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Magnetic local time dependency on cusp ion velocity dispersions in the mid-altitude cusp

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Abstract. Observations of cusp ion velocity dispersions made by the TIMAS instrument on the Polar spacecraft in the mid-altitude cusp during intervals of northward interplanetary magnetic field (IMF) reveal a clear ordering with magnetic local time (MLT). Between 1100 and 1300 MLT the injected ion velocity increased with invariant latitude for 78% of the cusp crossings, between 0900 and 1100 MLT this percentage reduced to 35% and between 1300 and 1500 MLT the percentage reduced to 57%. In contrast similar observations made during intervals of southward IMF revealed no MLT dependency. Between 0900 and 1500 MLT the injected ion velocity increased with invariant latitude for only 17% of the observed cusp crossings. We suggest that the difference in the MLT dependency between northward and southward IMF can be best explained by the different characteristics of polar convection patterns for sub-solar and lobe reconnection.

Introduction

Reconnection between the IMF and the magnetosphere, first proposed by *Dungey* [1961] is the principal mechanism whereby solar wind mass and energy gain entry to the magnetosphere. Extensive studies of sub-solar reconnection during intervals of southward IMF have been made [*Reiff et al.*, 1980; *Hones* 1984; *Smith and Lockwood* 1996]. Magnetosheath plasma injection into the magnetosphere via a discrete source region, the reconnection site, results in a velocity dispersion with the fastest injected ions reaching any given position first. *Woch and Lundin* [1992] observe that the velocity dispersion is dependent on the orientation of the IMF. *Lockwood and Smith* [1994] predict that complex structured velocity dispersion such as *Escoubet et al.*, [1992] staircase ion dispersion can occur, a result of time dependent sub-solar reconnection. They predict that a spacecraft moving away from a sub-solar reconnection site would typically observe a decreasing injected ion velocity. During intervals of northward IMF reconnection can occur poleward of the cusp [*Russell* 1972]. *Kessel et al.* [1996] made the first direct observation of lobe reconnection. They report observing sunward convection a characteristic feature of lobe reconnection in a sub-Alfvénic magnetosheath flow. Lobe reconnection in a super-Alfvénic magnetosheath flow would result in the reconnected field being dragged tailwards. A spacecraft moving outbound, crossing sunward convecting field lines towards a lobe reconnection site would encounter more recently reconnected field lines and therefore faster moving ions, effectively reversing the velocity dispersion pattern of a sub-solar reconnection site.

Another characteristic feature of lobe reconnection is the formation of reverse convection cells in the high latitude ionosphere [*Iijima et al.*, 1984; *Freeman et al.*, 1993; *Knipp et al.*, 1993; *Ruohoniemi and Greenwald* 1996; *Weimer* 1995]. The convection cells indicate the evolution of the reconnected field line. The formation of the reverse convection cells in the polar cap was explained by *Lyons* [1985] who proposed that a purely northward IMF resulted in a lobe reconnected IMF that 'over drapes' the magnetosphere. In a sub-Alfvénic magnetosheath flow this would drag the field line sunward which then has an equal probability of convecting over either the dawn or dusk flanks of the magnetosphere. The nature of the shape, motion and number of these convection cells is variable. The orientation of the IMF, the solar wind velocity and the dipole tilt of the Earth all influence these reverse convection cells. *Huang et al.* [2000a] have made a detailed study of reverse convection cells. They find that provided the IMF is stable the convection cells are also stable.

In the next section a survey of the MLT dependency of cusp ion velocity dispersions is made for intervals of northward and southward IMF. These observations are discussed in terms of dipole tilt angle and by contrasting polar convection patterns generated by sub-solar and lobe reconnection.

