IMF B_Y dependence of the extent of substorm westward electrojet

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In this paper the duskward extension of the westward auroral electrojet is investigated for substorm intervals on the basis of magnetograms recorded at the Indian Antarctic station, Maitri. The database comprises three years from 1998–2000. Based on an initial study of the magnetograms, an arbitrary local time of 2030 MLT is fixed to define the early manifestation of the substorm westward electrojet. Using this criterion 12 substorms are identified and the possible causes examined. Many of these events are observed to be associated with a moderate to intense ring current. The hourly average of the GSM B_Y-component of the interplanetary magnetic field (IMF) for the hour preceding the substorm onset at Maitri is negative for most of the events. It is suggested that the azimuthal shift of the auroral electrojets in the southern hemisphere resulting from a negative B_Y-component of the IMF influences the extent of the substorm westward electrojet. This finding implies that the IMF may have a role in controlling the longitudinal extent of substorm occurrence.

1. Introduction

The substorm phenomenon was first defined on the basis of the manifestation and behaviour of visual aurora in the auroral region by Akasofu (1964) using all-sky cameras. This was later followed by satellite observations in the magnetosphere, which led to a better understanding of the associated magnetospheric processes (Nishida 1978). Substorm effects may be separated into a directly driven component in which energy from the solar wind is directly deposited in the auroral region, and a loading–unloading component in which energy extracted from solar wind is stored in the magnetotail before being dissipated in the auroral region (Akasofu 1981). The enhancement in auroral electrojets (which form part of the DP2 current system) is believed to be a manifestation of the directly driven component, while the intense westward electrojet (also known as DP1 current system) occurring in the magnetic midnight sector during the expansion phase is considered a manifestation of the loading–unloading component (Kamide and Baumjohann 1993).

Auroral ground magnetogram signatures near the substorm onset region show a steep drop in the H-component corresponding to the passage of the westward travelling surge (Akasofu *et al* 1966). The westward travelling surge is considered to be the western extremity of the westward electrojet during the expansion phase of substorms. The westward motion of the surge can at times be irregular (Tighe and Rostoker 1981) and it comprises an upward field-aligned current at its head (Inhester *et al* 1981; Opgenoorth *et al* 1983). Recent multi-instrument and satellite studies of these surges (Lühr *et al* 1998; Marklund *et al* 1998) have revealed the fine structure of the associated electric fields and conductivities.

In this paper we make a study of substorm signatures in the westward electrojet that manifest at local times earlier than 2130 UT by making use of magnetograms from the Indian Antarctic station Maitri (Geomag. Lat. 67.14°S, Geomag. Long. 57.44°E). The cut-off time of 2130 UT is selected on the basis of a preliminary scanning of the magnetograms for the entire database. Magnetograms for the three years, 1998, 1999 and 2000,

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Table 1. *List of events.*

Event	Onset time at Maitri(UT)	Hourly average of IMF B_Y (nT)	Sym-H at onset(nT)
3 May 1998	2040	−2.20	−54
9 November 1998	2018	−7.52	−106
13 November 1998	2117	−10.84	−111
12 September 1999	2108	−6.80	−55
22 September 1999	2044	−12.20	+3
26 September 1999	2100	−0.98	−15
4 October 1999	2113	+0.27	−13
13 November 1999	2127	+1.08	−82
6 April 2000	1800	−16.58	−63
8 June 2000	2130	−1.76	−80
15 July 2000	1940	−0.03	−118
17 September 2000	2100	−13.38	−18

are considered for this purpose and an attempt is made to identify the factors that influence this early substorm occurrence. For this purpose interplanetary magnetic field conditions as well as ring current accompanying the events are examined, particularly since past studies have shown the auroral current systems to depend on the interplanetary magnetic field (Friis-Christensen and Wilhjelm 1975; Yeoman *et al* 2000) as well as the ring current (Feldstein *et al* 1999; Grafe and Feldstein 2000). In the identification of substorm negative bays in this paper, only those bays with a negative peak greater than 150 nT have been considered so as to avoid any ambiguity in their identification (Kamide 1993).

