Observations of near-conjugate high-latitude substorms and their low-latitude implications

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Geomagnetic substorms are triggered on the nightside of the earth's magnetosphere and the most dramatic effect is observed at the auroral latitudes (60°–70° magnetic). Magnetic field disturbances observed at a set of longitudinally distributed auroral stations are used to derive auroral electrojet (AE) indices being widely used to monitor substorm activities. We present observations of magnetic substorms having more prominent effect poleward of the standard auroral oval. Magnetic data from the third Indian Antarctic station, Bharati (BHA; corrected geomagnetic (CGM) coordinates: 74.7°S, 96.6°E) in conjunction with IMAGE chain data (near conjugate station Hornsund (HOR; CGM coordinates: 74.3°N, 108.5°E) have been subjected to detailed examination to study such substorms. The substorms presented in this study were mainly localized to high latitudes and hence the standard AE indices failed to monitor such substorm activities. Nevertheless, typical low-latitude features of substorm, for example, positive bay and Pi2 burst on the nightside were distinctly evident.

Keywords: Auroral electrojet, geomagnetic substorms, magnetic field disturbances, Pi2 pulsations.

A GEOMAGNETIC substorm is an important consequence of solar wind–magnetosphere–ionosphere coupling. Enormous amount of energy derived from the solar wind–magnetosphere interaction is explosively released into the auroral ionosphere and the magnetosphere[1]. Auroral break-up, enhancement in ionospheric and magnetospheric currents, enhanced cosmic radio noise absorption, Pi2 pulsations, etc. are important manifestations of a substorm. In general, a substorm is triggered at the nightside auroral latitude and the most dramatic effect is observed in the auroral region. Nevertheless, nearly all regions of the magnetosphere undergo significant magnetic and electric field changes during a substorm[2,3].

Magnetic field disturbances observed at different local times in the auroral region are the basis of widely used auroral electrojet (AE) indices which were introduced more than four decades ago[4]. The auroral zone stations near midnight and dawn come under the influence of an intensified westward electrojet during a substorm. This westward flowing ionospheric current depresses the earth's magnetic field. As a result, the stations near midnight witness sharp depression in magnetic field[1]. In contrast, the stations towards dusk witness eastward electrojet flowing in the ionosphere and consequently the magnetic field is enhanced during the course of a substorm.

The upper envelope of the horizontal (*H*) component disturbances observed at selected 10–12 auroral stations is called the AU index, which is a measure of maximum intensity of the eastward electrojet. Whereas the lower envelope of H disturbances, the AL index, gives an idea of the maximum intensity of the westward electrojet[4,5]. The difference between AU and AL is termed as the AE index. The three indices, AU, AL and AE are collectively known as AE indices and are often used to monitor substorm activities.

Recently, Kamide and Rostoker[6] strongly criticized the derivation and application of AE (= AU – AL). AU and AL indices representing maximum intensities of the eastward and westward electrojets respectively, are generated by different physical phenomena and are quite different in nature. The sum of the maximum intensities of two such different currents does not have physically interpretable meaning[6]. It was suggested that the westward electrojet is closely related to the substorm activity and hence the AL index should be used to monitor substorms, rather than AE.

Substantial magnetic and electric field changes are marked at lower latitudes during substorms. A typical positive bay in the *H* component of the geomagnetic field is often observed on the nightside[2]; however, the dayside magnetic signatures at lower latitudes are rather complex[7,8]. Lower-latitude ionospheric electric fields on the day as well as the nightsides of the earth are significantly altered due to the substorms. It has been shown that on occasions the high-latitude electric field associated with substorms can penetrate down to the equatorial latitudes[9,10]. On the dayside, the penetrated electric field drives a strong current due to the abruptly high ionospheric conductivity[7]. This current modifies the magnetic signature of a substorm on the dayside, whereas no such significant effect of penetrated electric field is observed in nightside magnetic field due to lower ionospheric conductivity.