Observations

The observations were made in the mid-altitude (5 to 8 earth radii) cusp region between 1996 and 1997. The measurements were made by the TIMAS instrument, [*Shelley et al.*, 1995] aboard the Polar spacecraft. The

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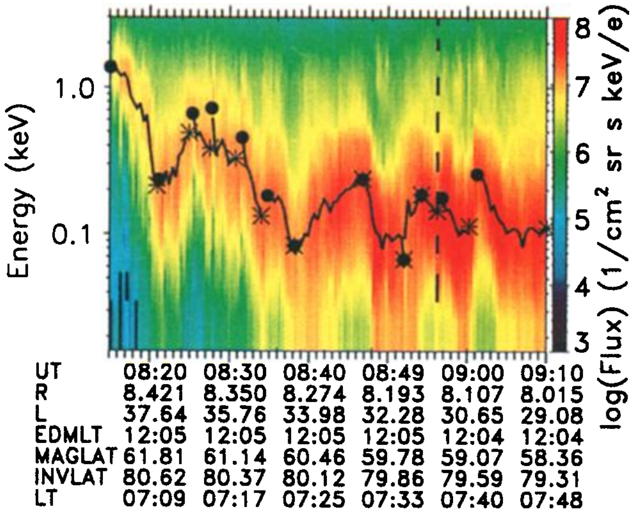

Figure 1. Spectrogram showing down-going H^+ ions. The solid line represents the drift velocity, (see text for details

orientation of the IMF was measured by the MFI instrument, [*Lepping et al.,* 1995]. The solar wind velocity, used to calculate the travel time to the earth (Wind to $X_{GSM} = 0$), was measured by the SWE instrument, [*Ogilvie et al.,* 1995]. Wind positions during the survey ranged from 40 to 230 Re sunward and within 40 Re of the earth sun line.

Cusp crossing intervals during which the solar wind velocity changed by more than 20% were excluded due to the uncertainty this variation would cause in deducing the travel time. A 20% uncertainty was included in the time lag when inferring the IMF B_Z orientation at the earth. The orientation was than accessed over the duration for which the quantifucation (described below) of the cusp observations are made. To simplify the observations only down-going ions with pitch angles less than 30° (all observations are made in the northern hemisphere) are included. This removes any up-going ionospheric and mirrored magnetosheath populations.

A single parameter of the observed individual magnetosheath ion injections is quantified. This is the sign of the gradient of the latitudinal velocity dispersion, $dv/d\Lambda / \mid dv/d\Lambda \mid$ where Λ is the invariant latitude. A three term drifting Maxwellian is fitted to the data to identify the bulk velocity. The fits were visually inspected and any poor fit was removed. Individual injection events were identified by discontinuous changes (positive or negative) in the velocity greater than 50 km/s (This corresponds to two energy steps of the detector) or a reversal in the velocity dispersion. Fitting the Maxwellian effectively limited the quantification to velocities greater than 100 km/s. This quantification rarely exceeded 1 hour of observation time. An example spectrogram of a cusp pass (11/1/1996) with the fitted drift velocity is shown in Figure 1. Polar was making an inbound pass through the northern, magnetosphere. The IMF B_Z component was northward between 3 to 6 nT. The solid cicles and stars mark the start and end times as described above. The gradient was deduced by performing a linear least squares fit to these marked intervals which is sufficiently accurate to deduce the average gradient. The number and duration of these features is highly variable. Some cusp crossings consisted of a single smoothly varying dispersion ramp lasting around 30 minutes. Other passes had in excess of 10 dispersion ramps with durations as short as a few minutes. The results for the entire set of deduced gradients are shown in Figure 2. Cusp crossings during intervals of southward IMF are shown in the upper panel (a), the lower panel (b) shows cusp crossings with northward IMF. The stars correspond to ion injections where the ion velocity increased with invariant latitude and the diamonds correspond to events where the velocity decreased. The bunching of the data into linear paths corresponds to cusp crossings with multiple discrete ion injections. Forty three cusp crossings were identified where the IMF is consistently northward and 48 were identified where the IMF was southward. The IMF southward events occur at a lower latitude than the IMF northward events consistent with reported IMF B_z effects on cusp location [*Newell et al.,* 1989; *Kremser and Lundin* 1990]. The majority of the IMF southward events have negative dispersion gradients, consistent with *Lockwood and Smith* [1994] predictions for mid-altitude cusp observations of sub-solar reconnection. The distribution of dispersion gradients