2. Observations

Table 1 shows a list of events identified in this study. The events are selected on the basis of their showing a sharp drop in the X-component characterizing a substorm expansion phase. The time of onset refers to the onset of the substorm negative bay at Maitri. The timing of onset is given in universal time (UT) and the magnetic local time (MLT) for the location of Maitri is approximately 1 hour behind universal time (UT). The third column of the table shows the hourly average of the GSM B_Y component of interplanetary magnetic field (IMF) corresponding to the hour preceding the negative bay onset at Maitri. The IMF data is from the Advanced Composition Explorer (ACE) spacecraft (Smith *et al* 1998; McComas *et al* 1998). The approximate IMF propagation time between the instant of satellite observation and its later interaction with the magnetopause has been computed by following the method used by Lester *et al* (1993) and Hairston and Heelis (1995). The expression for the transit time of IMF between satellite and magnetopause is given by

$$T_{\rm tr} = [X + Y \tan\varphi + (7\beta - 1)D]/V_{\rm sw}$$

where X is the distance between the Earth and satellite along the Earth–Sun line and Y is the distance of the perpendicular from the Earth–Sun line to the satellite in the GSE x-y plane. φ is the garden-hose angle of the solar wind, $(1+\beta)D$ and D are the geocentric distances of the subsolar bowshock and subsolar magnetopause, respectively, and $V_{\rm sw}$ is solar wind speed. According to Lester *et al* (1993) β varies between 0.20 and 0.25. In this paper the value of β is assumed to be 0.225 and φ is taken to be 45°. D is computed using the expression

$$D = [\alpha B^2/(2\mu_0 M_{\rm p} n_{\rm sw} V_{\rm sw}^2)]^{1/6} \quad \text{in } R_E$$

where α is the geometrical field compression factor at the magnetopause, B ($\approx$ 32000 nT) is the surface magnetic field strength at the Earth's equator, μ_0 is the permeability of free space, $M_{\rm p}$ is the mass of proton and $n_{\rm sw}$ is the solar wind particle density. α is chosen to be 2, which corresponds to an infinite plane current sheet approximation for the Chapman–Ferraro current. The uncertainty in the transit times computed for the events of this paper is estimated by varying β (0.20–0.25) and φ (30°–60°) and amounts to within ±7 minutes. A further factor of 2 minutes is added to the transit time computed above to take into consideration the Alfvén wave propagation time between the subsolar magnetopause and auroral ionosphere (Khan and Cowley 1999). It is this Alfvén wave, propagating along the newly opened reconnected field lines, that communicates the effects of dayside reconnection to the high latitude ionosphere. For the event of July 15th, 2000, data from GEOTAIL satellite (Kokubun *et al* 1994; Frank *et al* 1994) was used due to the unavailability of ACE

