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On the Duskside Low Latitude Signatures of Substorms

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Abstract

The phenomenon of substorms is accompanied by magnetic signatures on low latitude magnetograms. These signatures are known to be different on the dayside and nightside, with an amplification at the dayside dip equator. In particular, the low-latitude stations located in the dusk sector develop a positive bay in the horizontal component corresponding to the expansion phase of substorms. In this paper, we make a study of the dusk sector low-latitude response during 13 substorm events selected for the year 1999. Three stations lying approximately along the same geomagnetic longitude are selected for the purpose, with one of the stations Maitri lying in the auroral region. The remaining two stations are Ascension Island and M'Bour located geographically duskward of Maitri at low latitudes in the southern and northern hemispheres, respectively. An examination of the horizontal components at the low-latitudes shows the X-component developing a positive bay signature with no typical signatures in the Y-component. Variations in the Y-component are generally much less than those in the X-component. The X-component amplitudes of the three stations during the substorms show that the magnitudes of the amplitude of the low latitude stations are similar and occur at the same instant of time to within a minute. Further, the X amplitude of the low latitude stations shows an approximately linear relation to the X-component negative peak at Maitri, consistent with the behaviour of the substorm current wedge. On the other hand, the low-latitude X amplitude shows a non-linear relationship with the Y-component positive peak at Maitri. It is suggested that this could be due to auroral region conductivity enhancements. Spectral analysis of the magnetograms reveal periodicities in the range 40-130 min common to both the low latitude stations. These periodicities are seen at Maitri for only selected events. An examination of a dayside low-latitude magnetogram reveals that these periodicities may also be seen in the dayside hemisphere. The electric field signatures aboard the GEOTAIL spacecraft are studied for 3 substorm intervals during which the spacecraft was located in the tail region and it is found that the sunward component exhibits negative excursions during the expansion phase. For two of the events, low frequency oscillations in the sunward component of the electric field correspond well with periodicities observed in the low-latitude magnetic field. It is suggested that the low latitude periodicities reflect fluctuations in the substorm current wedge and that the sunward component of the electric field is responsible for these fluctuations.

Introduction

The substorm phenomenon is an interval of increased energy dissipation in the auroral ionosphere. Substorms are accompanied by signatures in magnetograms globally (Reddy et al., 1979). The discovery of the DP 2 current system by Nishida et al. (1966), studies on the latitudinal distribution of this current system (Nishida, 1968a) and the relation of this current system with the Interplanetary magnetic field (Nishida, 1968b), have revealed the nature of the relationship that exists between the high and low latitudes. These have been complemented by later radar studies at low-latitudes (Gonzales et al., 1979; Fejer et al., 1979) showing the behaviour of the equatorial electric field to be in concert with the auroral electric field, while a complex relationship was deduced between the equatorial electric field and the Interplanetary magnetic field (IMF) orientation in the north-south direction. Kikuchi et al. (1978) suggested that the convection electric field penetrates from the magnetosphere to the high latitudes along field lines, and from the high latitudes to the low latitudes almost instantaneously as the zero-order transverse magnetic waveguide mode. This mode allows waves of all frequencies to penetrate to low latitudes. The region 2 field-aligned currents present an obstruction to the direct penetration of the high-latitude fields to the low-latitudes (Kamide and Matsushita, 1981). However, this shielding is believed to be relaxed for currents with a sufficiently rapid temporal variation (Sastri, 2000).

Recently there has been renewed interest in the DP 2 current system and the low-latitude response to substorms. The DP 2 system was attributed to temporal electric field fluctuations in the magnetosphere associated with changes in magnetospheric convection (Nishida, 1968a). Kikuchi et al. (1996) on the basis of high-resolution magnetometer data from IMAGE network, Brazilian and African equatorial stations and EISCAT radar observations showed that the DP 2 in the auroral region is caused by the ionospheric Hall current. Radar studies near the dip equator in the dusk sector showed the F-layer vertical plasma drift to exhibit quasi-periodic fluctuations coherent with DP 2 observed on dayside magnetograms (Abdu et al., 1998). Thus, the DP 2 electric field also penetrates to nightside low latitudes. Similar fluctuations in radar data coherent with north-south component of the IMF were observed during another event in the midnight sector (Sastri et al., 2000).

The DP 2 current system may also exist during the entire course of a substorm (Clauer and Kamide, 1985). Sastri et al. (1992) using ionosonde data found a transient disturbance in F-region height both on the dayside as well as nightside during a substorm interval, and interpreted it to be the result of disturbance in the zonal equatorial electric field in response to the penetration of substorm-related high latitude electric fields. Kikuchi et al. (2000a) studied the evolution of dayside electric field in the equatorial and auroral ionospheres during a substorm using magnetometers and SuperDARN. They inferred an increase in convection electric field along with its instantaneous penetration, less than 10 sec, to low-latitudes during the growth phase. The latitudinal distribution of dayside signatures of a substorm was examined by Kikuchi et al. (2000b) and the amplitude of the negative bay was found to decrease with latitude. However, the bay amplitude was found to be amplified at the equator in addition to being coherent with the high latitude magneto gram signatures. The authors attributed the enhanced dip equatorial magnetic signature to ionospheric DP currents associated with the Region 1 field-aligned currents.

