7.1 Discussion: -

Determining the hourly occurrence of ULF waves and their seasonal variation is important for quantifying their propagation and generation mechanism properties. In this regard, the results of the analysis of diurnal and seasonal variation in the occurrence of very low latitude geomagnetic Pc4 pulsations during the whole year 2005 recorded at three stations (Nagpur, Hanle and Pondicherry) situated at very low latitudes in India have been reported in the chapter-4. Occurrence periods of events in each day were recorded and consequently monthly analysis of occurrence period corresponding to each hour data bin was carried out. The monthly results have indicated that although events occurred during all the hours of the day, yet the majority of occurrence was seen between 14 hr UT to 21 hr UT at all the three stations in nearly every month. The maximum occurrence peak was generally found to be in between 17 hr to 19 hr UT interval during all the months except in April and May when the maximum occurrence peaks were observed at 15-16 hr and 06-07 hr UT intervals respectively. Also it is evident from the graph of the hourly occurrence for the total year (Fig. 4.13) that the maximum occurrence peak was observed in the 17-18 hr UT interval with a succeeding secondary peak at 18-19 hr UT. The maxima were found decreasing in the station order Pondicherry, Nagpur and Hanle as is evident from the plot of the total year which seems to indicate that occurrence period decreases with increasing latitude but this pattern was not present in various months of the year. No clear dependence of pulsation occurrence period on latitude was found as the maximum occurrence peak periods were varying with latitude in a very complicated manner during the different months of the year. The variation in Y component occurrence was also found to be nearly similar to the X component with less power observed at all the three stations. It was found that in August, September and October the occurrence behavior at Nagpur and Pondicherry stations
was nearly similar but the behavior found at Hanle was different in comparison to the other two stations. The cause of this was the unavailability of data during most of the days in August, September and October. The main occurrence of Pc4 events observed in the current study between 14 hr UT to 20 hr UT time interval have also been reported in many previous studies [Takahashi et al. (2005), Obana et al. (2005), Ziesolleck et al. (1997), Zanandrea et al. (2004)]. Takahashi et al. (2005) reported Pc4 power enhancement from 1400 hr UT to 1600 hr UT at ground stations located on the nightside at low latitude station Guam (Geomagnetic lat. 5.82 N) and by comparing it with dayside power enhancement at Eusebio (Geomagnetic latitude = 3.62 N), they suggested 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. They also reported that nightside Pc4 pulsations were associated with a steady solar wind and low IMF cone angle and there was absence of substorm onsets or intensification. With these conditions they pointed to the possibility that Pc4 pulsations originated from the upstream region instead from processes occurring in the nightside magnetosphere. The present study also indicates the main occurrence peaks during local nighttime (15-20 hr UT) with many other Pc4 events in local daytime during the course of study, which indicates the possibility of origin of these waves from the upstream bowshock region instead from processes occurring in the nightside magnetosphere [Ansari et al., 2009(a)].

In the study of seasonal variation of occurrence the maximum occurrence peaks in the local winter and local autumn are found to be one hour later from the maximum occurrence peak of the total year occurring at 17-18 hr UT while the maximum occurrence peaks in local spring and local summer have occurred at the same time as found in the occurrence of total year data. The seasonal variation in Pc4 occurrence also shows the main
peaks in local winter and local autumn at the same time (18-19 hr UT) at all the stations as depicted in Fig. 4.14 and Fig. 4.17. These results are in agreement with the previous studies of Ansari and Fraser (1985) and Kuwashima et al. (1978) where the main occurrence peaks in winter and equinox did not change with time [Ansari et al., 2009(a)].