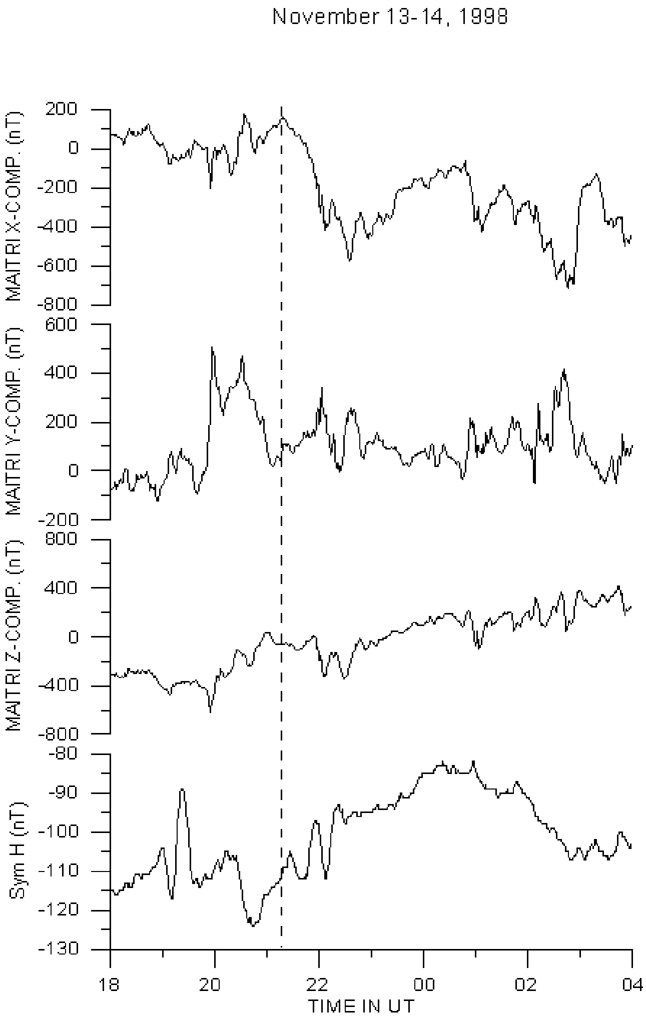

Figure 1(**a**). Maitri magnetograms for the event of 13th–14th November 1998. The bottom panel shows the Sym-H index which reveals the extent of ring current build-up. The dashed line shows the onset time of the substorm as viewed by the station. Note that MLT at Maitri is approximately one hour behind UT.

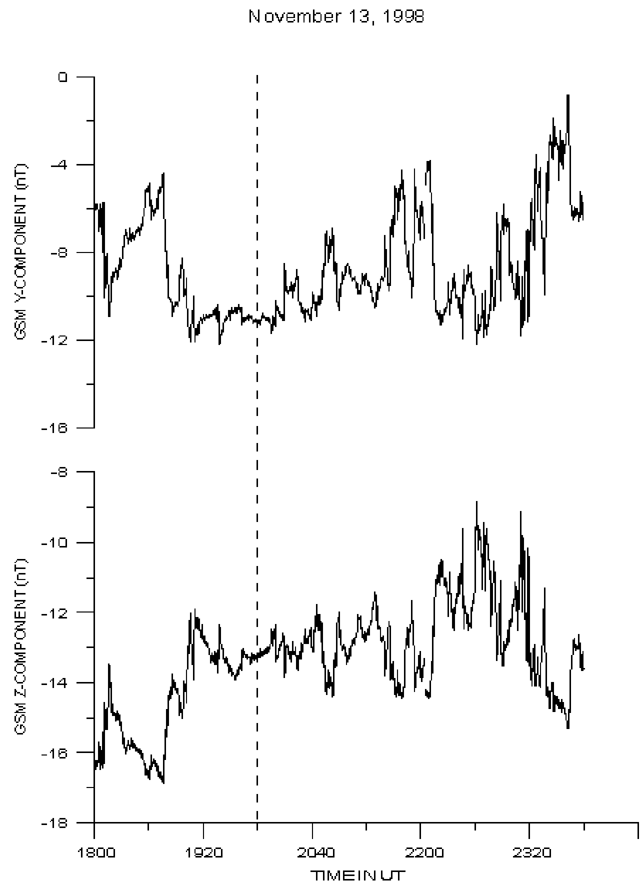

Figure 1(**b**). IMF B_Y and B_Z components in the GSM coordinate system for the event depicted in figure 1(a). The dashed line shows the instant corresponding to the onset of the substorm at Maitri and was determined by accounting for the transit time of the IMF between ACE satellite and Earth's high-latitude ionosphere.

data. The uncertainty in transit time computed for GEOTAIL is within ±1 minute.

The extent of ring current at the onset of the negative bay at Maitri is also indicated in the last column of table 1. The ring current is studied with the help of Sym-H indices (Iyemori 1990). These indices may be considered as being similar to high-resolution Dst indices (e.g., Iyemori and Rao 1996). We discuss below three of these events in detail.

Figure 1(a) shows the event of 13th–14th November 1998. The substorm onset at the station occurs at 2117 UT as seen by the sharp fall in the X-component. The dotted line marks the substorm onset as seen by the station. It is to be noted that the Z-component at the station is measured by considering the positive direction to be vertically upwards at the location. The Z-component trace for this event shows the westward electrojet to move poleward of the station at the onset. For several hours prior to the onset till the onset of the substorm Sym-H is less than −100 nT, showing the existence of an intense storm. The IMF components B_Y and B_Z (figure 1b) were strongly negative for several hours preceding the substorm onset and remained so even after the onset.

In figure 2(a), the decrease beginning at 2044 UT marks the time of substorm onset on 22nd–23rd September 1999 at Maitri. The total fall is in excess of 400 nT. The Z-component shows the westward electrojet to lie poleward of the station. Sym-H trace at onset is positive but is in the process of decreasing to a level of ∼ −150 nT, showing the development of an intense storm. At ∼19 UT, the IMF B_Y component (figure 2b) drops very sharply to −20 nT and remains below −10 nT till the substorm onset time and even beyond. The B_Z component too drops simultaneously with the B_Y component to ∼ 0 nT and a little later decreases further to ∼ −20 nT.