The study of substorm characteristics from magnetograms at low latitudes can go far in improving present understanding of the phenomenon (Rostoker, 1993). One of the reasons for this is the lesser degree of background magnetic disturbances at the low latitudes. While the low-latitude characteristics of high-latitude disturbances and DP 2 events have been well documented on the dayside, it is felt that little attention has so far been paid to the behaviour of nightside low-latitude fields during similar events (Abdu et al., 1998; Sastri et al. 2000). This paper makes an attempt towards contributing to a better understanding of the nighttime low-latitude magnetic fields during substorms. We study the magnetogram signatures from three locations- one in the auroral region, one in the southern hemisphere low latitude and the other in the northern hemisphere low latitude- simultaneously for 13 substorm events and present our observations. The three stations are Maitri (Geom Lat. 67°.03S, Long. 56°.96E), Ascension Island (Geom Lat. 2°.09S, Long. 56°.32E) and M'Bour (Geom Lat. 20°.39N, Long. 57°.28E) and all of them lie approximately on the same geomagnetic longitude (-57°). Magnetograms of one-minute resolution for the components X, Y and Z are considered We then examine and analyze the electric field data from the spherical probe experiment aboard GEOTAIL spacecraft and examine whether any relation is seen with the magnetograms of the three ground stations. The spherical probe experiment has been detailed by Tsuruda et al. (1994). The experimental set-up at Maitri has been described by Kalra et al. (1995).

Observations

Thirteen substorm events were examined in this study. The amplitudes at Ascension Island and M'Bour are similar as may be expected from a magnetospheric current source. The X-component peak at the low latitude stations is seen to relate well to the negative peak X-component at Maitri. An approximately linear relationship is seen. This is in agreement with the low-latitude signatures being due to the build-up of the substorm current wedge arising from the disruption of the neutral sheet current. Figure 1(a) shows a plot of X-component amplitude of Ascension Island against the X-component peak at Maitri. The relation of the low-latitude X amplitude with the Y-component at Maitri is shown in Figure 2(b). It is seen that the relationship between the two components is non-linear. A logarithmic curve gives a good fit to the observations.

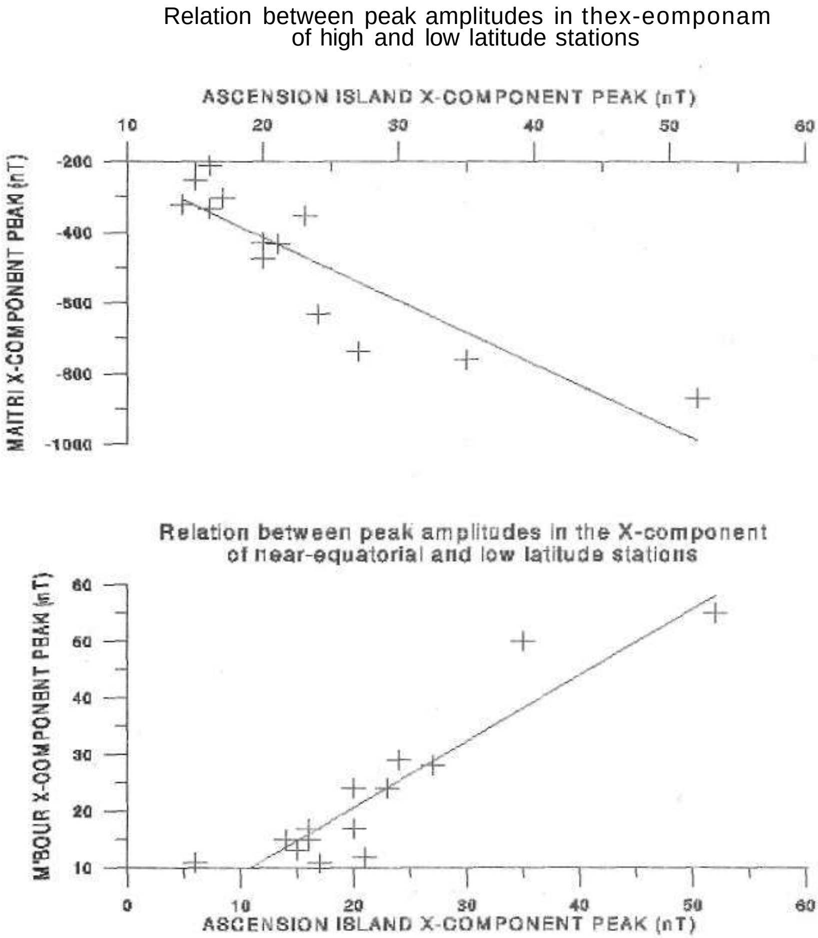

Fig. 1: The upper panel shows the approximately linear relationship between the X-component peaks at Maitri and Ascension Island. The lower curve depicts the non-linear relationship between the X-component at Ascension Island and the Y-component at Maitri. A logarithimic curve has been fitted.