The results of the analysis of diurnal and seasonal variations in the frequency of very low latitude geomagnetic Pc4 pulsations during the whole year 2005 recorded at the three stations situated at very low latitudes in India have been reported in the chapter-5. Diurnal variation in the frequency of Pc4 magnetic pulsations during the whole year 2005 indicated that there were coincident peaks found in the frequencies occurring simultaneously at all the stations between 04-05 hr UT and 18-19 hr UT interval which is clear from the plots of the total year (Fig. 5.13). The lower latitude stations Pondicherry and Nagpur also exhibited a peak in the frequency, occurring between 21-22 hr UT interval but it was absent at the comparatively higher latitude station Hanle. It can also be seen from the plots of total year that the frequency variation at all the stations showed ‘U-type’ pattern between 00-10 hr UT time interval and ‘inverted U-type’ pattern in between 12-24 hr UT time interval. Ansari and Fraser (1985) have also reported this type of behavior in the frequency variation in south-east Australia corresponding to Australian Eastern Standard Time (AEST) [Ansari et al., 2009(b)].

The seasonal variations in the average frequencies are found to be higher in the local summer than in the local winter as is evident from plots of Fig. 5.14 to Fig. 5.17. These results do not agree with those of Ansari and Fraser (1985) who reported higher average frequencies in local winter than in local summer at the south-east Australian stations. Kuwashima et al. (1978) has also reported peak frequency in winter and equinox that is contrary to our results. In addition, it is evident from Fig. 5.14 that in
Chapter 7: Discussion and Conclusion

general, the average frequency tends to decrease slightly throughout the day in local winter at Hanle and Pondicherry. Similar results have also been reported by Ansari and Fraser (1985) and Barker (1977). This trend has also been seen at synchronous orbit in Pc3 harmonic structure by Takahashi and McPherron (1982). The average frequency variation trend found at Nagpur was slightly different from other stations [Ansari et al., 2009(b)].

The relation of pulsation activity with the solar wind velocity and IMF magnitude are very much valuable for understanding the generation and propagation mechanisms of these waves, specially to check their origin in the region upstream to the bow shock. In this regard the results of the analysis of the dependence of occurrence of geomagnetic Pc4 pulsations, recorded at the three stations situated at very low latitudes in India, on solar wind velocity (Vsw) and magnitude of the interplanetary magnetic field (IMF) during the whole year 2005 have been reported in the chapter-6. It is observed from the graph 6.1.13, depicting dependence of occurrence period of Pc4 pulsations on solar wind velocity that the value of the solar wind velocity ranges from 250 km/s to 1000 km/s approximately in the whole year and occurrence of events observed nearly for all values of Vsw. The majority of Pc4 pulsation occurrence was found in between 300 km/s to 700 km/s Vsw velocity values. The maximum values of duration of pulsation events at all the stations are found corresponding to 300 km/s - 400 km/s Vsw values. However the graph showed the secondary maxima of occurrence nearly between 600 km/s to 700 km/s. The dependence of occurrence of Pc4 magnetic pulsations on the magnitude of IMF for the total year 2005 for all the three stations is shown in the fig. 6.2.13 [Ansari & Nafees, 2012(a)]. From the graph it is clear that although the occurrence of events was observed up to the IMF magnitude 22 nT but majority of events occurrence was seen when the value of IMF
magnitude was in between 2-10 nT with maximum occurrence found with the magnitude of IMF in between 4-6 nT. Nearly similar behavior was recorded at all the three stations Nagpur, Hanle and Pondicherry. Also it is evident from the monthly analysis that this trend of occurrence pattern was observed in nearly all the months. The duration of maximum occurrence was 5458 min. at the Nagpur station for the IMF values 4-5 nT. At Hanle station the duration of maximum occurrence was found 5116 min. while at Pondicherry station it was 6927 min. between the 4-5 nT values of IMF. For Hanle, the duration in Pc4 occurrence was found to be less dominant in comparison to other stations and the occurrence pattern was found slightly different from Nagpur and Pondicherry station. The main reason of this was the unavailability of data in most of the days in August, September and October 2005 for this station [Ansari & Nafees, 2012(a)].

