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Diurnal and seasonal variation in Pc4 occurrence at low latitudes in India

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A study has been carried out for Pc4 geomagnetic pulsations (in 6.7 - 22.2 mHz frequency range) recorded on ground at three very low latitude stations, viz. Hanle, Nagpur and Pondicherry, in India employing three axis fluxgate magnetometers, established and operated by Indian Institute of Geomagnetism (IIG), Navi Mumbai. Digital dynamic spectra for north-south (X), east-west (Y) and vertical (Z) components of the recorded data were constructed for each day for one year (1 January 2005 to 31 December 2005). The X- and Y-component of these dynamic spectra were investigated for carrying out statistical study of diurnal and seasonal variation of occurrence of Pc4 events. The main peaks of Pc4 occurrence were detected between 1500 hrs UT (2030 hrs IST) and 2000 hrs UT (0130 hrs IST). The monthly diurnal variation provided Pc4 peak occurrence between 1700 and 1900 hrs UT (2230 - 0030 hrs IST). The seasonal variation of hourly Pc4 occurrence in both local winter and autumn was detected at 1800 - 1900 hrs UT (2330 - 0030 hrs IST) that occurred one hour later than the main peak of occurrence for the total year determined at 1700 - 1800 hrs UT (2230 - 2330 hrs IST). However, the peak in the seasonal variation of hourly Pc4 occurrence for both local autumn and summer was detected at 1700 - 1800 hrs UT (2230 - 2330 hrs IST). The observed diurnal characteristics suggest that Pc4 pulsations detected on the nightside actually originated on the dayside by an extended origin of ULF waves in the bow shock.

Keywords: MHD waves and instabilities, Solar wind - Magnetospheric interactions, Geomagnetic pulsations

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1 Introduction

Pc3-4 geomagnetic pulsations are ultra low frequency magnetohydrodynamic (MHD) waves observed mainly in the dayside (0400-2000 hrs LT) magnetosphere[1-5]. A number of studies using ground station data demonstrated that Pc3-4 pulsations dominated in the dayside while Pc5 pulsations were dominant near dawn and dusk[6-10]. The source of these waves and their propagation mechanisms have not been fully understood till date.

The solar wind provides energy for the Earth's magnetospheric processes. Most of the daytime micro-pulsations activity in the Pc3-4 range (6.7-100 mHz) is thought to be related to the waves generated upstream of the bow shock by energetic ions reflecting off the shock and creating conditions for the wave generation[11-14]. This region, external to the magnetosphere, provides fast mode wave energy that may propagate across the magnetopause and with small radial damping, can cross the plasmapause and penetrate deep into the magnetosphere. The correlation between the occurrence of these waves and the values of the IMF cone angle (θ_{xB}), also supports the foreshock origin of these waves. A number of researchers reported Pc3-4 activity occurring predominantly when θ_{xB} was low (< 45^o) (refs 15-19). Several studies have also revealed that signal frequencies of Pc3-4 pulsations recorded at ground are correlated with IMF magnitude[20-22]. Le & Russell[23] found that the cone angle could also play a role in determining the frequency of upstream waves, although IMF strength was the most important parameter that controlled this frequency. Yumoto[24] compared the compressional wave frequencies in the magnetosphere with the energy distribution of reflected ion beams in the earth's foreshock recorded by the ISEE series of satellites and reported agreement with a model of upstream waves excitation by the ion cyclotron resonance mechanisms. These observations indicated that during small IMF cone angle, the upstream waves in the earth's foreshock whose frequencies were related to the magnitude of the IMF, could be convected through the magneto-sheath and transmitted into the magnetosphere, where they propagate in the compressional mode and couple to the other hydro-magnetic wave modes, e.g. trapped oscillations of fast magnetosonic waves in the Alfven trough, fundamental and higher harmonic standing oscillations of local field lines and were registered in the deep magnetosphere and at ground stations as magnetic pulsations[11-12].

The additional possibilities that were reported as principal sources of daytime continuous Pc3-4 pulsations were the well known mechanism of generation of surface waves by Kelvin-Helmholtz instability, i.e. by velocity shear instabilities at the magnetospheric boundary[25-29] and the global compressional mode resonance caused by variation in the solar wind pressure may be the other possible source of these waves. The impulsively stimulated compressional hydromagnetic cavity resonance can drive local field line resonance where the magnetospheric cavity eigen frequency matches that of the uncoupled torsional field-line oscillations[30–34]. A significant compressional component in the signals ensured that energy could flow deep inside the magnetosphere. Zhu & Kivelson[35] described three solutions of global mode oscillations and with one of those they suggested that the tunneling type of global mode might be particularly relevant to the generation of low latitude geomagnetic pulsations because it allowed perturbations at the magnetopause to excite hydromagnetic waves inside the plasmasphere. Samson *et al.*[36] and Waters *et al.*[37] also considered a waveguide model to explain the fine structure of low latitude Pc3-4 pulsations. Although the theoretical basis for cavity modes had been established by many researchers[31,35-38], the experimental evidence for these kind of modes was sparse[39-40].

