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Solar wind-magnetosphere-ionosphere coupling: Pi2 observations

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There had been a number of studies using satellite and ground based observations on the interaction between the solar wind and the magnetosphere, which shows highly complex temporal and spatial interaction between the two. The magnetotail provides an important channel for the flow of energy from solar wind to the ionosphere and atmosphere. Solar wind drives reconnection under certain conditions on the dayside magnetopause, connecting the interplanetary and geomagnetic fields. As a result, the field lines are swept back to the magnetotail where magnetic energy is built up. This stored energy may be converted to plasma kinetic energy either in continuous mode or impulsive mode. In either case, this kinetic energy appears in the energization of the electrons and ions which stream along the magnetic field line in the plasma sheet boundary layer towards the Earth. This flow of energized charged particles results in the form of energy deposition in the high latitude ionosphere and high latitude atmosphere manifesting in terms of aurora. It has been shown from the results obtained from the analysis of ground based magnetic data that, the solar wind driven energy through the magnetotail makes global appearance in the night side of the Earth in the form of Pi2 pulsations. Compressional waves, following plasma sheet thinning due to reconnection, move Earthward and cause plasmasphere to oscillate at discrete frequencies. The present analysis reveals that Pi2 energy is having a global impact on the low latitude in transferring the energy and momentum from solar wind to ionosphere through tail region. During a geomagnetic quiet period (Kp= -3), the scrutiny of the magnetic records from a wide chain of magnetic observatories in the low and mid latitudes gave signatures of plasmaspheric cavity oscillations at dominant frequencies of 11.72 mHz and 23.44 mHz. It has been confirmed from various other parameters such as solar wind dynamic pressure, interplanetary magnetic field and AE-indices that the observed waves are Pi2 type pulsations and may be associated with substorm onset.

Keywords: Magnetotail, Pi2 pulsations, Plasmaspheric cavity, Solar wind, Interplanetary magnetic field

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1 Introduction

Magnetic pulsations are the low frequency oscillation in Earths magnetic field and are broadly studied under ultra low frequency (ULF) ($f = 10^{-3}$-1 Hz) waves. ULF waves in Earth's magnetic field as indirect diagnostics of the state of the magnetosphere and the solar wind has been popular because it has both scientific and practical return[1]. The irregular and damped type of oscillation with periods in the range 40–150 s was observed by Meng *et al.*[2] under the nomenclature Pi2 pulsation in a wide range of magnetic local time and latitude on the ground. The magnetospheric substorm involves a repetitive process that dissipates electromagnetic energy of solar wind origin from the magnetosphere to the Earth’s upper atmosphere[2].

The concept of substorm was first elucidated by Akasofu[3], based on a large number of auroral images collected by ground-based all-sky cameras during the IGY era (1957–1958). Yumoto *et al.*[4] proposed the excitation and propagation mechanisms of the substorm associated global Pi2 pulsations. It is the near Earth plasma sheet disturbances which generates field aligned current and in turn produces two wave fronts that propagates Earth ward[5]. These two wave fronts constitute transverse polarized wave travelling along the ambient field and the compressional wave moving across the field lines. It is these compressional waves that move radially inward and generate global modes in the inner magnetosphere at low latitudes. This, in turn, under suitable condition may excite field line resonance locally coupling with transverse modes[5]. Low latitude in the context of Pi2 means field lines which are within plasmapause or L value of 4 or less. In earlier investigations[6-7], concurrent studies of day side and night time Pi2 pulsations showed a difference in their spectral contents. Different spectral contents are believed to be due to the different wave modes present in the day and night side hemispheres. Pc3 appears in the same frequency range during day side, which may mask the smaller amplitudes of Pi2. At lower latitudes, Pi2 may appear in a wider range of local time including the day sector, i.e. lower the latitude, wider the extent of occurrence in local times. Thus, the low-latitude Pi2 pulsations are one of the most widely used onset tools for substorm[2]. Plasma instabilities have been proposed by several researchers[8-13] as a possible mechanism for the cause of onset of magnetospheric substorms.

Solar wind changes may also result in the excitation of the magnetospheric internal instabilities that can in turn initiate substorm onset[14]. Magnetic field lines stretching anti-sunward in the magnetotail are common nightside feature during reconnection. The interplanetary magnetic field (IMF) conditions also make an important consideration for the role played in the observations of global Pi2 pulsations.