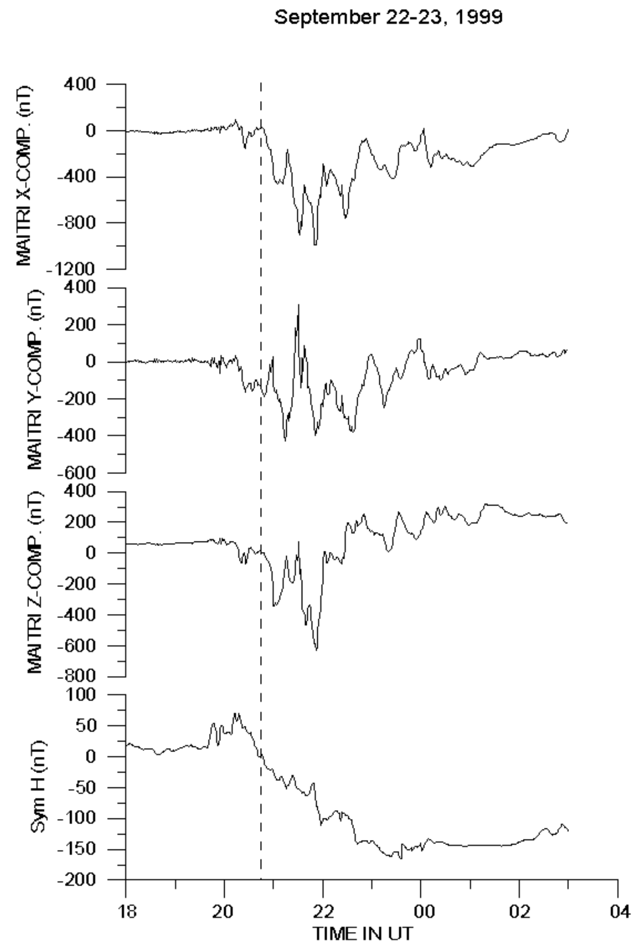

Figure 2(**a**). Maitri magnetograms for the event of 22nd–23rd September 1999. The bottom panel shows the Sym-H index. The dashed line shows the onset time of the substorm as viewed by the station.

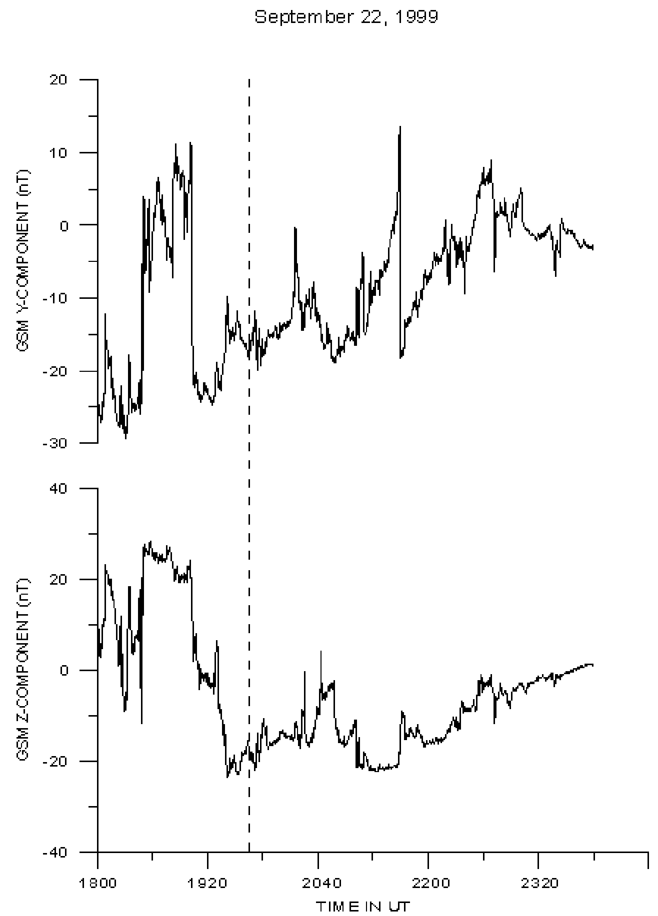

Figure 2(**b**). IMF B_Y and B_Z components in the GSM coordinate system for the event depicted in figure 2(a). The dashed line shows the instant corresponding to the onset of the substorm at Maitri.