The diurnal variation of period and frequency of Pc3-4 waves recorded at ground stations and their dependence on latitude and geomagnetic indices Kp are also of vital importance in identification of their source and propagation modes. Several studies have been carried out in the past, both experimentally[1,7,41-43] and theoretically[12,26,30,37,44,45]. These studies indicated that the pulsation periods changed in a very complicated manner with the geomagnetic latitudes. The theoretical models proposed to date are not able to fully explain all the observational facts[46]. It may be noted that the major part of geomagnetic pulsation studies have concentrated on data obtained from satellites and also from ground stations at middle and high latitudes, while very low latitudes and deep equatorial regions have received little attention in the past. Therefore, to understand the generation and propagation mechanism of these waves at very low latitudes, it is important to study Pc3-4 events extensively in these regions. The present paper reports the results of investigation of diurnal and seasonal variation of occurrence of Pc4 waves at very low and near equatorial latitudes in India for the period 01 January to 31 December 2005.

2 Data and analysis

Geomagnetic data for north-south (X), east-west (Y) and vertical (Z) components of the Earth's magnetic field for the duration of the study were recorded using three axis flux gate magnetometer array[47] situated at very low latitudes in India at Hanle, Nagpur and Pondicherry with one second sampling interval. The magnetometer array was established and operated by the Indian Institute of Geomagnetism, Navi Mumbai. The coordinate details of the recording stations along with their abbreviations and schematic representation of locations are shown in Table 1 and Fig. 1, respectively. Time is always stated in hrs UT such that IST = UT + 5:30 hrs.

The analysis of temporal and spatial variations of the Pc3-4 pulsations involved several steps. The data, calibrated in all respects, were used for carrying out the analysis. The geomagnetic X, Y and Z components of the recorded time series were filtered using a zero-phase shift six order Butterworth type "band pass" filter for the frequency range 05-40 mHz (ref. 48). The analysis for every day data was carried out for X and Y components for the whole year by selecting the events from the spectra constructed by the MATLAB program. The digital dynamic spectra for selected events were prepared taking the window of 1024 points with sliding of half window size and consequently recording the frequency ranges and occurrence periods. Figure 2 depicts an example of digital spectra of the day while Fig. 3 illustrates

Table 1 — Coordinate details of recording stations

Recording stations	Geographic co-ordinates		Geomagnetic co-ordinates	
	Longitude, °E	Latitude, °N	Longitude, °E	Latitude, °N
Pondicherry (PON)	79.92	11.92	151.97	02.50
Nagpur (NAG)	79.00	21.10	151.93	11.72
Hanle (HAN)	78.97	32.78	151.89	23.38

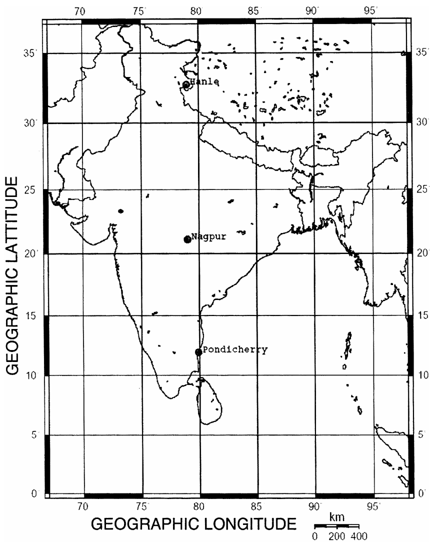

Fig. 1 — Schematic map of locations of recording stations

5-40 mHz filtered pulsations data recorded at Nagpur during 17:48 - 19:12 hrs UT on 27 Jan 2005.

3 Results

The statistical characteristics of very low latitude geomagnetic pulsations in Pc4 category in India were investigated in the current study for north-south (X) and east-west (Y) components of these waves. While considering the statistical characteristics of diurnal and seasonal variations of these pulsations, it is total duration of events that is more important than total number of events in a particular hourly bin. Therefore, the total duration of events in minutes has been taken into consideration. The hourly occurrence of Pc4 events for the three stations for January 2005 is shown in Fig. 4. Time is expressed in hrs UT on the horizontal axis while total duration of events for the