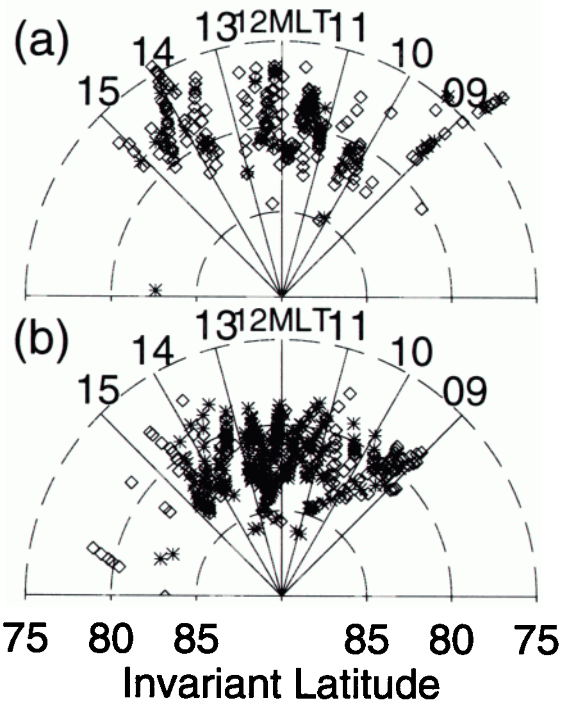

Figure 2. Velocity dispersion gradients plotted against magnetic local time. Positive, asterisks (negative, diamonds) dispersion indicates an increasing (decreasing) ion velocity with invariant latitude, (a) corresponds to events where the IMF was southward, (b) corresponds to events where the IMF was northward.

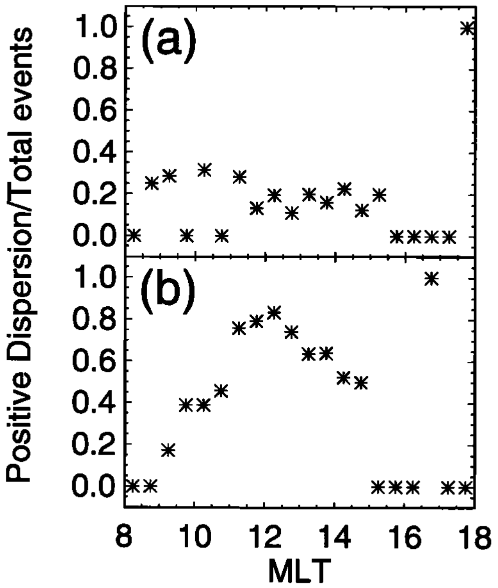

Figure 3. The average ratio of the number of positive dispersion gradients to total number of events is calculated and binned in 0.5hr MLT, (a) corresponds to events where the IMF was southward, (b) corresponds to events where the IMF was northward.

for IMF northward events is more complex. Between 1100 to 1300 MLT the majority of the events have a positive dispersion gradient, at other local times there is a greater admixture of dispersion gradients. To quantify this MLT dependency the averaged fraction of the number of positive dispersion gradients to total number of events is calculated and binned (width 0.5 hours) in MLT, for both IMF southward and northward events. The results are shown inFigure 3. A clear difference in the MLT dependency can be readily seen, for the IMF southward events the average ratio between 0900 and 1500 MLT is 0.17 and shows little variation while for the IMF northward events between 1100 and 1300 MLT this ratio is 0.78 and reduces to 0.35 between 0900 and 1100 MLT and to 0.57 between 1300 and 1500 MLT.

Discussion

A clear difference in the MLT characteristics between sub-solar (IMF southward) and lobe (IMF northward) injection events exist. Close to 1200 MLT the majority of the IMF northward events have positive dispersion gradients consistent with sunward convection from a lobe reconnection site. At other local times this dispersion gradient becomes more mixed.