The following text of the discussion part is being reproduced from Ansari et al., 2009(a):

There are two possible locations for the external origin of pulsations, at the magnetopause and upstream from the magnetopause. Surface waves generated by the K-H instability are important at the magnetopause [Yumoto (1984), Kivelson and Pu, (1984), Wu (1986)] while upstream from the magnetopause large amplitude waves in the quasi-parallel bow shock are swept back into the magnetosheath and then penetrate the magnetosphere and couple to the standing oscillations of the magnetospheric field lines (Greenstadt 1972). This coupling may occur at all latitudes (Yumoto & Saito 1983).

The characteristics of the waves excited by the K-H instability are dependent on the length of the field lines and the plasma density at the magnetopause (Chen and Hasegawa, 1974). The association of
westward propagation of Pc3 waves with left hand (LH) ellipticity pre
noon and eastward propagation with right hand (RH) ellipticity after
noon for the azimuthal pair of stations (Ansari and Fraser, 1986) is
consistent with the waves generated at the magnetopause by the K-H
instability. The Pc3 noon peaks in occurrence (Ansari and Fraser,
1985), however, cannot be explained by this mechanism. It is also
difficult to see how the externally excited evanescent surface waves
with large damping rates can propagate deep into the magnetosphere
and through the plasma pause to couple with the field line resonance at
low latitudes. In addition the threshold velocity for the K-H instability
involves the angle between the magnetic fields across the
magnetopause. Hence on a statistical basis it is likely that the
magnetopause is more unstable for higher solar wind velocity (Ansari
2007).

Greenstadt et al. (1983) has presented the first direct evidence for
the propagation of external Pc3-4 wave power into the magnetosphere.
They verified with individual events from ISEE 1-2 spacecraft that
same frequencies in 10-100 mHz band were observed in the
magnetosheath and also in the magnetosphere with lower power.
Tomomura et al. (1983) also reported similar results from six months
data of ISEE in the 3 - 30 mHz band. 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 (Burton et al. 1970). 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. (1983) who have shown that the wave spectral power is generated in the magneto-sheath around noon. The quasi-parallel shock transition has been found to be highly turbulent (Greenstadt et al. 1977). Furthermore the amplitude of bow-shock-associated waves seems to be dependent on the magnetosonic Mach Number (Formisano et al. 1973) and therefore on the solar wind velocity. The association of higher probability of Pc3 occurrence at low latitudes with higher solar wind velocity is therefore more likely to be a consequence of bow-shock associated waves. The results of Yumoto et al. (1984) support this mode of Pc3 wave generation and resonance. Using the data of search coil magnetometers from two Antarctic stations (sub-auroral Pc3), Chugunova et al. (2003) have found that the suggested idea about the possibility of two channels of the penetration of primary upstream turbulence, i.e., via the cusp and via the lobe flanks is statistically feasible. More recently Howard & Menk (2005) have undertaken the study of Pc3-4 waves recorded on the ground with the IMAGE magnetometer array at higher geomagnetic latitudes (56°- 76°) during January & March 1998. The occurrence and the frequency of these waves have suggested that they are generated by the upstream ion-cyclotron resonance mechanism, with no evidence of generation by the Kelvin-Helmholtz instability. Also, in their study with Pc3-4 geomagnetic pulsation data recorded at very low and equatorial latitudes (L = 1.0 -1.2) in Brazil, Zanandrea et al. (2004) discuss the observed characteristics of Pc4 is due 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
Chapter 7: Discussion and Conclusion

global mode or trapped fast mode in the plasmasphere during field line oscillations at very low and equatorial latitudes. Takahashi et al. (2005) have pointed a common upstream wave energy source for Pc4 pulsations observed on the nightside. They have observed strong low latitude Pc4 pulsations on dayside by IMP–8 during the period of nightside Pc4 pulsations [Ansari et al., 2009(a)].