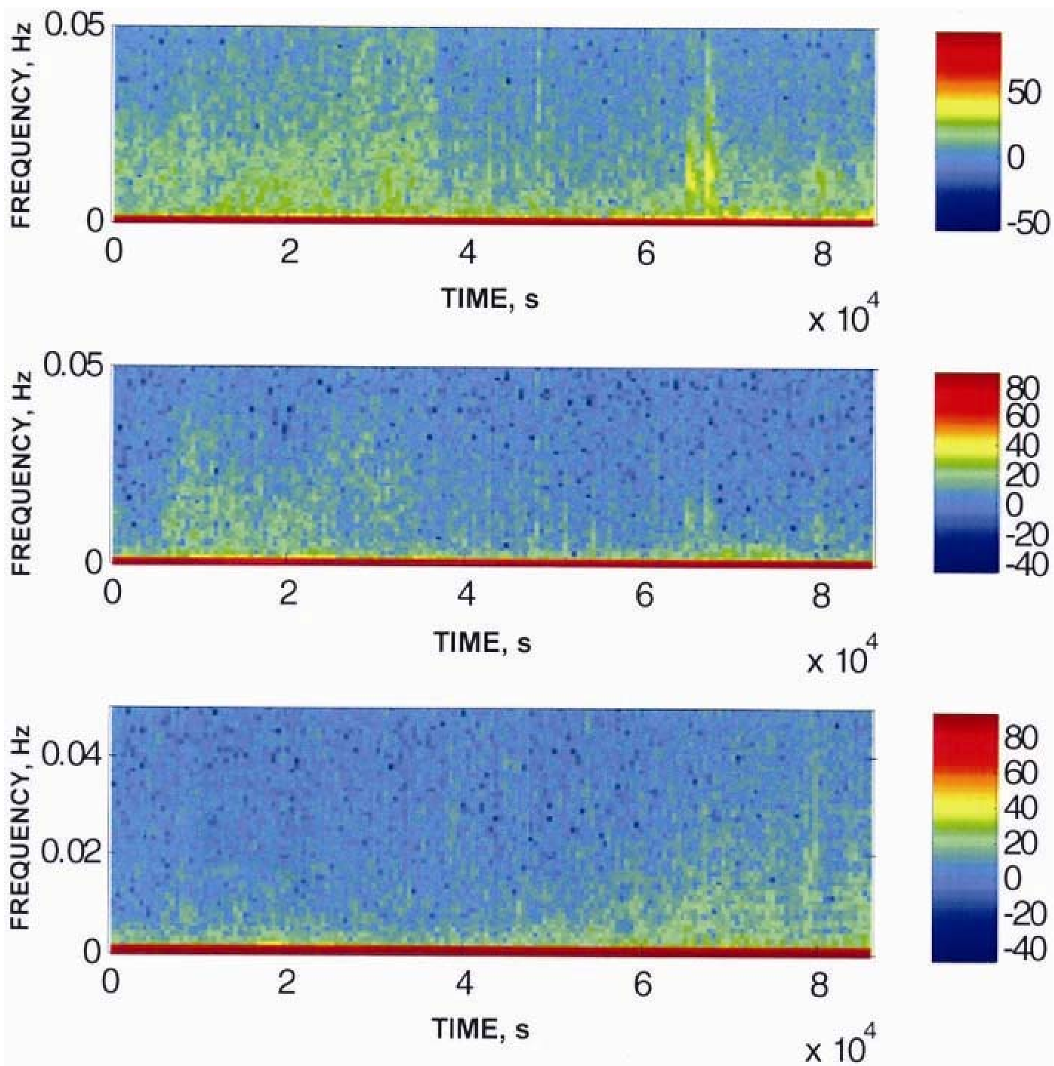

Fig. 2 — Dynamic spectra of full day on 27 January 2005 at Nagpur. Relative intensities are indicated by various colours. Top, middle and bottom panels depict the X, Y and Z components of the spectra

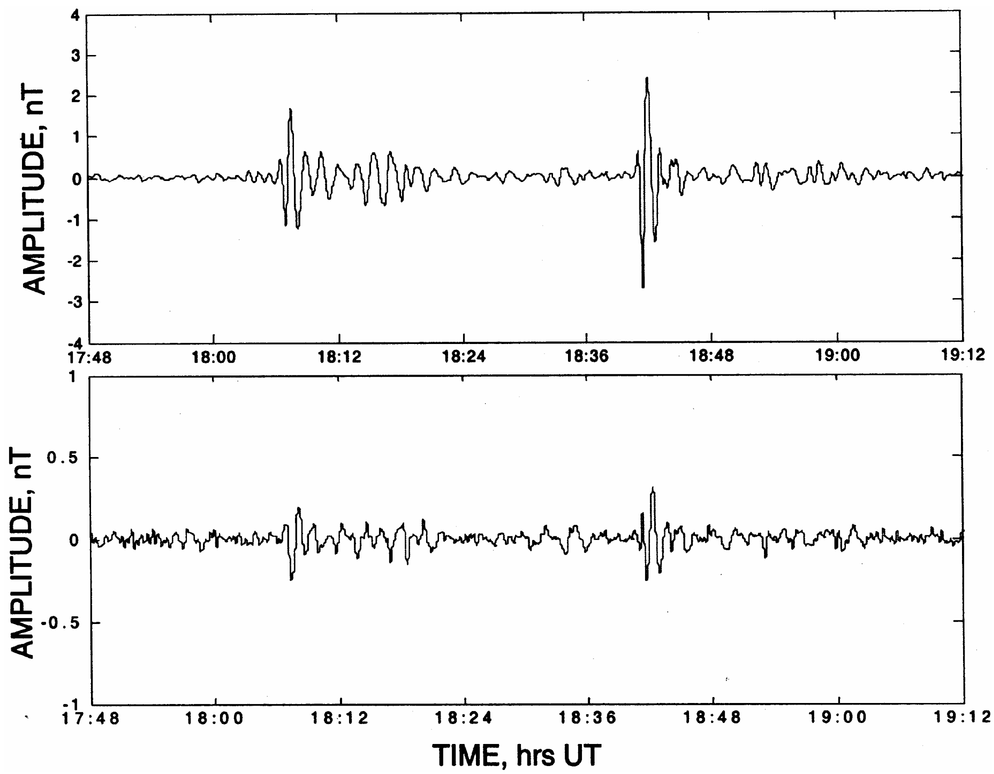

Fig. 3— Filtered pulsations (in the interval 5-40 mHz) at Nagpur on 27 January 2005. Top and the bottom panels depict north-south (X) and east-west (Y) components of the amplitudes of pulsations, respectively