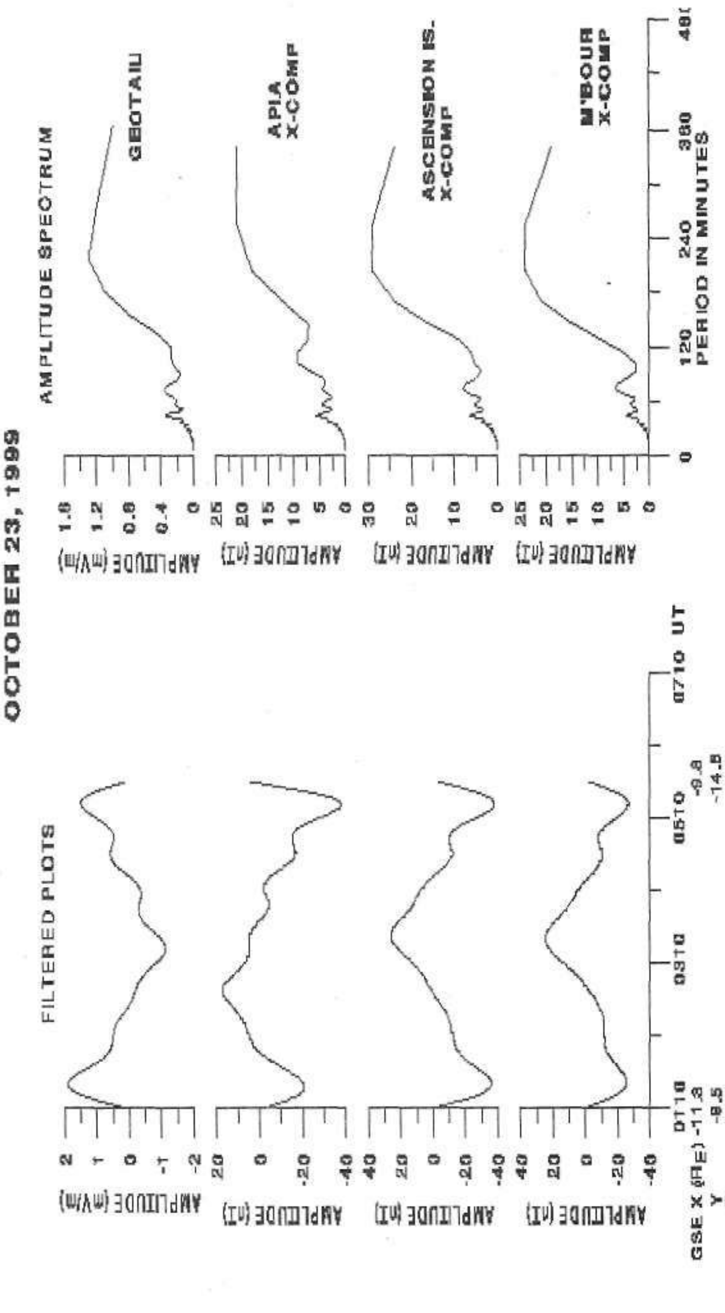

Fig. 2: Magnetograms for the substorm event of October 23, 1999, at the three nightside stations used in this study. All three stations lie approximately along the geomagnetic longitude ~57°. Variations in the Y-component at low latitudes during the substorm are seen to be much less than those in the X-component.

Figure 2 shows magnetograms of a sample event for the night of October 22, 1999. The substorm onset is at -0225 UT. The behaviour of the two low-latitude stations are similar, with the X-component showing a slight dip followed by a positive bay development. The peak of the positive bay coincides with the peak of the substorm expansion phase observed in the X and Y components at Maitri. Signatures in the low-latitude Y-component are not found to be as consistent as the X-component. Also, the magnitude of variations in the Y-component is much less than in the X—component. The sunward electric field in the magnetotail measured aboard GEOTAIL during this substorm are shown in figure 3. The X-component magnetogram at Maitri is also plotted so as to correlate the behaviour of the electric field to the substorm phases. Frequent negative excursions are observed during the expansion phase.

The filtered output of the event of Figure 3 is depicted in Figure 4 along with the amplitude spectrum. A band pass filter is used for the range 40-180 minutes. Since the X and Y components at Maitri do not show periodicities identical with the low latitudes for this event, it has been omitted from this plot. The filtered waveforms at the low-latitude stations correlate very well with that of the sunward component of magnetotail electric field.

