement of precipitating ions), with a different spacecraft (DMSP), and in a different regions (low-altitude). Based on this similarity, the following physical scenario is proposed to explain the apparent discrepancy for IMF $+B_y$ conditions.

[23] Careful analysis of the IMAGE FUV images reveals that the pre-noon sector almost always has more intense proton emissions regardless of IMF conditions. This is probably the consequence of the low- to medium-energy ion drift paths within the magnetosphere that preferentially intersect the magnetopause in this sector. A fraction of the drifting ions precipitate into the high latitude ionosphere through wave scattering [*Anderson et al.*, 1996] near the boundary. This feature would thus exist not only in the IMAGE FUV images, but also in the DMSP SSJ/4 ion data (IMAGE remotely senses while DMSP directly measures those ions which encounter the magnetopause and precipitate). This feature of non-reconnection-associated precipitating ions may significantly alter the interpretation regarding cusp spot and cusp precipitation studies.

[24] In this study, only the brightest spot in an image was tracked. Therefore, during IMF $+B_y$ conditions, an unexpected and only apparent IMF dependence might emerge if a non-cusp-associated dawnside spot had an intensity that exceeded that of an actual cusp spot located in the dusk sector. Since there was no *a priori* information on $B_y$ used in the spot selection process, this is one of the few human biases introduced. The fact that so many of the spots occur before noon MLT suggests this effect may be substantial and should be carefully investigated in future studies.

## 5. Conclusions

[25] From comparison of the Tsyganenko model mapped locations and observed locations of 56 cusp aurora events it is concluded that for northward IMF, anti-parallel reconnection can account for some but not all observed dependences. The majority of events possessed approximately coincident observed and predicted spot locations. The observed versus predicted magnetic latitude plot shows a strong trend between spot location and dipole tilt, consistent with previous results. However, the observed versus predicted plot for magnetic local time for both positive and negative IMF $B_y$ produced unanticipated results. We stress that this study has specifically explored and quantified the strengths and weaknesses of the anti-parallel merging hypothesis. It has specifically explored and quantified the comparison between proton aurora spot observations and expectations from the anti-parallel merging hypothesis. The comparison between observations and the expectations from the component merging hypothesis has not been explored here. Thus, this hypothesis is not eliminated as a viable candidate for reconnection at the magnetopause.

[26] Although a mapping effect may cause the ionospheric footpoint for IMF $-B_y$ to grow faster in the dawn direction, the opposite effect does not occur for IMF $+B_y$. However, the unanticipated IMF $+B_y$ results can be explained by intense proton emissions which occur preferentially in the pre-noon sector. These emissions may be a consequence of the low- to medium-energy ion drift paths within the magnetosphere preferentially intersecting the magnetopause in this sector and presumably precipitating in the high latitude ionosphere. Therefore, the results of this study indicate that dawnside cusp precipitation should especially be studied further.

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