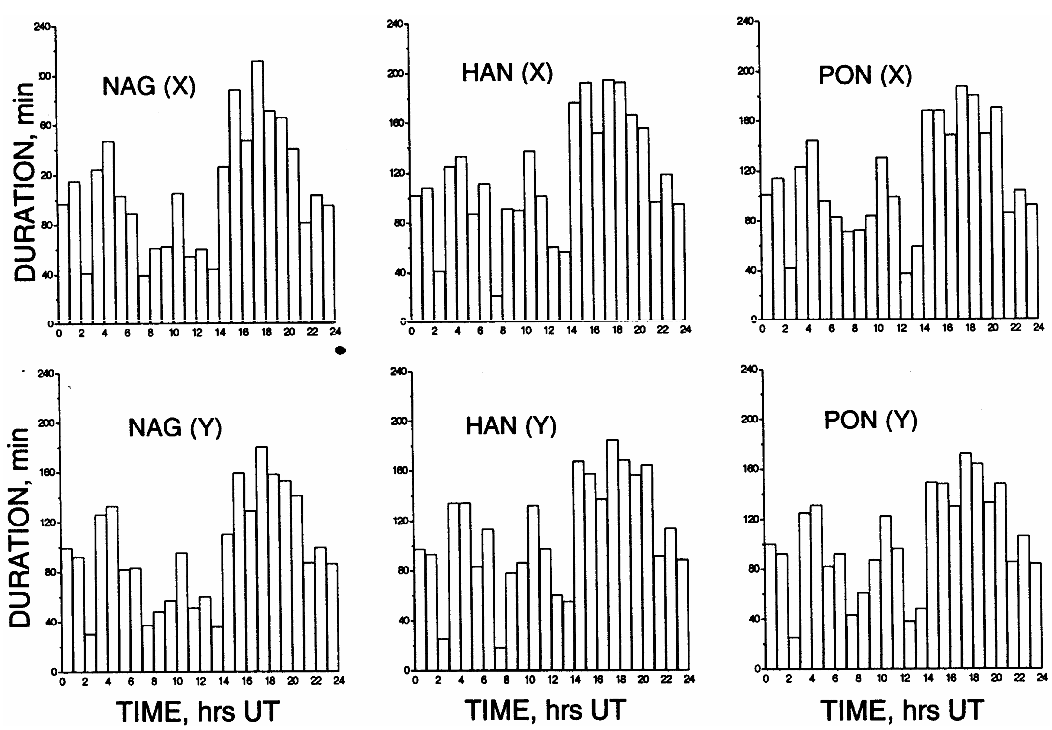

Fig. 4 — Diurnal variation in Pc4 occurrence at all three stations in January 2005

corresponding hour for the whole month is depicted on the vertical axis expressed in minutes. It is evident that pulsations have occurred during all the hours of the day while major occurrence was observed between 1400 and 2100 hrs UT at the three stations. The main statistical peak in the Pc4 occurrence was observed during 1700-1800 hrs UT at the three stations with maxima decreasing in the order at Nagpur, Hanle and Pondicherry. At Nagpur, the main peak during 1700-1800 hrs UT had duration of 211 min while the secondary peak during 1500-1600 hrs UT had duration of 188 min. However, in the Y-component of Nagpur data, main peak was detected during 1700-1800 hrs UT with duration of 180 min, while two secondary peaks during 1500-1600 hrs UT and 1800-1900 hrs UT had durations 159 min and 158 min, respectively. At other two stations, Hanle and Pondicherry, the main peak was observed during 1700-1800 hrs UT having durations of 194 and 187 min, respectively. Similar results were detected in the other monthly plots of the year except in May 2005 when the main peak occurred during 0600-0700 hrs UT having duration of 272 min.

The variation of the total hourly occurrence of Pc4 events for all the three stations for the whole year 2005 is plotted in Fig. 5. It is evident that the occurrence was prevalent during all the hours of the day with major events being observed during 1500-2200 hrs UT at the three stations. The occurrence pattern was nearly same for all the stations and the maximum occurrence was observed during 1700-1800 hrs UT with a succeeding secondary peak during 1800-1900 hrs UT. The total duration of maxima in the Pc4 occurrence were found to decrease in the order at Pondicherry, Nagpur and Hanle. Variations in the Y component occurrence were observed to be nearly similar but had relatively less power. At Hanle, the duration in Pc4 occurrence was detected to be less dominant in comparison to the other stations. The main reason was unavailability of data on many days in August, September and October 2005 for this station. The major occurrence of Pc4 events observed in the current study between 1400 and 2000 hrs UT have also been reported in previous studies both at low and high latitudes[5,49-51].

The seasonal variations of diurnal occurrence of these very low latitude Pc4 waves are presented in Figs (6)-(9). Figure 6 depicts the diurnal occurrence in winter season. Although Pc4 events were observed in all the hours but major events occurred during 1500-2000 hrs UT. The maxima peaks were found during 1800-1900 hrs UT at all the stations.

The diurnal occurrence in the spring season is depicted in Fig. 7. The hourly occurrence can be divided in two main intervals: 0500-1100 hrs UT; and