The data series have been padded with zeroes to makeup 1024 data points and the frequencies obtained are hence harmonics of this value. All the amplitudes have been tested for statistical significance using Nowroozi's (1967) test and a few that do not qualify the test are given in bold lettering. It was felt that these amplitudes that failed the test may still be significant since identical frequencies are observed to be present in the other data being correlated. Shimshoni (1971) has shown that amplitudes which fail Nowroozi's test may still be statistically significant. In any case even if the frequencies for which the amplitude failed Nowroozi's test were to be excluded, it would not make any significant difference to our result. The table shows the difference in phase between Ascension and M'Bour to be consistently small. GEOTAIL was in the magnetotail for only 3 of the events (Jan 15, May 2 and Oct 23). Frequencies common to those found on the low-latitude magnetograms are found in only 2 of these 3 cases, Jan 15 and Oct 23. The GSE coordinates of the satellite at the beginning and ending times for these two events are Jan 15 [X=(-2.3)-(-6.4), Y=(12)-(12.6), Z=(-1.4)-(-1.9)], Oct 23 [X=(-11.3)-(-9.8), Y=(-9.5)-(-14.6), Z=(-2.5)-(-2.8)]. It is seen in the table that there are events for which frequencies are not identical at the stations and satellite. In these cases, the frequencies are neighbouring

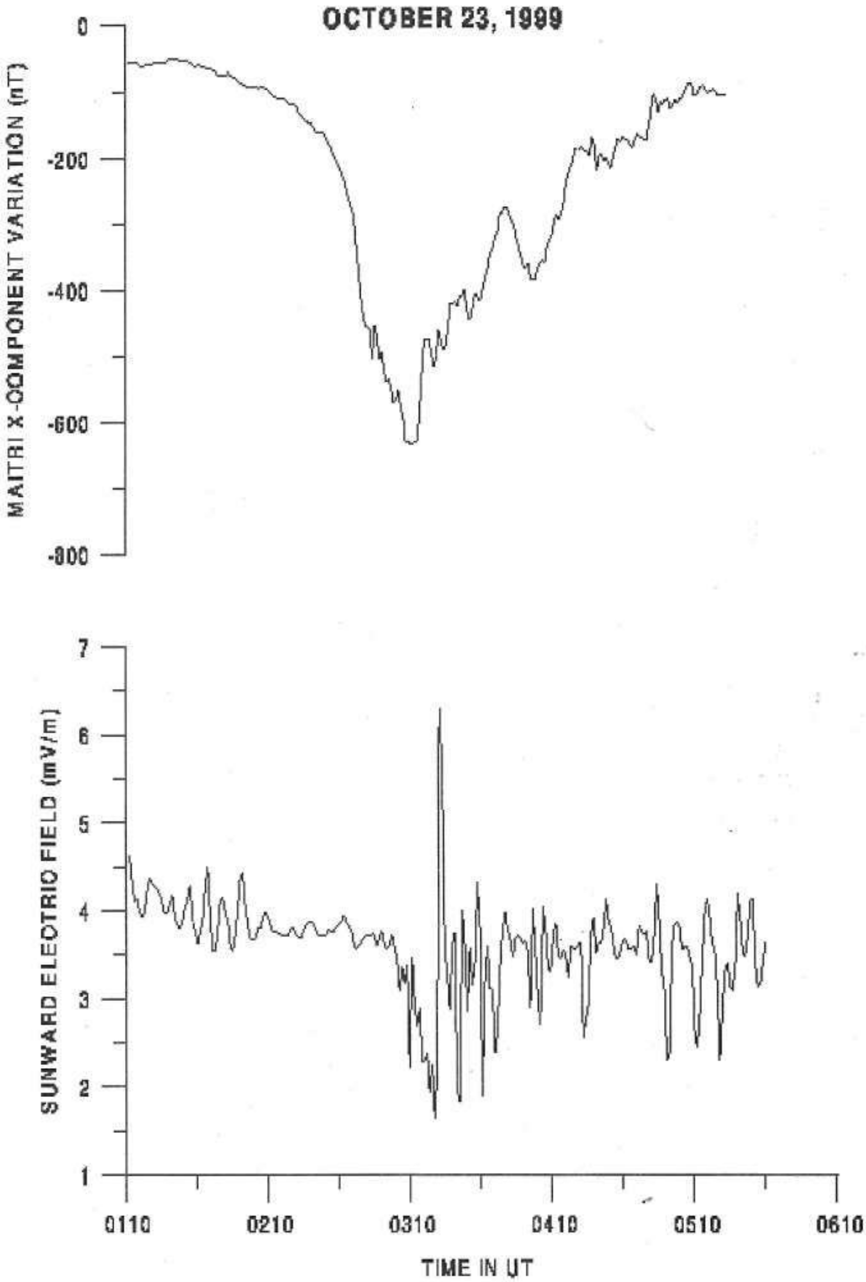

Fig 3: The sunward component of electric field aboard GEOTAIL shown with the X-component of the substorm event at Maitri. Negative excursions in the electric field are seen during the expansion phase of the substorm.