The decreases in the H components of the magnetic field prior to onset indicate that field lines were stretched tailward. After the onset, the increase in the H components of the magnetic field indicates that field lines were released as a consequence of depolarization[2]. The IMF can be continuously southward for many hours and magnetosphere becomes very dynamic and series of substorm can occur[14].

In the present study, ground based magnetic data has been analyzed from seven low latitude stations during geo-magnetically quiet period (Kp = 3). The structures and spectral characteristics of the Pi2 magnetic pulsations and its association with the fluctuations in auroral indices has been investigated as well as the IMF conditions as controlling factors for these observations.

2 Data and Analysis

The data of 8 h (1600-2400 hrs UT) on 31 August 2006 sampled at 1 Hz from ground based digital fluxgate magnetometers of seven stations have been used in the present study. This chain consists of six Indian stations and one Chinese station. The IMF conditions were taken from the WIND satellite. AE-indices sampled at 1 min and 1s magnetic data of WMQ (Chinese station) have been taken from the World Data Centre (WDC), Kyoto. The co-ordinates of ground stations used for the present studies have been given in Table 1. The analysis has been confined to H-component of geomagnetic field as it is more relevant for low latitude stations. It may be noted from the longitudes of the stations in the chain that the night time phenomena is being considered.

The time variation of H-component of magnetic field in the chain for the considered time interval has been presented in Fig. 1. The data were band-passed in the frequency 8-30 mHz. The band-passed data were subjected to spectral analysis. The dynamic spectra have also been constructed by performing short term Fourier transform (STFT) using 512 points windows with the overlapping of 502 points. The data have been divided in four corridors for the convenience of understanding. The band passed versions of these corridors have been presented in Figs 2(A-D). The power spectral densities of the complete 8 h data have been shown in Fig. 2(E). The dynamic spectra of the chain have been presented in Fig. 3. The last corridor has been omitted for some reason. This means Figs 3(A-B) corresponds to Figs 2(A-B), respectively; and Fig. 3(C) corresponds to combination of Fig. 2(C). Solar-wind dynamic pressure as observed from the WIND satellite during the considered time has been shown in Fig. 4. IMF conditions as observed from WIND have been depicted in Fig. 5. Auroral indices (viz. AL, AU and AE) as obtained from WDC, Kyoto have been shown in Fig. 6. It may be noted that there is a time delay of around 1 h for the solar-wind to reach from the satellite to the magnetosphere.

3 Observations and Results

H-component of geomagnetic data from the stations shows an impression of simultaneous

Table 1 — Co-ordinates of stations

Station	Geog lat	Geog long	Geomag lat	Geomag long	Source	L
Hanle (HNL)	32.78° N	78.96° E	23.71° N	153.33° E	IIG	1.19
Jaipur (JPR)	29.90° N	75.80° E	18.13° N	149.80° E	IIG	1.11
Shillong (SH)	25.56° N	91.88° E	15.70° N	164.72° E	IIG	1.08
Nagpur (Ngp)	21.15° N	79.08° E	12.12° N	152.33° E	IIG	1.04
Alibaug (ABG)	18.62° N	72.87° E	10.17° N	145.15° E	IIG	1.03
Visakhapatnam (VSK)	17.68° N	83.32° E	08.34° N	156.09° E	IIG	1.02
Urumqi (WMQ)	43.80° N	87.7° E	34.11° N	162.21° E	WDC Kyoto	1.46

presence of Pi2 pulsations in night side of the globe at low latitudes. It has been assumed that four corridors in the data length of eight hours spanning from 1600 to 2400 hrs UT. For the analysis part, all the corridors have been dealt separately to get into the details of their structures. These four corridors have been chosen as: first corridor during 1700-1800 hrs UT; second corridor during 2100-2200 hrs UT; third corridor during 2200-2300 hrs UT; and lastly fourth corridor during 2300-2400 hrs UT.

The filtered data shows the multiple Pi2 events occurring simultaneously at different stations as shown in Fig. 2. The amplitude of the pulsations in the last corridor is small as compared to other corridors. So, the discussion is confined to the first three corridors. That is why the dynamic spectra of the last corridor have not been presented. However, in the computation of power spectral density, the whole data length of 8 h has been considered. The power spectral densities for all the seven stations reveal two dominant peaks at 11.7 and 23.4 mHz as shown in Fig. 2(E). In first corridor, there are two Pi2's with onset time of 17:35 and 17:55 hrs UT in the second there is one Pi2 with onset time at 21:45 hrs UT; and in the third corridor there are two Pi2's with onset at 22:35 and 22:75 hrs UT. In totality, Figs 2 and 3 convey about the complex structures of these multiple events having temporal and spatial dependence. The bursty nature of occurrence is the characteristic of Pi2 pulsations.