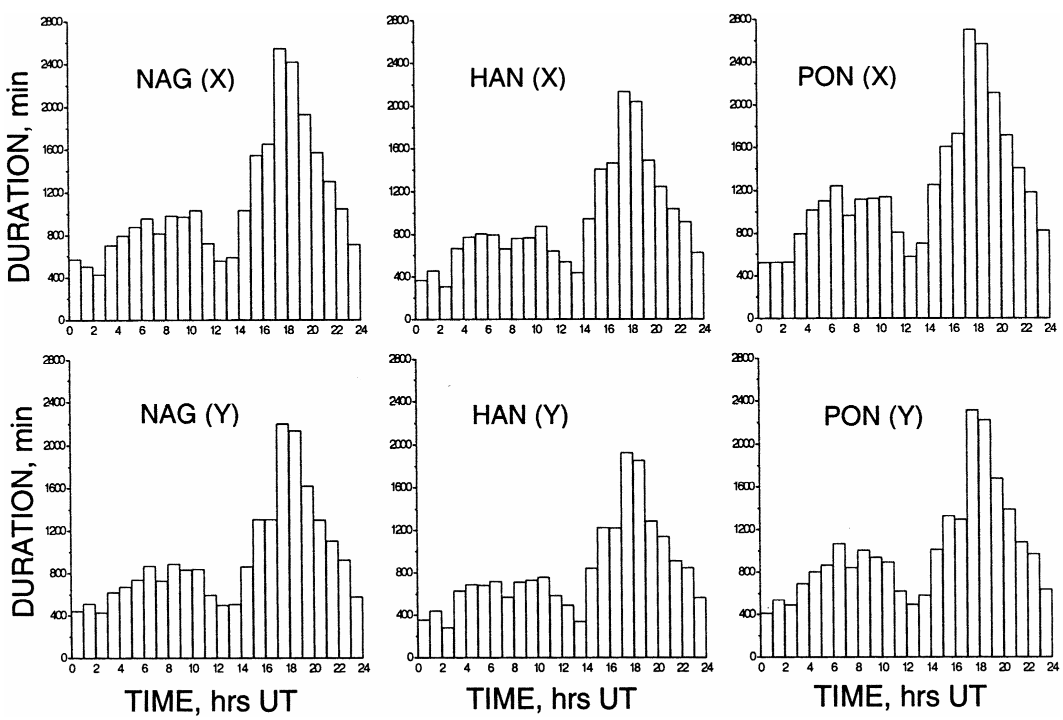

Fig. 5 — Diurnal variation in Pc4 occurrence at all three stations for the year 2005

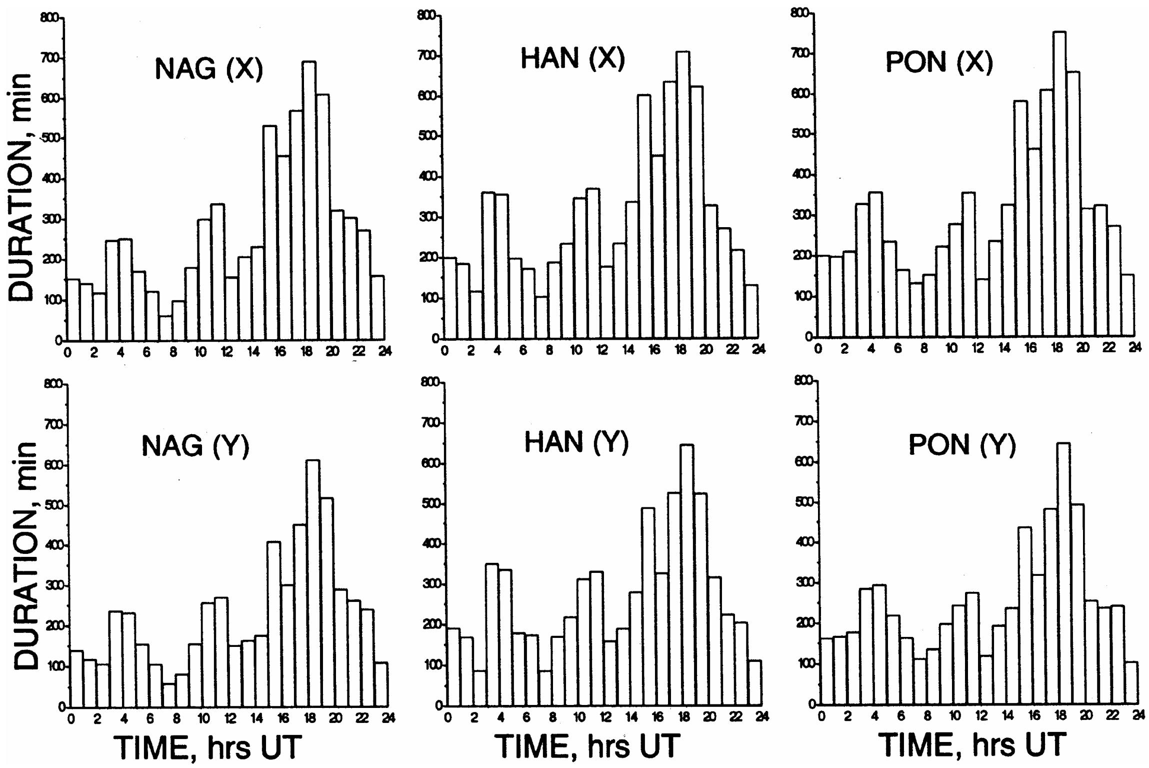

Fig. 6 — Diurnal variation in Pc4 occurrence at all three stations in winter season of 2005