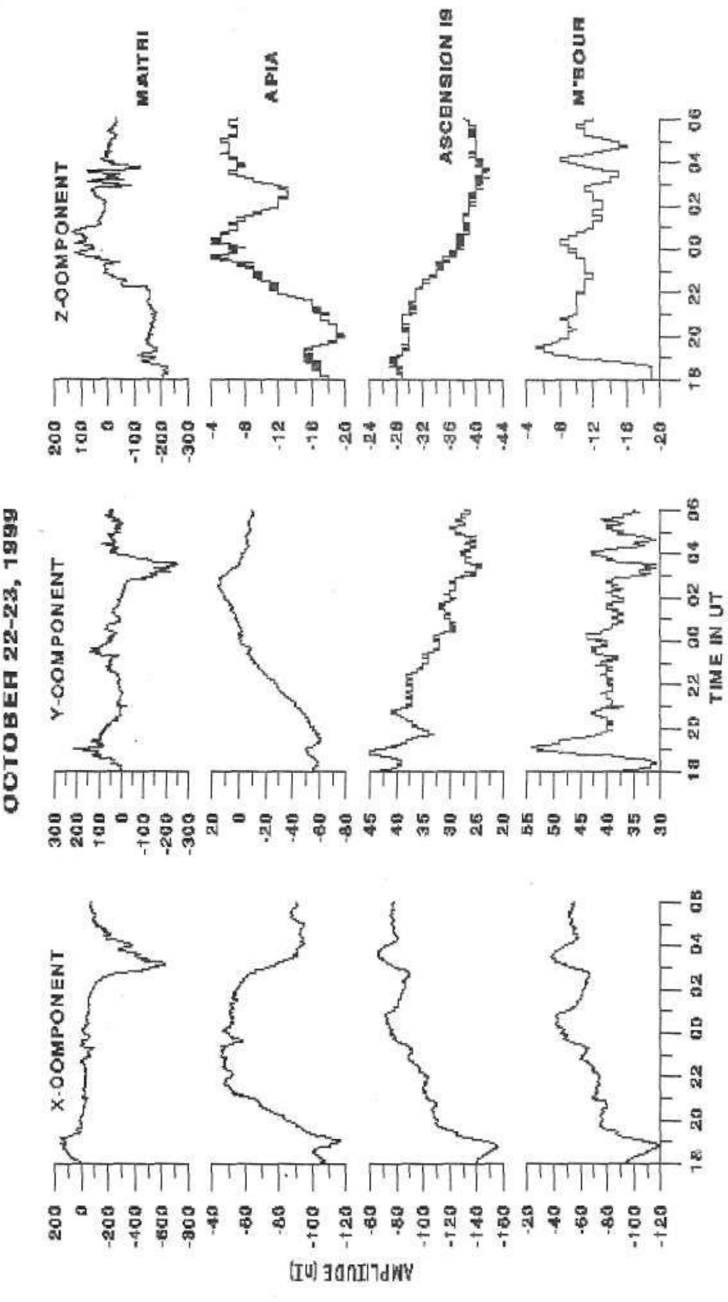

Fig. 4: Filtered plots and amplitude spectrum of the substorm event shown in Figure 2. The filtering is done in the range 40-180 minutes. The filtered electric field pattern is remarkably similar to the low-latitude components, except for being in anti-phase. The amplitude spectrum shown in terms of periodicities shows the presence of identical periodicities. At the bottom of the filtered plots is given the satellite coordinates (GSE) for the beginning and end of the interval.

harmonics. Also, since the satellite data is sampled at 64 seconds, the discrete frequency levels are slightly different for the electric field data.

Discussion

We have shown that the amplitudes of the low-latitude X-component correlate well with the negative peak magnitude of the X-component at Maitri. Since our study concerns stations only along a particular geomagnetic meridian, we have studied the relation between the peak values of the magnetic components. A study of the relationship between the high and low latitudes on the basis of detailed time development of magnetic fields would require a number of mid-latitude stations distributed across several longitudes to decipher the exact position of the wedge and is beyond the scope of this paper. The correlation obtained by us is in agreement with the low-latitude magnetic signatures being due to the disruption of the magnetospheric neutral-sheet current and its diversion through the auroral ionosphere. A similar result was obtained by Liihr and Buchert (1988) on the basis of simultaneous comparison of satellite and auroral ground data during a substorm when the satellite was in the tail at -14 R_E. They found a clear anticorrelation between northward component of ground magnetometer and Bz (GSM) component of satellite magnetometer data indicating a diversion of the cross-tail current through the auroral ionosphere. Vagina et al. (1997) made use of meridian chain of magnetometers in the northern hemisphere high latitudes along with mid-latitude magnetograms and found a strong correlation between the computed total current of the westward ionospheric current and the total current of the substorm wedge obtained using inversion methods. The positive signature in the Y-component at auroral latitudes is due to the influence of the westward traveling surge (WTS). It is caused by anticlockwise ionospheric Hall current encircling upward field-aligned current (FAC) at the surge's head (Opgenoorth et al., 1983). The segment of the Hall current in front of the surge directed southward is responsible for the positive Y-component signature. The WTS is the western extremity of the substorm current wedge and the upward FAC at its head is the segment of the current wedge carrying the return current to the neutral sheet. Hence, a relation may also be expected between the Y-component and the low latitude X-component. A definite but non-linear and logarithmic relation is seen between the two. This observation may be attributed to the enhanced conductivity of the auroral ionosphere as a result of particle precipitation. The ionospheric Hall and Pedersen conductances in the auroral region have been shown to increase significantly with increase in geomagnetic activity (Hardy et al., 1987). Hence for large intensity substorms, this increased conductance would contribute towards the enhancement of the Hall currents responsible for the Y-component signature on the ground magnetogram, thus showing the departure from a linear relationship.