Dominant peaks at 11.7 and 23.4 mHz at one glance might appear harmonically related. It has been confirmed that it is not so as revealed by the dynamic spectra (Fig. 3). They occur at different instant of time. The 11.7 mHz wave occurs in the first corridor, whereas 23.4 mHz wave occurs in second and third corridors.

The solar wind dynamic pressure has important influence on the Earth's magnetosphere. When the dayside magnetosphere is compressed by an enhancement of the solar wind pressure, the magnetopause current is intensified, which results in an increase of the geomagnetic field in the dayside magnetosphere and on the ground[15].

The data from the WIND satellite about the IMF and dynamic pressure reveals that the delay time is

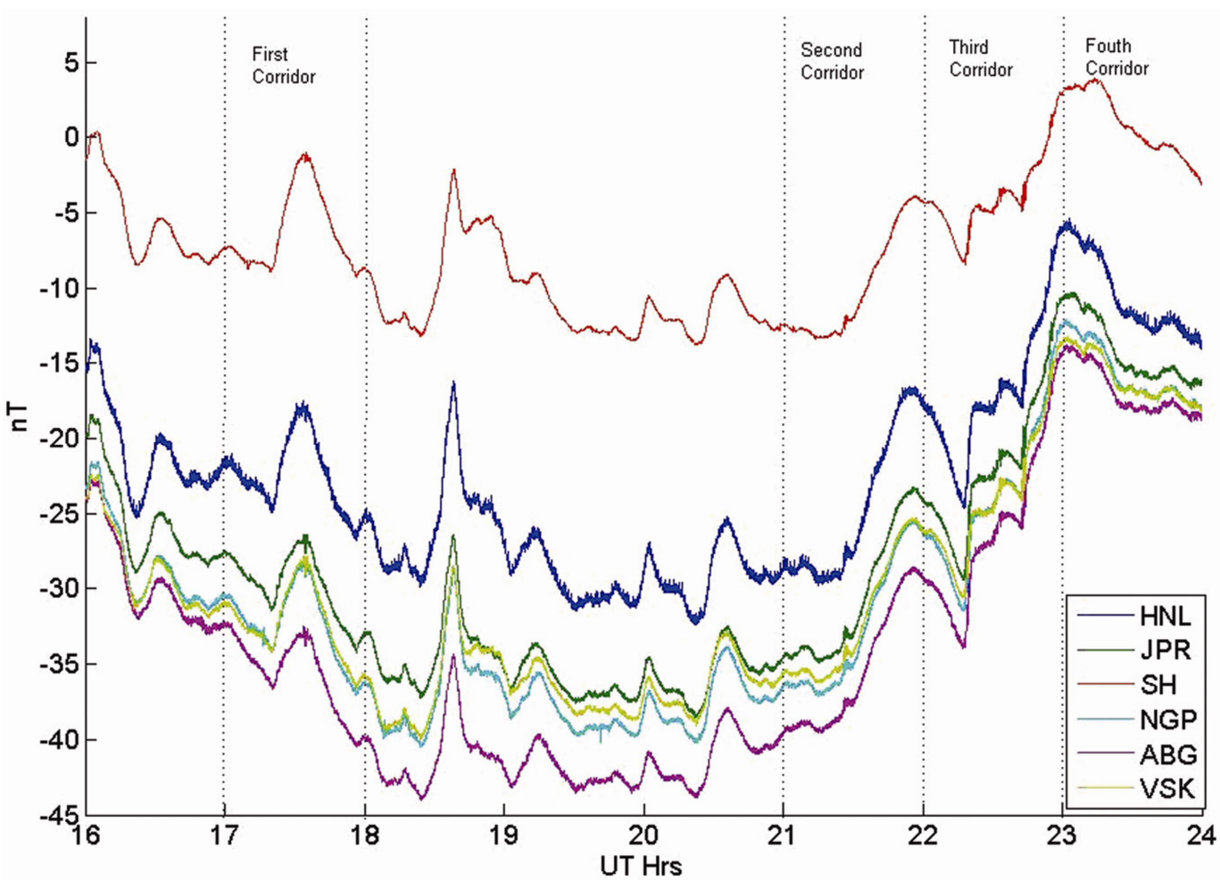

Fig. 1 — Raw data of H-component of magnetic field from six Indian stations

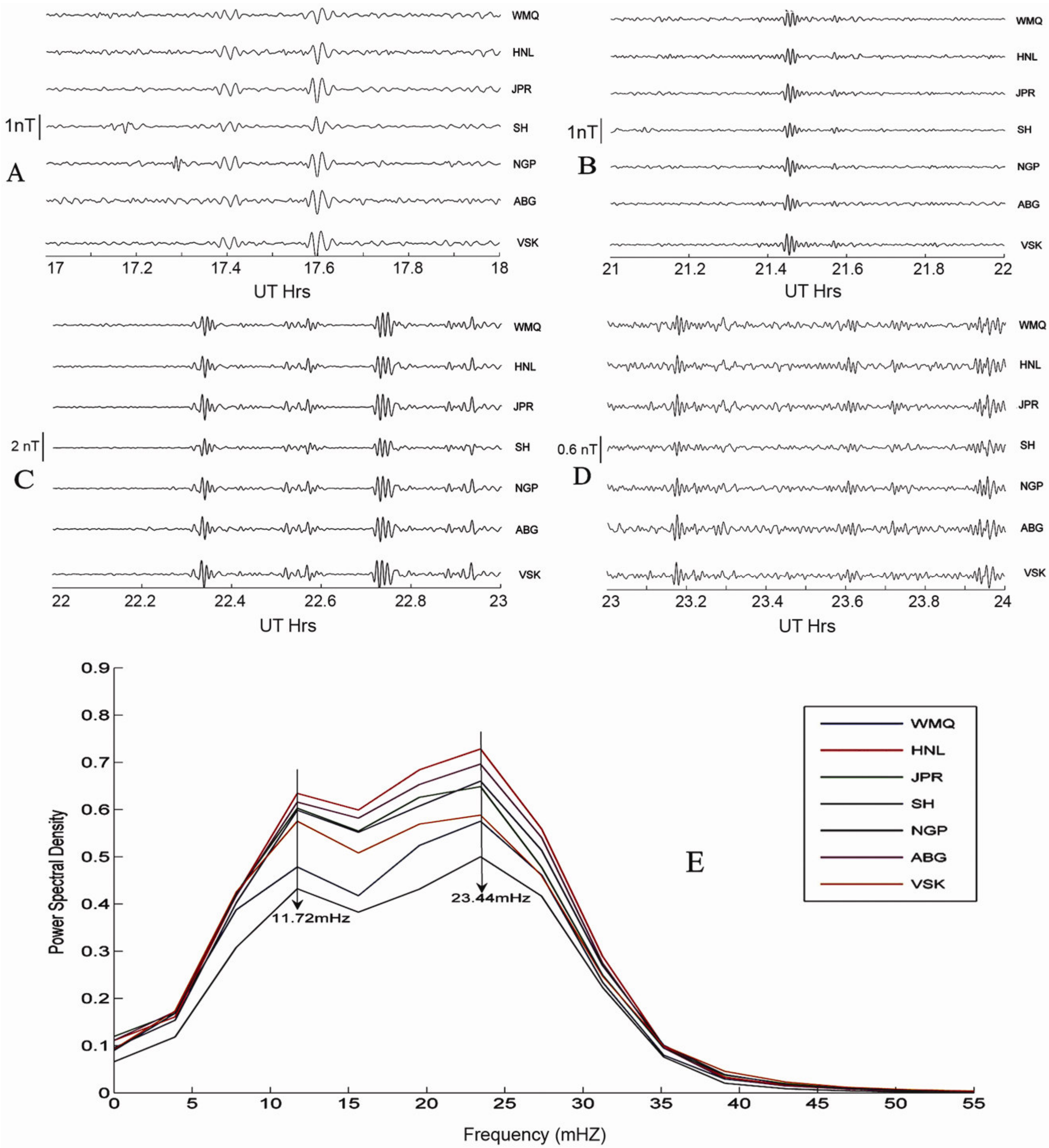

Fig. 2 — (A-D) Filtered data of H-component of magnetic field from seven stations in: (A) Corridor 1, (B) Corridor 2, (C) Corridor 3, and (D) Corridor 4; (E) Power spectral density

about 1.07 h between the observation on ground and at WIND with radial distance of 1473900 and Vsw of 381.7 km s^{-1}. As the first event is picked up at around 17:35 hrs UT, which is about 1.05 h after the intense initiation of dynamic pressure as expected from the delay time estimate. Figure 4 shows the dynamic pressure and the polynomial fit to the dynamic pressure curve (red curve).