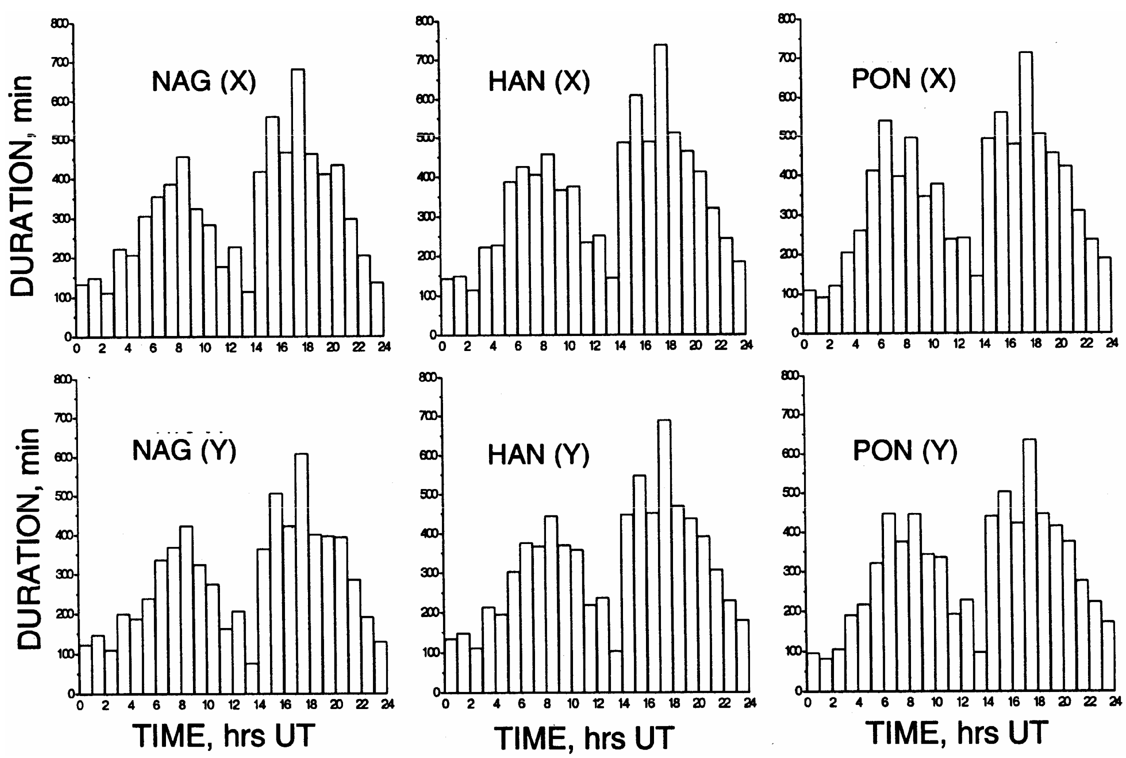

Fig. 7 — Diurnal variation in Pc4 occurrence at all three stations in spring season of 2005

1400-2100 hrs UT, but the major occurrence was detected in the interval 1400-2100 hrs UT. The maxima peaks were observed during 1700-1800 hrs UT at all the stations. The maximum occurrence in the 0500-1100 hrs UT interval was detected during 0800-0900 hrs UT for both Nagpur and Hanle while for Pondicherry it occurred during 0600-0700 hrs UT. Figure 8 shows the diurnal variation in Pc4 occurrence in the summer season. It is evident from the plot that the occurrence behavior at Nagpur and Pondicherry were similar. The main cause of different behavior at Hanle was the unavailability of data for a number of days in August. Pc4 events were observed in all the hourly domains but the majority of events were found during 1700-2300 hrs UT with the peak maxima observed during 1700-1800 hrs UT at all the stations. The diurnal variation in Pc4 occurrence in the autumn season is shown in Fig. 9. In this case also, the occurrence behavior at Nagpur and Pondicherry was found to be similar but different at Hanle. The main cause of this difference at Hanle was the unavailability of data for a number of days in September and October 2005. The majority of occurrences at all the stations were observed in the interval 1500-2100 hrs UT with the maximum peak occurring during 1800-1900 hrs UT. The main peaks in the local winter and local autumn were found to occur one hour later from the main peak of the total year detected during 1700-1800 hrs UT while the main peaks in local spring and local summer have occurred at the same time as detected in the occurrence for total year data. The seasonal variation in Pc4 occurrence also shows the main peaks in local winter and local autumn at the same time (1800-1900 hrs UT) at all the stations as depicted in Figs 6 and 9. These results agree with the previous studies[7,52] where the main occurrence peaks in winter and equinox did not change with time.

4 Discussion

The energy source for Pc3-4 waves observed on the ground may either be external or internal to the magnetosphere. Internal sources of energy include instabilities associated with the cyclotron, bounce and drift motion of particles whose distribution functions are anisotropic. Free energy internal sources include pressure gradients, velocity shears and rapid changes in the magnetospheric geometry associated with sub-storms. It should also be noted that the bounce resonance mechanism[53] is not a likely source of Pc3-4 waves. This mechanism was found to be most plausible for shorter wavelengths and great