In this study, periodicities in the range of 40-130 minutes are seen at low latitudes in both hemispheres during substorms. These seem to be long-period magnetohydrodynamic (MHD) waves associated with substorms. Further, these waves are not always detectable at Maitri. Similar long-period waves greater than 30 minutes and associated with substorms were studied by Wang et al. (1977). On the basis of magnetogram signatures they found that these waves are found at all latitudes and suggested that they were hydromagnetic waves generated by cavity resonance of the plasmasphere. In this paper, we have spectrum analysed the data from all the stations considered and have brought out the specific periodicities common to all the stations. An examination of the periodicities in the H-component at a dayside low-latitude station Apia (Geom. Lat. -15.55, long. 262.15) showed periodicities identical with those on the nightside for two of the events, July 30 and Oct 23. Thus, these periodicities may also propagate to the dayside hemisphere. For the July 30 event the 54-minute periodicity was seen and for the Oct 23 event all three periodicities were evident. An examination of the sunward and duskward components of the electric field in the magnetotail was made for the events when GEOTAIL was located in the tail region. The spacecraft was in the tail region for 3 of the events - Jan 15, May 2 and Oct 23. Periodicities identical to those on ground were seen in the sunward component for the Jan 15 and Oct 23 events. For these 2 events the GSE Y-component magnitude of the spacecraft location was -12 R_E, it appears that the spacecraft was in the low-latitude boundary layer. The observed periodicities seem to have their origin in substorm processes in the magnetotail. As suggested by Kikuchi et al. (1978), it is possible that electric fields in the magnetosphere penetrate to low latitudes through the high latitudes to which they are mapped. The identical periodicities observed on the dayside seem to support this mode of propagation. Kikuchi et al. (2000b) have demonstrated that auroral electric fields during a substorm indeed penetrate to the dayside low latitudes. They showed that the DP ionospheric currents had a major role in the substorm related disturbances at the low latitudes. Since ionospheric currents in the dark hemisphere are negligible, it appears that the periodicities seen at Ascension Island and M'Bour should be accounted for by a different explanation. It is hence suggested that these result from MHD waves related to fluctuations in the current wedge and their direct penetration to the ground. This could be a result of the loss of shielding associated with Region 2 field-aligned currents, which in turn is a consequence of the cross-tail current disruption (Rostoker, 1996). In our case, the fact that the periodicities observed at the low-latitudes are not always seen at Maitri could be an indication that these long-period waves are sometimes obscured by the DP 1 currents in the auroral region.

Some of the periodicities discussed in this study overlap with periodicities associated with the DP 2 current system, timescales of which are of the order of an hour (Nishida, 1968a). Also, Clauer and Kamide (1985) have shown that DP 2 may continue to exist during the expansion phase of substorms. It may hence be suspected that at least some of the periodicities of this study are a result of DP 2. Nishida (1968b) had shown that DP 2 fluctuations observed on ground magnetograms are coherent with the north-south component of the interplanetary magnetic field (IMF). We hence spectrum analysed the GSM B_z component of the IMF using data from the WIND satellite. A clear absence of the ground periodicities was observed thereby suggesting that these periodicities have more to do with the magnetotail dynamics during the substorm phenomenon.

Bauer et al. (1995) used magnetometer and plasma instrument data aboard AMPTE/ IRM satellite to study low-frequency waves in the near-Earth plasma sheet. According to them the magnetic field power spectra in the range 17 min to 2 hours may be expected to reflect the substorm dynamics in the tail region. They attribute the field variation in the X (GSM) direction to changes in the neutral sheet current. From our study we add that these changes in the neutral sheet current could be influenced by the fluctuations in the sunward component of electric field.