The auroral oval is quite dynamic, expands equatorward and contracts poleward in accordance with change in interplanetary magnetic field (IMF), solar wind pressure variations and the strength of substorm activity[11,12]. There is certain probability that a substorm can trigger beyond the standard auroral oval and the AE stations cannot monitor substorm electrojet activity precisely. Earlier reports suggest that substorms, localized poleward of the standard auroral oval, are quite frequently observed in the winter hemisphere during the descending phase of a solar cycle[13,14]. However, substorms triggered poleward of the auroral oval during contraction and normal

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substorms (triggered in the auroral region) represent the same physical phenomenon[15]. Lui *et al.*[15] described a substorm event triggered poleward of the auroral oval (~ 70.4° magnetic latitude) whose low-latitude signatures were not evident.

It is a general belief that the substorm disturbances are mirror images in the opposite hemispheres, though conjugate auroral observations have shown significant asymmetries between the two hemispheres during a substorm[16–18]. However, limited availability of magnetic records in the southern auroral region (most of the oval region being in ocean) restrains the study of conjugate characteristics of magnetic signatures of auroral electrojets[19,20].

In this communication, we present observations of magnetic substorms from the Indian Antarctic station, Bharati (BHA) and its near conjugate station, Hornsund (HOR). Using magnetic data from low-latitude station, Alibag (ABG), we demonstrate that the low-latitude signatures of substorms are distinctly evident despite the fact that AE indices fail to monitor such substorms.

We operated a digital flux-gate magnetometer (DFM) at the third Indian Antarctic station, Bharati, Larsemann Hill, during the last five (XXVI–XXX) Indian Scientific Expeditions to Antarctica (ISEA). The magnetic field components at BHA were recorded at 1 h, 1 min and 1 s intervals. The Indian station BHA (corrected geomagnetic (CGM) coordinates: 74.7°S, 96.6°E; magnetic local time (MLT) = Universal time (UT) + 01:46) and IMAGE chain station, HOR (CGM: 74.3°N, 108.5°E; MLT = UT + 02:56) lie nearly in the same magnetic flux tube and form a near-conjugate pair. Hourly, minute and 10 s resolution magnetic data from IMAGE chain stations in the northern hemisphere are available on-line (http://www.space.fmi.fi/image/reqform/dataform.html). In the present study, we used 1 min magnetic data from BHA and IMAGE stations. Simultaneous 1 s resolution magnetic data from low-latitude station, ABG (geomagnetic coordinates: 10.3°N, 146.6°E; MLT = UT + 4:58), located in the western coast of the Indian subcontinent, was used to examine the low-latitude signature of the substorm which is not registered by standard AE indices.

Geomagnetic indices (AU, AL and ASY) were obtained from WDC Kyoto (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html). Interplanetary and solar wind conditions were recorded by instruments aboard the ACE satellite and were made available by CDAWeb (http://cdaweb.gsfc.nasa.gov/istp_public/).

We present case studies of two important substorms clearly localized poleward of the standard auroral observatories, on 2 March 2008 and 21 December 2009. Fortunately, for the event of March, the POLAR satellite (located at $X = -2.91$ *Re*, $Y = 1.53$ *Re*, $Z = -5.96$ *Re* in the geocentric solar magnetospheric (GSM) coordinate system; here *Re* is the radius of the earth = 6378 km) could capture ultraviolet (UV) images of auroral activities in the southern hemisphere. However, no such satellites were operational during the event of December 2009.

First let us consider the event of 2 March 2008. Figure 1 depicts IMF and solar wind conditions as observed by instruments aboard the ACE satellite located outside of the earth's magnetosphere at ($X = 235.7$ *Re*, $Y = 36.5$ *Re*, $Z = 8.4$ *Re*) in GSM coordinate system. In order to compare the interplanetary observations with ground magnetic data, IMF and solar wind data have been delayed by 40 min taking into account the travel time of the solar wind at an average speed of ~ 600 km/s from the location of the satellite to the magnetopause of the earth.

The top two panels in Figure 1 show components of IMF, whereas the next two panels show solar wind velocity and density and dynamic pressure respectively, during 20:00–02:00 UT on 2–3 March 2008. In the fifth panel from the top, *H* disturbance at BHA and HOR shows sharp depression of ~ –400 nT during the event A as marked by pair of dotted vertical lines. Substorm indices AU and AL do not show any significant change in this interval; however, a substorm activity can be identified in AU and AL during event B without appreciable field changes at high latitudes.