In interplanetary magnetic field (Fig. 5), there is a turning of Bz component of IMF from north to south, thereby, enhancing the reconnection process**.** It reflects the energization of magnetosphere as the consequence of shifting of IMF from northward to southward[16]. Enhanced solar wind dynamic pressure in combination with southward IMF forms the favourable environment for triggering a substorm which has been put in support from the auroral indices.

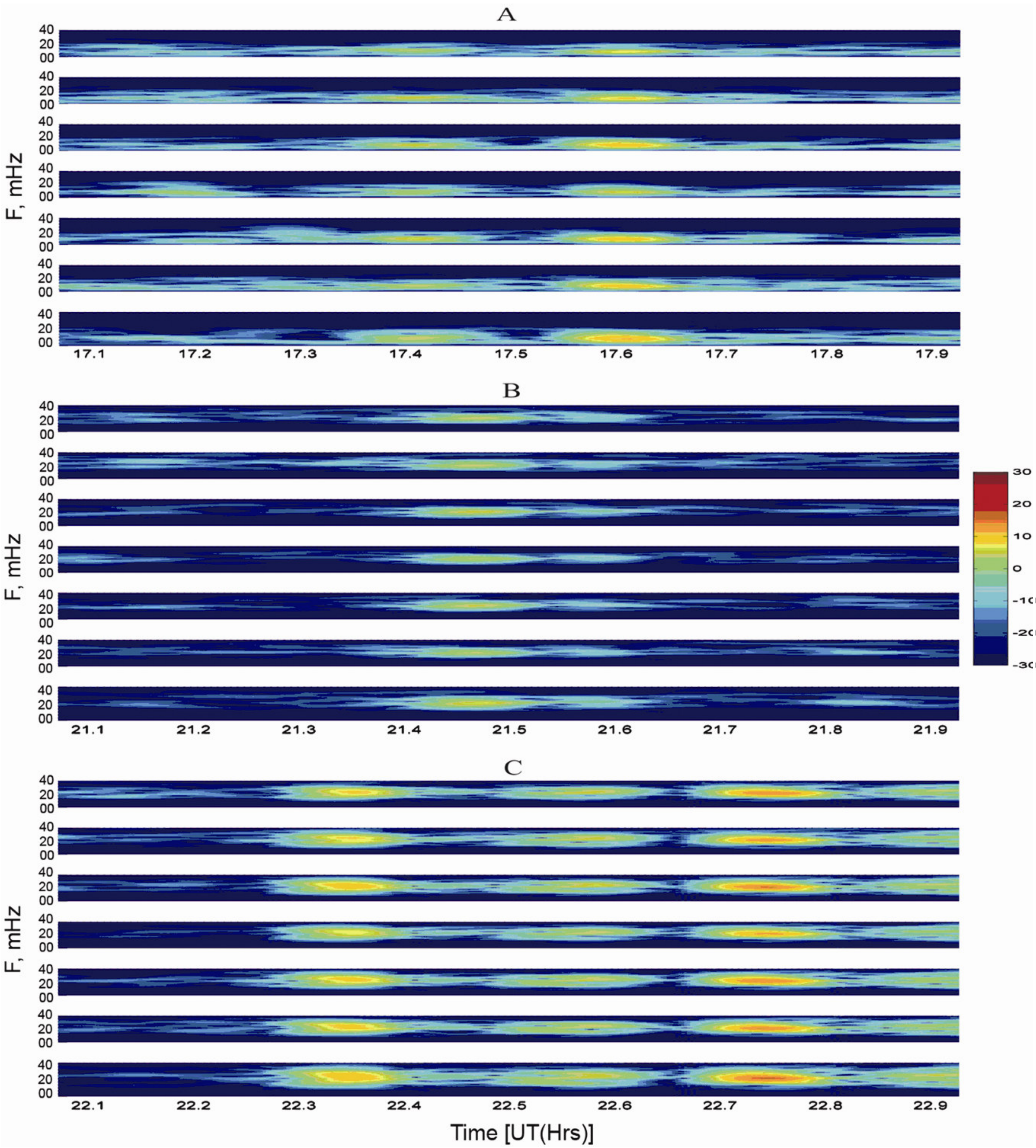

Fig. 3 — Dynamic spectra of H-component of magnetic field in: (A) Corridor 1; (B) Corridor 2; and (C) Corridor 3

The selection of magnetic index to use for prompt characterization of substorm energetics is very important for the modelling of ionosphere and high frequency radio wave propagation during substorm events[17].