As mentioned earlier, periodicities observed at the low-latitudes during substorms may be interpreted as periodicities in the current wedge. Since these periodicities are also seen in the sunward component of the tail electric field, it may be suggested that this component of the electric field is closely associated with the wedge current. As the negative peak in the filtered electric field precedes the positive peak in the X-component (filtered data) at the low-latitude stations, this electric field possibly has a modulating influence on the wedge. The spacecraft was in the dusk sector for the event of Jan 15 and in the dawn side for the Oct 23 event. The electric field shows sharp negative excursions corresponding to the expansion phase of the substorms. Even though the GEOTAIL spacecraft was displaced considerably from the midnight meridian with magnitude of GSE Y-component -12 R_E, comparison with earlier studies (Roux et al., 1991; Maynard et al, 1996) of the sunward component of electric field suggest that the behaviour of this component of the electric field is similar throughout the near-earth magnetosphere, showing intense fluctuations. Increased fluctuations are seen in the sunward component of the electric field beginning with the substorm growth phase. The behaviour of the electric field in the GSE X-direction (E_x) has not been well understood (Smits et al., 1986). Kelly et al. (1984) studied the motion of current sheet associated with a substorm using ISEE 1 and 2 satellites and suggested that the E_x component was related to the motion of high speed plasma at the center of the current sheet towards a direction away from midnight (in an azimuthal direction). It appears that the importance of the changes in the sunward component of the electric field during substorms lies in its attempt to modify the predominantly earthward magnetospheric bulk plasma motions caused by the dawn-dusk electric field, by introducing an azimuthal component to the motion. Most of the studies concerning magnetospheric electric fields to-date have concentrated on the dawn-dusk component of the tail electric field. In view of the relationship of the sunward component of the magnetotail electric field with low latitudes, revealed in this study, it appears that more attention needs to be paid to this component of electric field, particularly during substorms.

In this study our observations are based mainly on the observatories lying along a particular geomagnetic longitude (~57°). However we believe that our findings would hold for stations lying across a range of longitudes since the substorm current wedge in the magnetosphere expands azimuthally, both towards the dawnside as well as duskside (Nagai, 1982). Thus, our study may be expected to represent the behaviour of a considerable extent of the nightside low latitudes.

Conclusions

The results of this study may be summarized as follows:

The peak of the X-component substorm bay at low latitudes is linearly related to the negative peak of the X-component at auroral latitudes as expected for the substorm current wedge model. The relation of the low-latitude X-component peak with the auroral Y-component positive peak is non-linear well represented by logarithmic relationship. This seems to be due to the conductivity enhancement in the oval during intense substorms.

The X-component at low-latitudes during substorms shows periodicities in the range 40-130 minutes. Common periodicities are observed in both northern and southern hemispheres and sometimes in the auroral oval. Dayside low latitude stations may also show periodicities identical to those on the nightside.

The sunward component of the magnetotail electric field shows negative excursions during the expansion phase of substorms. It also exhibits periodicities identical to those observed at low-latitudes during substorms. This may be interpreted as the current wedge being modulated by this component of the electric field.

The auroral station does not always show periodicities observed at the low latitudes. It appears that the periodicities may be obscured by the DP 1 currents. The role played by the sunward component of the magnetotail electric field during substorms needs to be investigated in more detail.

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References

Abdu, M. A., Sastri, J. H., Luhr, H., Tachihara, H., Kitamura, T., Trivedi, N. B., Sobral, J. H. A., 1998. DP 2 electric field fluctuations in the dusk-time dip equatorial ionosphere. Geophys. Res. Lett. 25 (9), 1511-1514.

Bauer, T. M., Baumjohann, W., Treumann, R. A., Sckopke, N., 1995. Low-frequency waves in the near-Earth plasma sheet. J. Geophys. Res. 100 (A6), 9605-9617.

Clauer, C. R., Kamide, Y., 1985. DP 1 and DP 2 current systems for the March 22, 1979 substorms. J. Geophys. Res. 90 (A2), 1343-1354.

Cooley J.W., Tukey, J. W., 1965. An algorithm for the machine calculation of complex Fourier series. Math, of Comput. 19, 297-301.

Fejer, B. G, Gonzales, C. A., Farley, D. T., Kelley, M. C, 1979. Equatorial electric fields during magnetically disturbed conditions 1. The effect of the interplanetary magnetic field. J. Geophys. Res. 84 (A10), 5797-5802.

Gonzales, C. A., Kelley, M. C, Fejer, B. G, Vickrey, J. F, Woodman, R. F, 1979. Equatorial electric fields during magnetically disturbed conditions 2. Implications of simultaneous auroral and equatorial measurements. J. Geophys. Res. 84 (A10), 5803-5812.

Hardy, D. A., Gussenhoven, M. S., Raistrick, R., 1987. Statistical and functional representations of the pattern of auroral energy flux, number flux and conductivity, J. Geophys. Res. 92 (All), 12,275-12,294.

Kalra, R., Ajay Dhar, Unnikrishnan, K., Jeeva, K., Daga, D. M., Girija Rajaram, 1995. Changes in the auroral electrojet currents inferred from geomagnetic field variation at Maitri and northern conjugate stations, pp 87-101, Scientific report of 11th Indian expedition to Antarctica, Tech. Publication No. 9, Dept. of Ocean Development, New Delhi, India.

Kamide, Y., Matsushita, S., 1981. Penetration of high-latitude electric fields into low latitudes. J. Atmos. Terr. Phys. 43 (5/6), 411-425.

Kelly, T. J., Russell, C. T, Walker, R. J., 1984. ISEE 1 and 2 observations of an oscillating outward moving current sheet near midnight. J. Geophys. Res. 89 (A5), 2745-2754.Kikuchi, T., Araki, T, Maeda, H., Maekawa, K, 1978. Transmission of polar electric fields to the equator. Nature 273, 650-651.