Ground and satellite-based observations of aurorae have proved that the auroral break-ups are the best indicator of substorm onset[21]. A less intense auroral arc at the nightside auroral latitude is commonly observed during the early stage of an isolated substorm. The arc first

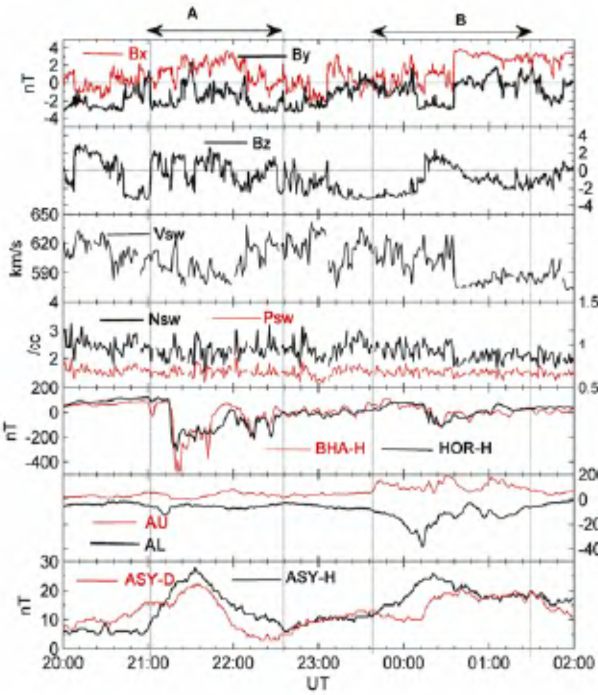

Figure 1. (Top to bottom) Components of the interplanetary magnetic field (IMF), solar wind velocity, density and dynamic pressure variations as observed by the ACE satellite, *H* disturbance at high-latitude near-conjugate stations, AU, AE and ASY indices on 2–3 March 2008. Event A shows a substorm localized to high latitude, whereas event B represents a normal substorm. Interplanetary observations are delayed by 40 min to compare with the ground data.