It has been seen that magnetic auroral electrojet (AE) index, which was proposed and introduced by Davis & Sugiura[18], is an important indicator of the disturbance state of the magnetosphere via current coupling to the auroral zone ionosphere.

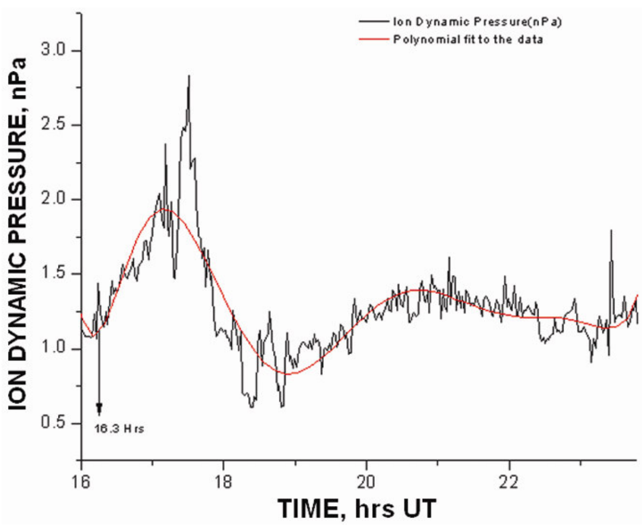

Fig. 4 — Solar wind dynamic pressure with a point of intense initiation at about 1630 hrs UT

The global substorms are identified using a sudden, persistent decrease in the AL index. The onset of this global expansion is taken to be the time of the Pi2 burst nearest in time to the beginning of the AL decrease[19]. Here, in the present study, IMF triggered substorms are identified through visual scanning of the filtered data. An attempt has been made to see the response of Pi2's with the auroral indices. It has been found in very good correlation for a series of substorms with individual drops and jumps in AL and AU indices. From Fig. 6, it is very much pertinent that AL seems to be more responsive to the substorms than AU. AL index appear to be better correlated with onset times of Pi2's as compared to AU index.

4 Discussions and Conclusions

The ground based measurements of H-component of magnetic field from the low-latitude (L=1.02-1.46) stations have been used to study structures and spectral properties of Pi2 events.

The amplitudes vary with in the range 0.15 - 1.8 nT, but they are different at different latitudes and different times. Thus, the amplitudes of Pi2 oscillations show spatial and temporal variations. In the period of about 6.5 h, multiple events with different spectral properties have been observed. But there are two discrete dominant frequencies of 11.7 and 23.4 mHz.