Kikuchi, T, Liihr, H., Kitamura, T., Saka, O., Schlegel, K., 1996. Direct penetration of the polar electric field to the equator during a DP 2 event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar, J. Geophys. Res. 101 (A8), 17161-17173.

Kikuchi, T, Pinnock, M., Rodger, A., Luhr, H., Kitamura, T., Tachihara, H., Watanabe, M., Sato, N., Ruohoniemi, M., 2000a. Global evolution of a substorm-associated DP 2 current system observed by SuperDARN and magnetometers. Adv. Space Res.Kikuchi, T., Liihr, H., Schlegel, K., Tachihara, H., Shinohara, M., Kitamura, T. -I., 2000b. Penetration of auroral electric fields to the equator during a substorm. J. Geophys. Res. 105 (A10), 23251-23261.

Liihr, H., Buchert, S., 1988. Observational evidence for a link between currents in the geotail and in the auroral ionosphere. Ann. Geophys. 6, 169-176.

Maynard, N. C, Burke, W. J., Basinska, E. M., Erickson, G. M., Hughes, W. J., Singer, H. J., Yahnin, A. G, Hardy, D. A., Mozer, F. S., 1996. Dynamics of the inner magnetosphere near times of substorm onsets. J. Geophys. Res. 101 (A4), 7705-7736.

Nagai, T, 1982. Observed magnetic substorm signatures at synchronous altitude. J. Geophys. Res. 87 (A6), 4405-4417.

Nishida, A., Iwasaki, N., Nagata, T., 1966. The origin of fluctuations in the equatorial electrojet: A new type of geomagnetic variation. Ann. Geophys. 22, 478.

Nishida, A., 1968a. Geomagnetic D_P 2 fluctuations and associated magnetospheric phenomena. J. Geophys. Res. 73 (5), 1795-1803.

Nishida, A., 1968b. Coherence of geomagnetic DP 2 fluctuations with interplanetary magnetic variations. J. Geophys. Res. 73 (17), 5549-5559.

Nowroozi, A. A., 1967. Table for Fisher's test of significance in harmonic analysis. Geophys. J. R. astr. Soc. 12, 517-520.

Opgenoorth, H. J., R. J. Pellinen, W. Baumjohann, E. Nielsen, G. Marklund and L. Eliasson (1983), Three-dimensional current flow and particle precipitation in a westward travelling surge (observed during the Barium-Geos rocket experiment), J. Geophys. Res., 88, 3138-3152.

Reddy, C. A., Somayajulu, V. V., Devasia, C. V., 1979. Global scale electxodynamic coupling of the auroral and equatorial dynamo regions. J. Atmos. Terr. Phys. 41, 189-201.

Rostoker, G, 1993. Low latitude signatures of substorm activity, J. Atmos. Terr. Phys. 55 (7), 985-994.

Rostoker, G, 1996. Phenomenology and physics of magnetospheric substorms. J. Geophys. Res. 101 (A6), 12,955-12,973.

Roux, A., Perraut, S., Robert, P., Morane, A., Pedersen, A., Korth, A., Kremser, G, Aparicio, B., Rodgers, D., Pellinen, R., 1991. Plasma sheet instability related to the westward traveling surge. J. Geophys. Res. 96 (A10), 17,697-17,714.

Sastri, J. H., Ramesh, K. B., Ranganath Rao, H. N., 1992. Transient composite electric field disturbances near Dip equator associated with auroral substorms. Geophys. Res. Lett. 19, 1451-1454.

Sastri, J. H., 2000. Equatorial ionosphere under disturbed conditions. J. Ind. Geophys. Union. 4 (2a), 65-76.

Sastri, J. H., Liihr, H., Tachihara, H., Kitamura, T -I., Rao, J. V. S. V., 2000. Electric field fluctuations (25-35 min) in the midnight dip equatorial ionosphere. Ann. Geophys. 18, 252-256.

Shimshoni, M., 1971. On Fisher's test of significance in harmonic analysis. Geophys. J. R. astr. Soc. 23, 373-377.

Smits, D. P., Hughes, W. J., Cattell, C. A., Russell, C. T., 1986. Observations of field-aligned currents, waves, and electric fields at substorm onset, J. Geophys. Res. 91 (Al), 121-134.

Tsuruda, K., Hayakawa, H., Nakamura, M., Okada, T, Matsuoka, A., Mozer, F S., Schmidt, R., 1994. Electric field measurements on the GEOTAIL satellite. J. Geomag. Geoelectr. 46, 693-711.

Vagina, L. I., Sergeev, V. A., Kotikov, A. L., Shishkina, E. M., 1997. On the relationship between parameters of substorm current wedge and westward electrojet. Adv. Space Res. 20 (3), 477-480.

Wang, C. S., Lee, T., Kim, J. S., 1977. Substorm-associated long-period hydromagnetic waves. J. Geophys. Res. 82 (19), 2867-2874.