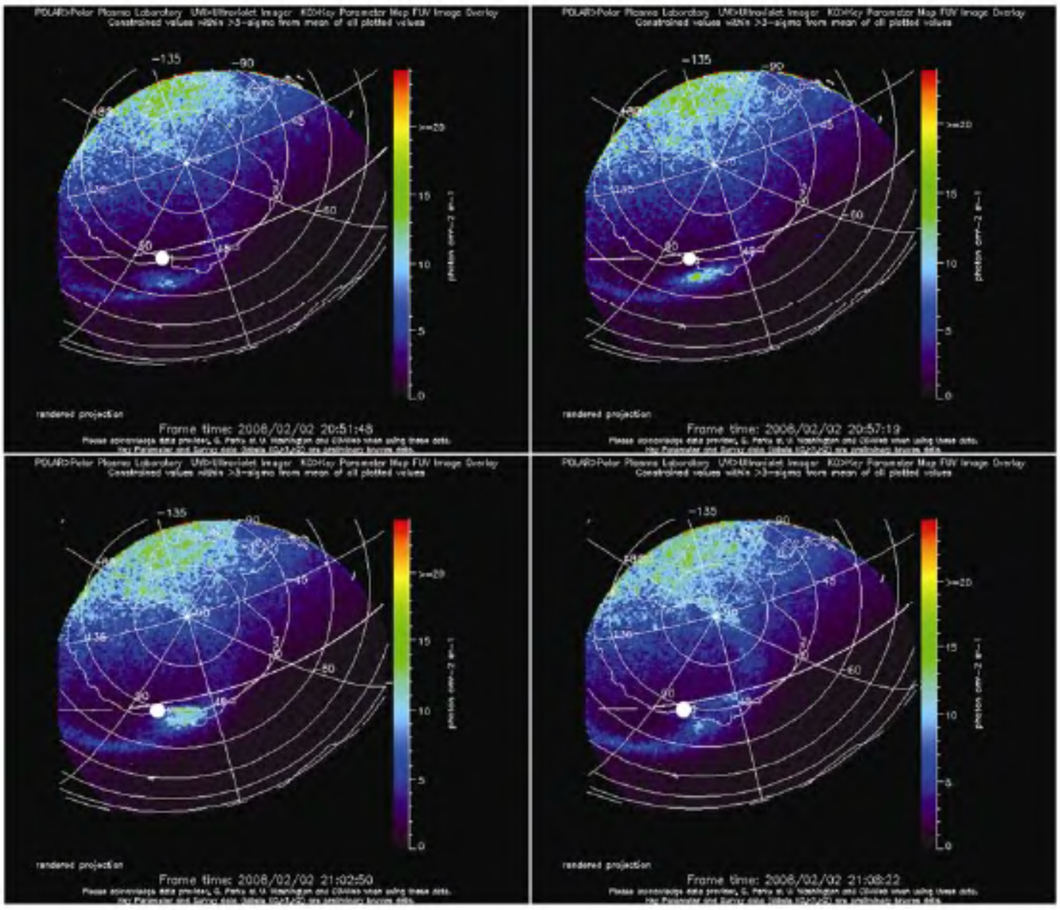

Figure 2. Ultraviolet images of auroral activity from the POLAR satellite during the event of 2 March 2008. Left panel on the top indicates that there is no significant auroral brightening at 20:51 UT. However, right panel on the top shows a burst of aurora at 20:57 UT equatorward of the station BHA (indicated by a white dot) in southern hemisphere which expanded poleward at 21:02 UT (left plot, bottom) and faded away later (right plot).

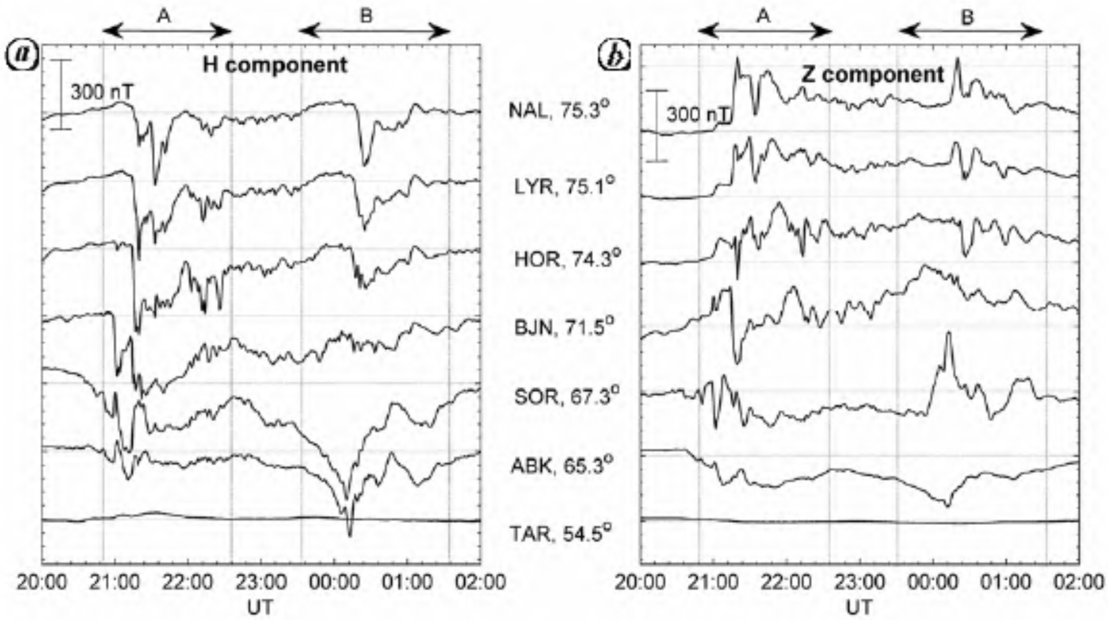

Figure 3. *H* (***a***) and *Z* (***b***) components at closely spaced IMAGE chain stations (~ 100° magnetic meridian) on the nightside of the earth. Event A is localized poleward of standard AE observatory ABK. Opposite variations in *Z* component between stations BJN and HOR demarcate the centre of the westward electrojet for the event A and between ABK and SOR for the event B.

migrates equatorward due to the stretching of the nightside magnetotail[22]. After the onset of the substorm, the stretched magnetic field lines rapidly return to the dipolar configuration causing the aurora to move poleward[23].