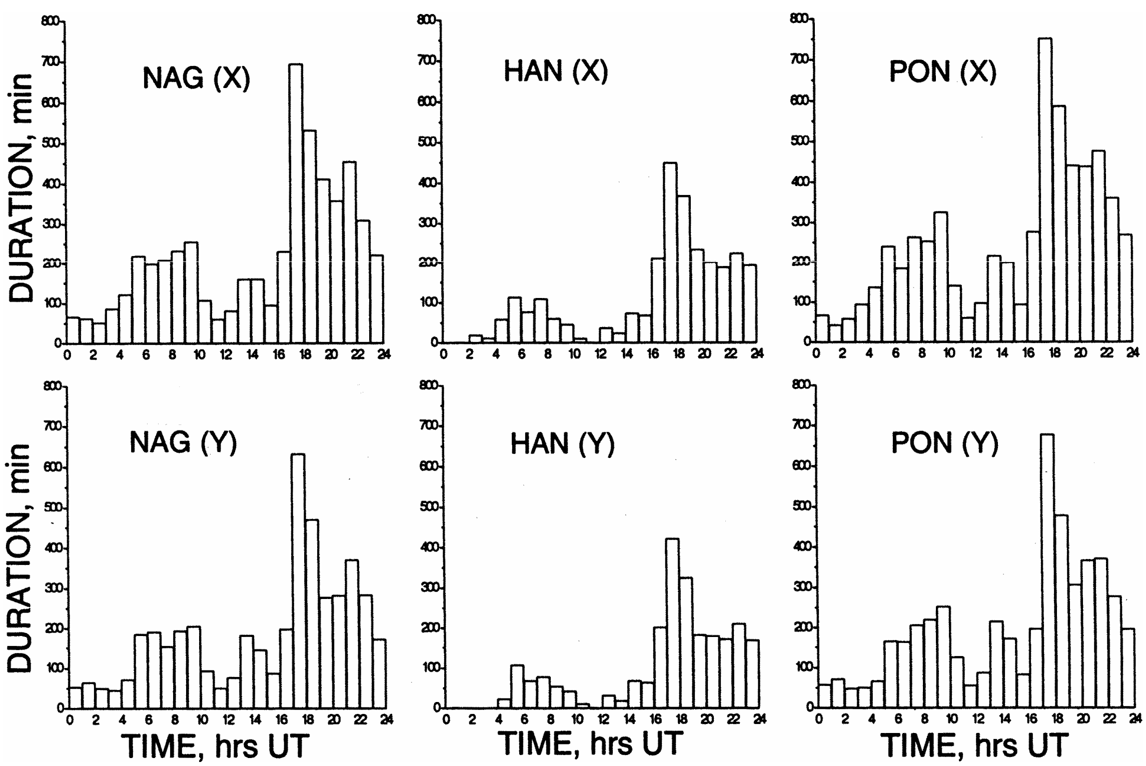

Fig. 8 — Diurnal variation in Pc4 occurrence at all three stations in summer season of 2005

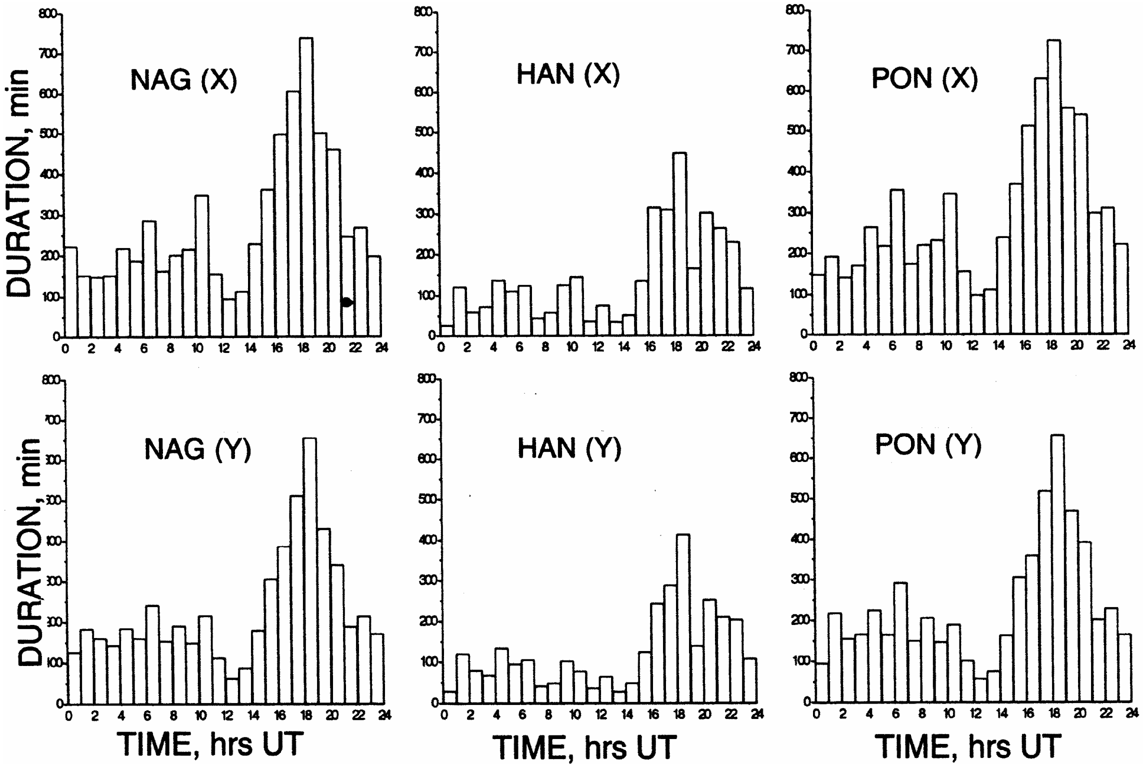

Fig. 9 — Diurnal variation in Pc4 occurrence at all three stations in autumn season of 2005

localization in longitude. Such localized waves have been observed in space at geostationary orbit[54,55] but are screened from the ground by the magnetosphere. There is no comprehensive theory of internal excitation of Pc3-4 waves till date that could explain the external control which is compatible with observations[14] and generally models for the external excitation of these waves are favored.