Figure 3(a) shows a substorm at 2100 UT for 26th–27th September 1999, with a peak X-component decrease reaching ~ -200 nT and with the IMF B_Y positive at substorm onset. The station in this case too is located equatorward of the westward electrojet during the substorm as shown by the negative variation in the Z-component trace. The ring current is negligible for this event. In figure 3(b) it is seen that the IMF B_Y component is predominantly negative for ~ 45 minutes preceding the substorm onset, at times hovering about the 0 nT level and spiking to positive values. As the onset time nears, it decreases to ~ -10 nT. The B_Z component also fluctuates about the 0 nT level for the hour preceding the onset and decreases to less than -10 nT with the approach of the onset time.

It is seen that among the 12 events listed in table 1, there are only 2 events that show a positive average IMF B_Y during the hour preceding the onset of the substorm. Though many of the substorms are accompanied by a moderate to intense ring current at onset, there are 4 events which show a negligible ring current presence. These results are discussed in detail below.

3. Discussion

The observations presented above have revealed that the occurrence of substorm westward electrojet at earlier local times is related to a negative IMF B_Y component. Though such events seem to occur often during moderate and intense storms, the existence of 4 events which show a negligible ring current build-up at the substorm onset suggests that such events can also occur during non-storm conditions.

The variation of the high-latitude current system with the polarity of IMF B_Y was first shown by Svalgaard (1968). Further the association of IMF B_Y with the high-latitude current systems, including seasonal effects, was discussed by Friis-Christensen and Wilhjelm (1975). These authors investigated the effects of B_Y for different polarities of B_Z component during steady state IMF

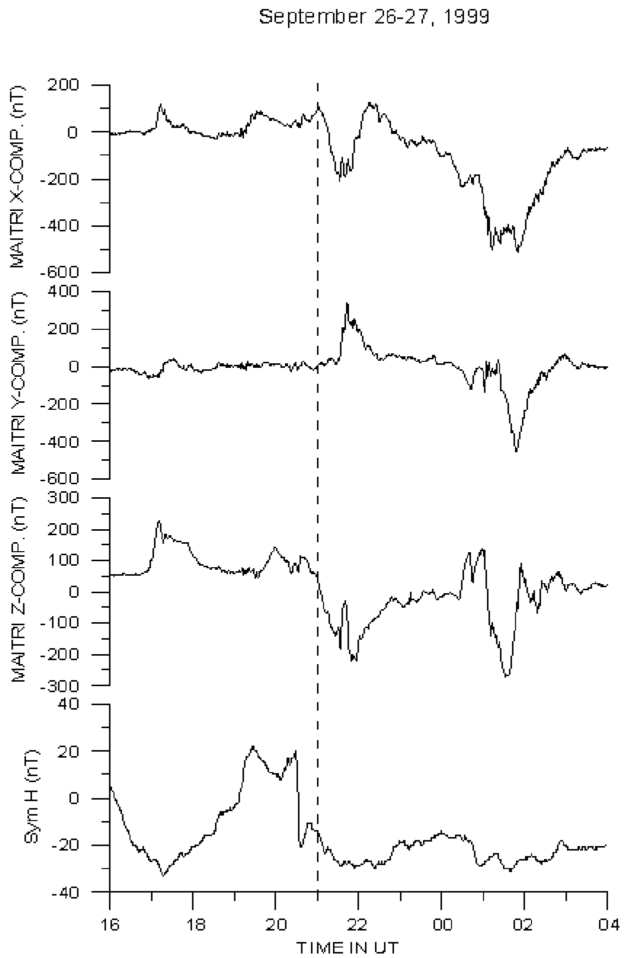

Figure 3**(a)**. Maitri magnetograms for the event of 26th–27th September 1999. The bottom panel shows the Sym-H index. The dashed line shows the onset time of the substorm as viewed by the station.