In Figure 2 we depict the UV images of the POLAR satellite during 20:52–21:08 UT. White dots in the figure represent the location of the BHA station and the grid shows geographic coordinates. Auroral break-up is evident equatorward of BHA at 20:57 UT (right panel, top) and has expanded poleward (i.e. towards BHA) at 21:02 UT (left panel, bottom) followed by a sharp depression in the magnetic field at BHA. The next frame shows that the auroral activity fades away; however, further images (not shown here) indicate bright auroral activity. It should be noted that the poor image quality and time resolution during the event do not reveal the equatorward migration of the aurora before the onset of the substorm. Similar auroral images are not available in the conjugate northern hemisphere, but the ground magnetic data at the near conjugate station, HOR, show grossly similar substorm features (see Figure 1).

A substorm activity introduces asymmetric magnetic field disturbance at low-latitude and can be identified using ASY indices[24]. Enhanced magnetic field asymmetry is evident in Figure 1 during both events (A and B), despite the fact that the substorm A was not identified in the AE indices.

Closely spaced IMAGE chain stations in the northern hemisphere provide an opportunity to study the latitudinal characteristics of these substorms. Standard AE observatory, ABK near midnight (where maximum disturbance is expected), does not show any appreciable field change during the event A (Figure 3). Consequently, AL index does not indicate significant change during the event.

Intensified westward electrojet depresses the H field over a wide range of latitudes[25]. Stations, poleward of ABK, observe depression in the H field which gets maximized at HOR. The centre of the westward electrojet can be estimated using Z disturbance. Poleward of the centre of the electrojet, the H component is depressed and the Z component is enhanced, whereas equatorward of the centre of the electrojet, both H and Z components are depressed[1,26]. For event A, depression in H is observed to be the most prominent near station HOR and the Z variations are grossly opposite between stations BJN and HOR after the onset of the substorm, as shown in Figure 3. This suggests the fact that the centre of the substorm electrojet was lying between BJN and HOR for event A. The centre of the electrojet was between ABK and SOR for a normal substorm (event B) as shown in Figure 3.

Positive bay and Pi2 bursts on the nightside low-latitude are typical features of a magnetic substorm[27]. Low-latitude station, ABG, on the nightside of the earth, clearly observed positive bay and Pi2 bursts during event A, as depicted in Figure 4. As for event B, it was sunrise time at station ABG; we do not observe similar positive bay or Pi2 pulsations.

Now let us consider the event of 21 December 2009. A magnetic substorm (~ –300 nT) localized to high latitudes was observed during 20:00–21:15 UT on 21 December 2009 without any clear signature in the AE indices. Figure 5 shows the IMF and solar wind conditions as

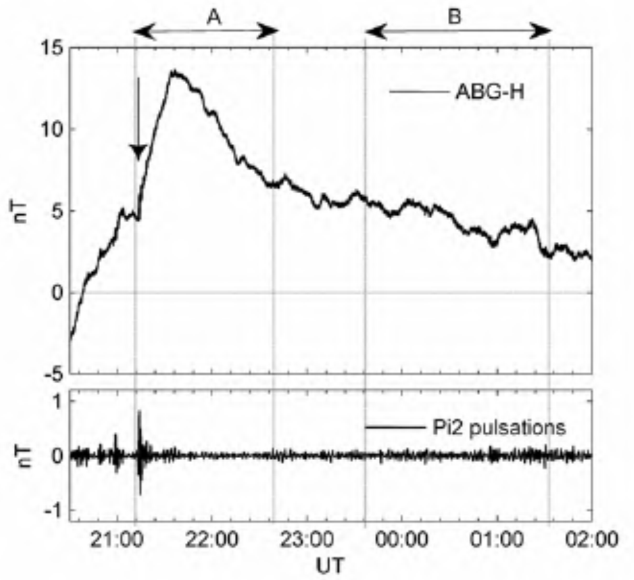

Figure 4. Top panel shows a clear positive bay during the event A at low-latitude station ABG, which starts with the onset of Pi2 burst (bandpassed H in frequency range 5–25 mHz) displayed in bottom panel.