There are two possible locations for the external origin of pulsations, at the magnetopause, and upstream from the magnetopause. Surface waves generated by Kelvin-Helmholtz instability are important at the magnetopause[27-29,56]. Upstream from the magnetopause, large amplitude waves in the quasi-parallel bow shock are swept back into the magnetosheath and then penetrate the magnetosphere[57].

The first direct evidence for the propagation of external Pc3-4 wave power into the magnetosphere has been presented by Greenstadt *et al.*[58]. Using a few individual events from ISEE 1-2 spacecrafts, they have verified that same frequencies in 10 – 100 mHz band were observed in the magneto-sheath and also in the magnetosphere but lower power was observed there. Similar results were reported by Tomomura *et al.*[59] from six months of ISEE data in the 3 – 30 mHz band. These researchers further demonstrated that compressional oscillations dominated in the magneto-sheath around local noon while transverse Alfven waves were observed within the magnetosphere.

Yumoto *et al.*[12] have identified compressional waves in GOES-2 magnetometer data in association with Pc3-4 ground pulsations at low latitudes. However, this wave energy does not necessarily have to be monochromatic. A broadband source could couple to a field line resonance at middle or low latitudes to provide the monochromatic waves seen at ground stations.

The transmission of upstream wave energy into the magnetosphere probably occurs predominantly near the sub-solar region. This is a requirement for these waves to gain access to low latitudes. The index of refraction of the magnetospheric plasma decreases with decreasing radial distance except at the plasmapause[60]. This decrease should refract waves away from radial propagation reducing the wave energy that can penetrate to low latitudes, allowing access only to those waves that are nearly radially propagating. This is supported by the results of Tomomura *et al.*[59] who have shown that the wave spectral power is generated in the magneto-sheath around noon.

If it is assumed that significant Pc3-4 wave energy can penetrate to low latitudes, then there are a number of possible excitation mechanisms available for wave generation. These are collective transverse surface wave eigen oscillations at the plasmapause (L_{pp}); fundamental toroidal mode standing oscillations at L = 1.1 and L = 1.76 – 2.6 and higher order harmonics at L = 2.0 – L_{pp}; and trapped oscillations in the equatorial plane between the two peaks of the Alfven velocity at L = 1.7 – L_{pp} (ref. 12).

The toroidal field line resonance theory of Southwood[44] and Chen & Hasegawa[26] provides the mechanism by which waves are seen on the ground. In this mechanism, the wave polarization characteristics depend on the azimuthal wave propagation direction and the latitude of the recording station with respect to that of field line resonance.

Zanandrea *et al.*[51] have analyzed simultaneous Pc3-4 geomagnetic data at very low and equatorial latitudes (L = 1.0 - 1.2). The characteristics of the observed Pc4 events have been attributed to the increase of ionospheric conductivity and intensification of equatorial electrojet during daytime that regulated the propagation of compressional waves generated in the foreshock region and transmitted to the magnetosphere and ionosphere at low latitudes. They have suggested that the source mechanism of the observed Pc3-4 modes may be the compressional global mode or trapped fast mode in the plasmasphere during field line oscillations at very low and equatorial latitudes.

In their attempt for locating source of Pc4 pulsations observed on the nightside, Takahashi *et al.*[49] have pointed to a common upstream wave energy source. They have observed strong low latitude Pc4 pulsations on dayside by IMP-8 during the period of nightside Pc4 pulsations. However, the spectrum of upstream magnetic field oscillations at IMP-8 was characterized by broadband power below 20 mHz instead of a strong peak at the frequency of the observed ground Pc4 pulsations.

In the light of above discussed excitation mechanisms and the observed results of the diurnal and seasonal variation of low latitude Pc4 pulsations, it is suggested that the upstream waves are a major source of Pc4 pulsations detected on the nightside which were originated on the dayside and most likely by an extended region of ULF waves. It is further suggested that the plasmaspheric cavity mode resonance may have played a role in filtering the broadband input to the magnetosphere. The results of the present study are also in agreement with the observed characteristics of ULF upstream waves by Heilig *et al.*[61]. However, the control of solar wind speed, interplanetary magnetic field strength and cone angle are to be investigated for reconciling foreshock Pc4 wave generation predictions with ground observations. These studies are in progress.

5 Conclusion

Determining the hourly occurrence of ULF waves and their seasonal variation is important for quantifying their propagation and generation mechanism properties. With this aim, the results of the analysis of diurnal variation in the occurrence of Pc4 geomagnetic pulsations for the year 2005 recorded at three stations, situated at low latitudes in India, have been reported in the present study. The seasonal variation in the hourly occurrence of these pulsations were also studied and reported. The majority of occurrence of Pc4 events observed in the present study, during 1400 - 2000 hrs UT (local nighttime), have also been reported in a number of previous studies. Several other Pc4 events in local daytime were also found during the course of the present study. The results are in agreement with suggestions of Takahashi *et al.*[49], who reported that the pulsations detected on the nightside originated on the dayside and most likely by an extended region of ULF waves in front of the bow shock and not from processes occurring in the nightside magnetosphere as there was absence of sub-storm onsets or intensification. Similar results were also reported by Villante *et al.*[20] The main peaks in Pc4 occurrence at local winter and local autumn found at the same time at all the three stations agree with the previous studies of Ansari & Fraser[7] and Kuwashima *et al.*[52] where the main occurrence peaks in winter and equinox did not change with time. As the stations array was spread over a latitudinal range of 21° only, it was not sufficient for identification of latitude dependence of Pc4 pulsation occurrence since the data from large-scale latitudinal separation was required for this purpose.

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