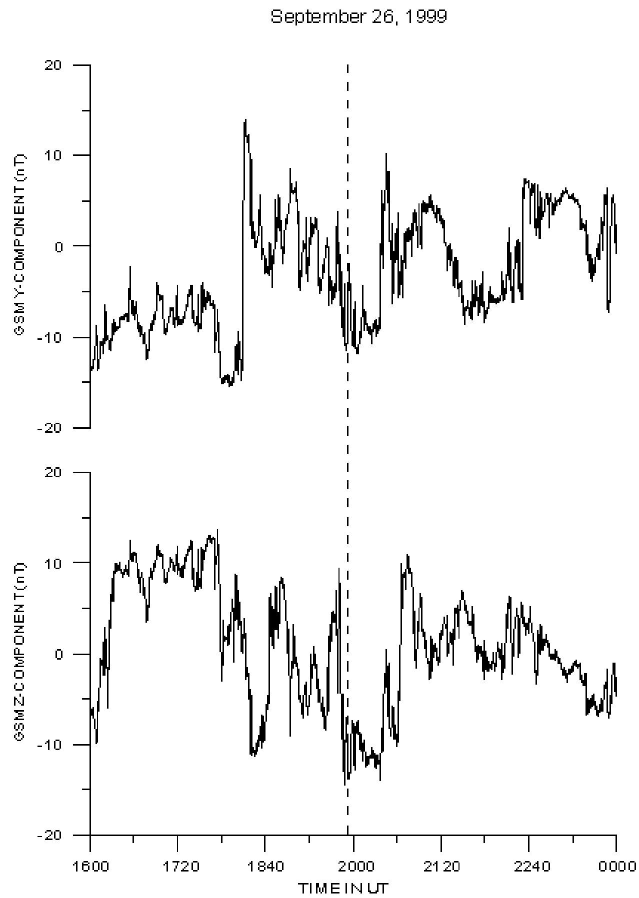

Figure 3**(b)**. IMF B_Y and B_Z components in the GSM coordinate system for the event depicted in figure 3(a). The dashed line shows the instant corresponding to the onset of the substorm at Maitri.

conditions. In particular, they noticed that for negative B_Z, the polarity of B_Y governed the dawn-dusk shift of the high-latitude 2-cell current system. Burch *et al* (1985) inferred a B_Y-dependent plasma convection model for the northern hemisphere for conditions of southward IMF using plasma, electric field and magnetic field data from the Dynamics Explorer 1 and 2 spacecrafts and found the coexistence of different types of convection cells. Rodger *et al* (1984) found the local time of occurrence of the Harang discontinuity to be earlier (later) for the northern hemisphere (southern hemisphere) for positive B_Y and *vice-versa.* According to the authors this implied an azimuthal shift of the auroral electrojet current system with the polarity of B_Y. The observations presented in this paper are in conformity with the study of Rodger *et al* (1984), considering that the Harang discontinuity would lie to the west of the westward electrojet. However, a difference exists in the selection of events in this paper and in the paper of Rodger *et al* (1984). The events of the latter paper were confined to moderately disturbed magnetic conditions to enable easy identification of the Harang discontinuity on the magnetograms, whereas in the current paper the events are all during disturbed substorm conditions. Figure 4 shows our observations graphically by making a linear fit to the plot of average IMF B_Y against local time. The fair amount of scatter reflected in the plot may be attributed to the use of a single station, which is not necessarily situated at the westernmost extremity of the substorm westward electrojet for all the events. The linear fit suggests the direct dependence of the local time of substorm electrojet on IMF B_Y and compares well with that obtained by Rodger *et al* (1984) for the position of the Harang discontinuity at the Antarctic station Halley Bay. The mechanism of penetration of IMF B_Y to the auroral zone and its influence on the geomagnetic field lines was discussed by Cowley (1981). According to the author, reconnection on the dayside results in the penetration of the magnetic field to the tail along the newly open