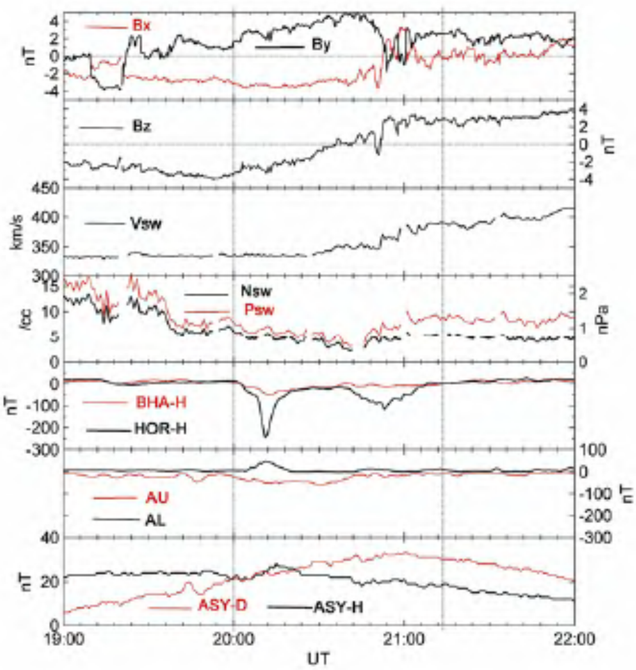

Figure 5. Same as Figure 1, but on 21 December 2009. The interplanetary data are shifted by 60 min in this case. A substorm disturbance is evident at HOR, whereas fairly weak magnetic disturbance is observed at BHA. The substorm is not registered by auroral indices (AU and AL).

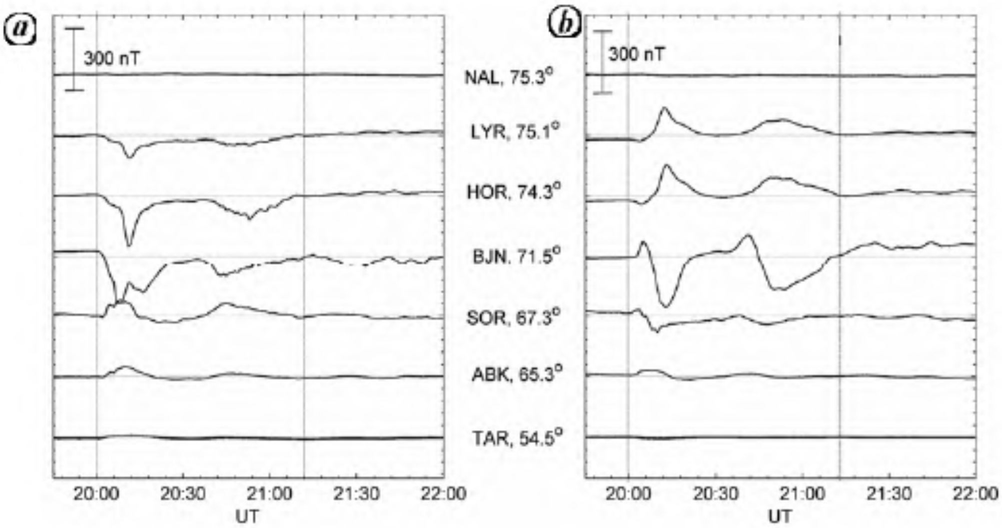

Figure 6. *H* (***a***) and *Z* (***b***) components at the IMGAE chain stations on 21 December 2009. The centre of the westward electrojet clearly lies between BJN and HOR.

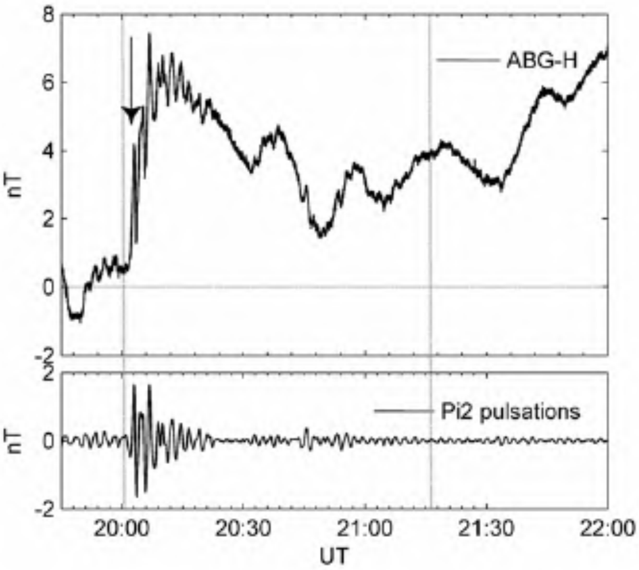

Figure 7. Same as Figure 3, but for the event on 21 December 2009.

observed by the ACE satellite located at (X = 218.2 *Re*, Y = 1.5 *Re*, Z = –6.0 *Re*) in GSM coordinates. The ACE satellite data have been delayed by 60 min taking into account the travel time of the solar wind to the magnetopause at a constant speed of 365 km/s. In this case, clear depression (~ –250 nT) is observed at HOR, but the disturbance is fairly weak at the near conjugate station BHA.