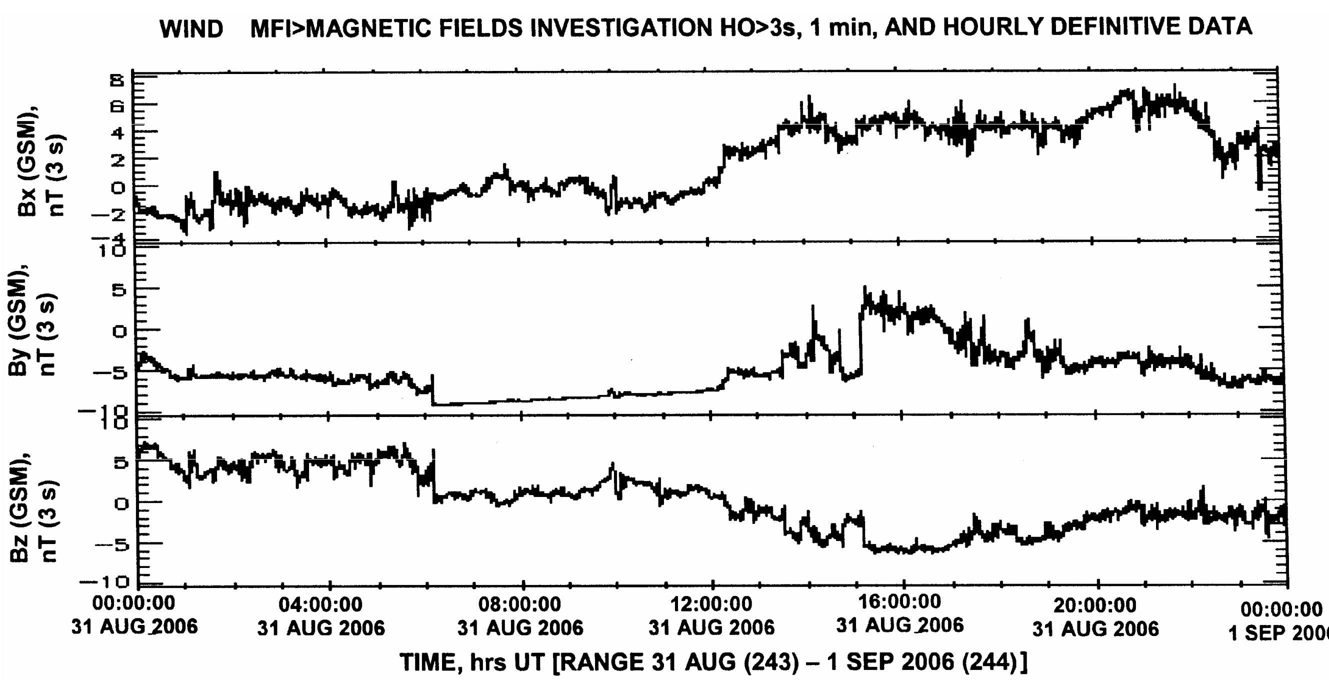

Fig. 5 — Interplanetary magnetic field

The IMF and solar wind dynamic pressure has been taken from WIND satellite. It has been estimated a delay of about 1.05 h between the shocks of dynamic pressure observed at WIND and at Earth using radial distance of 1473900, and solar wind velocity (Vsw =381.7 km s^{-1}). The dynamic pressure during 1600-2400 hrs UT has been plotted in Fig. 4, with a polynomial fit of order 8 in the red color. And it is very clear that shock at WIND is observed at 16:30 hrs UT whereas first event has been received at about 17:35 hrs UT. It does not mean that these events are attributed to the solar wind dynamic pressure but this play a vital role in combination with southward Bz component of the IMF.

Lower panel of Fig.5 shows Bz component for 24 h, and it is very clear that though there was a turning of Bz from north to south at 1200 hrs UT but there is a steep southward turning in Bz at 1500 hrs UT after which it remained stable till 1700 hrs UT. Sustained southward IMF with an enhanced solar-wind dynamic pressure appears to favour the onset of substorm.

AE index is one of the good indicators in diagnostic of magnetospheric state[18]. The overall picture of AE index in Fig. 6 shows a sudden rise after 16 h and has a rise of about 800 nT in two hours. The sudden, persistent decrease in AL index provides a good identification of substorms[19]. AL seems to be more responsive to Pi2 events as compared to AU. The response of AL and AU index in event by event case has been investigated, and it has been seen that major drops in AL are well correlated with the Pi2's. As seen in Fig. 7, amount of drop in AL does not convey