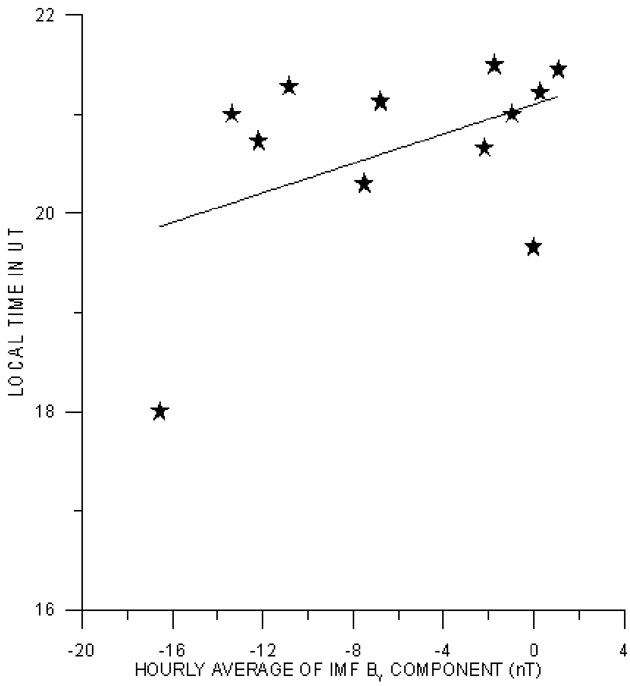

Figure 4. Plot of the local time of the substorm onset against the hourly average IMF B_Y for the hour preceding the substorm onset, for the events of this study. A linear fit has been drawn.

field lines. This field then penetrates further to the closed field lines through reconnection occurring in the magnetotail. Penetration of IMF B_Y into the magnetotail has been observed using satellite magnetic field measurements by Fairfield (1979) and Cowley and Hughes (1983). Cowley (1981) further postulated that inside the closed field lines this B_Y field modifies the existing dipole field and causes a shift in the feet of closed field lines, with the direction of shift depending on local time. A consequence of this is the change in the conjugate regions of the field lines. The direction of shift is opposite in the northern and southern hemispheres and reverses with polarity of IMF B_Y. In the dawn-dusk meridian this B_Y magnetic field causes the feet of geomagnetic field lines to shift in latitude and in the noon-midnight meridian it manifests as a longitudinal shift in the field lines. Changes in the position of field lines result in changes in the flow pattern of ionospheric currents. Yeoman *et al* (2000) observed the high-latitude ionospheric convection patterns exhibiting a high level of conjugacy for intervals of zero B_Y, while for non-zero B_Y the conjugacy was controlled by the magnitude and polarity of B_Y. Holzworth and Meng (1984) in a statistical study using DMSP auroral images of the southern hemisphere found the polar cap to move duskward (dawnward) with $B_Y > 0$ ($B_Y < 0$).

In table 1, it is seen that two of the events – 4th October 1999 and 13th November 1999 – show a positive B_Y. This is possibly because of the selection of arbitrary cut-off time as 2130 UT to select the events of this paper. Indeed the onset time for these two events is quite close to 2130 UT. However, the remaining events conforming to negative IMF B_Y justify our choice of cut-off time.

Akasofu *et al* (1966) noted that the westward travelling surges were observed in the early evening local time sector during intervals of very high Dst. They linked the early occurrence of the surges to the equatorward movement of the auroral oval during times of high Dst. As a consequence, an auroral observatory would move into the polar cap where it would record the surge at an earlier local time. As the surge is the westward extremity of the expanding substorm westward electrojet, it is very likely that our observations in this paper may have relevance to the behaviour of the westward travelling surge. The magnetic signature corresponding to the passage of the surge across the meridian of an auroral observatory corresponds to the steep negative bay in the X-component of magnetograms (Akasofu *et al* 1966). Positive bays in the Y-component characterizing the surge (Tighe and Rostoker 1981; Rostoker *et al* 1980) are not observed at onset in all the events of this paper. Such a signature in the Y-component is a sign of the surge head passing in the vicinity of the observatory. However such behaviour of the surge needs to be evaluated on the basis of events specifically selected on the basis of the Y-component signature. Since this is beyond the scope of the present paper, we merely point out the potential implications of our results on the surge characteristics. Any influence of the IMF B_Y on the extent of propagation of the surge is significant since it would imply that the IMF aids not merely in triggering substorms (Kamide *et al* 1977; Liou *et al* 2003), but also in defining its spatial extent. It is pointed out that the spatial extent in the magnetotail is closely related to that in the ionosphere since the two regions are magnetically mapped. The cross-tail current is known to complete part of its circuit through the auroral ionosphere during substorms as a westward ionospheric current (Lühr and Buchert 1988).

4. Conclusions

In this paper substorm events at an Antarctic station, Maitri, occurring earlier in local time have been studied and it is shown that the local time extent of the westward extremity of the substorm westward electrojet is associated with a negative B_Y component of interplanetary magnetic field. This finding is significant since it reveals the possible influence of the IMF on the longitudinal extent of substorm occurrence.

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