The *H* and *Z* component perturbations at the IMAGE chain stations lying in the northern hemisphere are shown in Figure 6. The amplitude of disturbance is maximum (~ –300 nT) at BJN and decreases to ~– 250 nT at the poleward station HOR. Based on the phase-reversal in *Z* disturbance between stations BJN and HOR, it can be inferred that the centre of the electrojet was lying between BJN and HOR during the substorm. Although asymmetry in the magnetic field at low-latitudes is not obvious in Figure 5, clear positive bay and Pi2 burst at the nightside low-latitude station ABG are evident during the onset of the substorm in Figure 7.

Magnetic substorms are observed as a consequence of diversion of the tail current into the inner magnetosphere at a distance around 10–25 *Re* on the nightside of the earth either due to changes in IMF and solar wind conditions, or internal plasma instabilities[28,29]. These distant magnetic field lines map to auroral latitudes at the surface of the earth and result in dramatic effect in the magnetic field at auroral latitudes. During quiet magnetospheric conditions, the merging of field lines and diversion of tail current may take place further deeper into the magnetotail[3], and the most dominant magnetic field fluctuations are observed poleward of auroral latitudes. Consequently, AE indices do not monitor such substorms.

We have presented two substorm events, on 2 March 2008 and 21 December 2009, confined to higher latitudes during local midnight. These substorms were not reflected in the standard AE indices. The centre of the electrojet for both events was lying poleward of the 71° magnetic latitude. The amplitude of disturbances was comparable and varied in tandem at the two near-conjugate stations for the 2 March 2008 event, whereas for the event on 21 December 2009, higher amplitude was observed in the northern hemisphere than in the southern hemisphere.

It is known that a substorm triggered at some latitude propagates poleward; more easily and deeply in the dark hemisphere than those in the sunlit hemisphere due to significant difference in the ionospheric conductivity[14,20]. During the month of December, high-latitude station HOR (northern hemisphere) and BHA (southern hemisphere) were respectively in dark and sunlit hemisphere respectively. As a consequence of lower conductivity in the northern hemisphere during December (deprived of sunlight), the substorm propagated easily to HOR. Whereas at BHA in the southern hemisphere, where ionospheric conductivity was higher during December, the substorm disturbance was confined to a narrow latitudinal region and did not leap efficiently to BHA.

During the event of 2 March 2009, night-time condition was observed at BHA. This would result in a drop in the ionospheric conductivity over BHA. Expectedly, when the two near-conjugate stations are in dark, substorm-associated disturbance will penetrate deep into the polar latitudes in both the hemispheres. As shown in Figure 1, comparable magnetic field disturbances were observed at BHA and HOR.

A magnetic substorm makes significant magnetic field changes at low latitudes on the nightside of the earth. Positive bay in *H* component, ASY *H*/*D* enhancements and Pi2 bursts associated with auroral substorms have been extensively studied for the identification of substorm onset[2,24,27,30]. However, low-latitude implications of polar substorms have got less attention despite the fact that there is no physical difference between the substorm triggered at the auroral and polar latitudes[15]. We showed that the low-latitude signatures of substorms were clearly identified even if AE indices fail to monitor them. However, for the event of 21 December 2009, ASY enhancements were not clear (bottom panel, Figure 5) unlike the event of 2 March 2008 when ASY enhancement was quite evident (Figure 1). As the ASY indices are computed using magnetic data from 5 to 6 longitudinally distributed stations, there is a probability that weak and localized substorms may not be observed at any of these selected stations. In such cases, substorms may not appear clearly in the ASY indices.

Finally, it may be concluded that the inclusion of high-latitude data in the meridian of standard AE stations could improve the AE indices to identify substorms occurring at latitudes higher than the standard auroral latitudes.

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