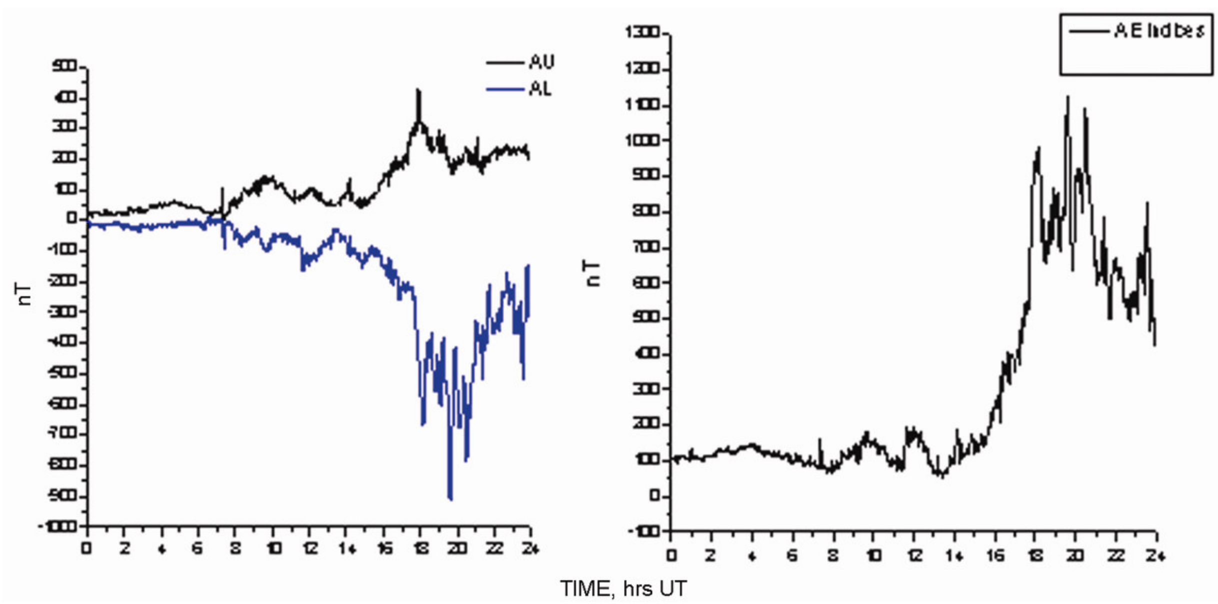

Fig. 6 — Left panel shows AL and AU Indices; Right panel shows AE Indices with time in minutes

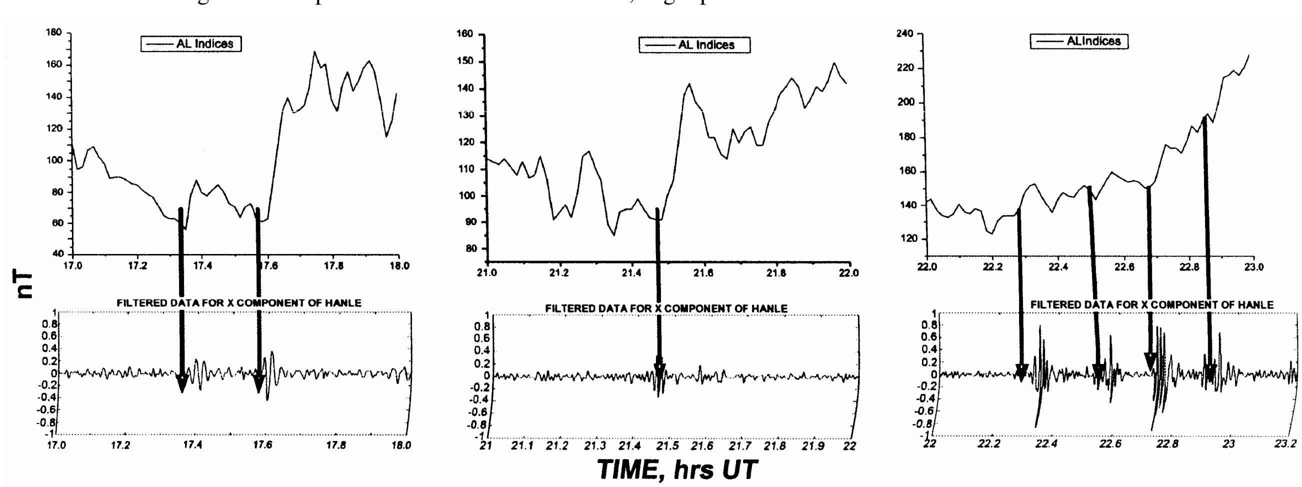

Fig. 7 — AL indices with respective Pi2's

about the intensity of Pi2. For example, the amplitude of Pi2 at 17:35 hrs UT is about 0.25 nT with the drop in AL of about 30 nT, but for the strongest event in context with the amplitude correspond to the the drop in AL of 25 nT.

The Pi2 pulsations observed at low latitude in the night side are compressional/fast component. The Pi2 compressional/fast-mode component at low latitude maps directly to the H-component on the ground. These form a clear example of cavity oscillations at discrete frequencies of 11.72 and 23.44 mHz. These Pi2's are being correlated with the substorms onset with AL indices on event to event basis. IMF and solar wind dynamic pressure and consequently the AL indices conveys a good example of extraction of solar wind energy to the ground at low latitudes in the form of multiple Pi2's with wider range of local night time. But these global cavity modes at longer stretch of longitude and latitudes need to be confirmed.

Low latitude Pi2 pulsations provide an important tool to study solar wind-magnetosphere interaction and dynamic coupling of magnetosphere and ionosphere[20]. Therefore, it has great relevance for space weather forecasting. The area of study needs to be better explored with the coordinated ground and satellite data. This forms a part of the future studies.

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