Lyons [1985] notes that sunward convection from a lobe reconnection site can only occur in a sub-Alfvenic magnetosheath flow. The magnetosheath flow velocity increases with distance from the sub-solar point, hence lobe reconnection in the northern winter hemisphere places the reconnection site further from the sub-solar point than for a summer dipole tilt. A systematic difference in the dipole tilt between cusp crossings with a positive and negative dispersion for the northward IMF events would also indicate that the magnetosheath flow was influencing the observations. For positive dispersion cusp crossings the average dipole tilt angle was 2.8 ± 12.6° for the negative dispersions the tilt angle was −3.8 ± 16°. Both positive and negative velocity dispersion gradients were observed with a large range of dipole tilt angles (hence the large variance) indicating that the dipole tilt angle did not systematically effect the dispersion gradients.

The WIND observations used to infer the IMF B_Z orientation at the earth were made over a large range of positions. There was no systematic difference found in the location of WIND during intervals where northward IMF was inferred and positive dispersion gradients were observed in comparison to observations of negative dispersion gradients also made when the IMF was northward.

Another possibility is the more complex polar convection pattern associated with lobe reconnection which results in the formation of reverse convection cells in the polar cap. *Freeman et al.* [1993] observe two additional cells if $\mid B_z/B_y \mid \gg 1$. When $\mid B_z/B_y \mid \simeq 1$ *Knipp et al.* [1993] observe a single reverse convection cell in the polar cap. *C-S. Huang et al.*, [2000b] recently made a detailed case study of a lobe reconnection event with SuperDARN. They observed a four cell convection pattern, symmetric about the noon-midnight meridian, when $\mid B_z/B_y \mid \geq 3$, the convection had a sunward component over the polar cap roughly between 1000 and 1400 MLT, at other times the convection had a tailward component. The similarity in the range of MLT's for a sunward convection and our observed distribution of positive dispersions in MLT indicates that the four cell convection pattern could explain the MLT variation in the observed cusp ion velocity dispersions. The convection over the polar cap between 1000 to 1400 MLT results in a spacecraft moving poleward observing a positive velocity dispersion as detailed in the introduction. Outside these local times the field line convection has an anti-sunward component (a field line reconnected at a sub-solar site would also convect with an anti-sunward component) resulting in a poleward moving spacecraft observing a negative velocity dispersion. However the observations were made over a wide range of $\mid B_z/B_y \mid$, as B_y increases the ionospheric convection pattern becomes increasingly asymmetric about the noon-midnight meridian [*Knipp et al.*, 1993] changing from a four to a three cell convection. This asymmetry effects the range of MLT's over which the convection velocity has a sunward component. For $B_y < 0$ sunward convection shifts into the morning, for $B_y > 0$ this shift is to the afternoon. An attempt was made to relate the observed MLT dependence of the velocity dispersion gradient to IMF B_y however no criteria was placed on the stability of the IMF B_y component. The results were ambiguous most probably due to the variability of the B_y component.

Finally Figure 3(a) shows that 17% of the observed velocity dispersions had a positive gradient when the IMF B_z was southward. *Lockwood and Smith* [1994] predict that such disersion gradients can occur if the field line convection velocity decreases after reconnection or they can be a result of compressive motion of the magnetopause.

Conclusions

The observations presented in this letter reveal a clear ordering of lobe reconnection cusp events. These observations are consistent with reconnection resulting in reverse, sunward, convection in the polar cap. The variation in the velocity dispersion gradient was not effected by variation in the dipole tilt angle indicating that, for this study, an extreme dipole tilt probably does not move the reconnection site into a super-alfvénic region of the magnetosheath. The average $| B_z/B_y |$ for IMF northward events is 1.6 this would most probably result in a three cell ionospheric convection pattern which is asymmetric about the noon-midnight meridian. Variability and uncertainty in the deduction of $| B_z/B_y |$ precluded a detailed comparison with the distribution of the dispersion gradients in MLT. The observations presented here suggest that for a wide range of $| B_z/B_y |$ with $B_z > 0$ results in sunward convection over at least part of the polar cap with tailward convection occurring on field lines located away from 1200 MLT.

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