Vellante et al. (2004) reported that the frequency of compressional wave observed by CHAMP was very close to the expected frequency of upstream waves in the earth’s foreshock and with their observational results they discussed that the upstream waves are the main cause of the day time Pc3 pulsations and supported the predictions of Yumoto et al. (1984). Heilig et al. (2007) also reported in their comprehensive study of ULF upstream waves observed in the topside ionosphere by CHAMP satellite and on the ground by MM100 magnetometer array that they found a steep rise in compressional wave power after sunrise and also another increase after 19:00 LT, lasting until midnight at low latitudes. They also found higher wave power input with higher speed solar wind. The results of present study are also in agreement with the observed characteristics of ULF upstream waves by Heilig et al. (2007) who supported with their results, a partial but direct propagation of compressional waves from the sub-solar magnetopause through the magnetosphere towards the earth, as proposed by Yumoto et al. (1984). The results of dependence of occurrence of these pulsations on solar wind velocity are in agreement with the internationally reported study of Ansari (2008), who has demonstrated through his study that the occurrence probability of low latitude ULF Pc3 pulsations recorded at four ground stations in south-east Australia depends on solar wind velocity with a threshold at about 300 km/s and ranging up to 700 km/s. He indicates that it is likely the bow-shock associated waves,
Chapter 7: Discussion and Conclusion

originating from the direct interaction between the solar wind and the magnetosphere, exciting the Pc3 pulsations. In the light of above discussed excitation mechanisms and the observed results of the diurnal and seasonal variation of low latitude Pc4 pulsations and their dependence on solar wind velocity and IMF magnitude, it is suggested that the upstream waves are a major source of Pc4 pulsations detected on 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 [Ansari et al., 2009(a)].

Lei et al. (2008) reported that the solar wind velocity exhibit a very harmonic 9-day variation during the first 270 days of the year 2005. Concerning it, year 2005 may be very interesting for solar wind related source. In this regard efforts made to trace this periodicity in present data of Pc4 pulsations and data of solar wind velocity but this periodicity could not be observed in the data concerned. Perhaps it was not possible to trace this periodicity with the data used for analysis as there was unavailability of data for several days in August, September and October for Hanle and Nagpur stations.

7.2 Conclusion: -

The statistical characteristics of very low latitude geomagnetic pulsations in Pc4 frequency range in India have been investigated in the current study and the results of the analysis of diurnal and seasonal variations in the occurrence and frequency of Pc4 events at these latitudes during the whole year 2005 at the three stations Hanle, Nagpur and Pondicherry and their dependence on solar wind velocity and interplanetary magnetic field (IMF) magnitude have been reported. The
majority of occurrence of Pc4 events was seen between 14 hr UT to 21 hr UT at all the three stations in nearly every month. The maximum occurrence peak was generally found in between 17 hr to 19 hr UT interval in all the months except in April and May when the maximum occurrence peaks were found at 15-16 hr and 06-07 hr UT respectively. The majority of occurrence of Pc4 events observed in our studies between 14 hr UT to 20 hr UT (local nighttime) has also been reported in many previous studies. Many other Pc4 events in local daytime were also found in the course of the present study. The results are in agreement with suggestions of Takahashi et al. (2005) who reported and suggested 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 substorm onsets or intensification. Similar results were also reported by Villante et al. (1999), Engebretson et al. (1989). The main peaks in Pc4 occurrence at local winter and local autumn found at the same time at all the three stations also agree with the previous studies of Ansari and Fraser (1985) and Kuwashima et al. (1978). No clear dependence of pulsation occurrence period on latitude was found as the maximum occurrence peak periods were varying with latitude in a very complicated manner during the different months of the year [Ansari et al., 2009(a)].

The frequency variation plot for the total year at all the stations indicated ‘U-type’ pattern between 00-10 hr UT interval and ‘inverted U-type’ pattern in between 12-24 hr UT interval, which is similar to the results of Ansari and Fraser (1985). The seasonal variations in the average frequencies found to be higher in the local summer than in the local winter are in contrast to the results reported by Ansari and Fraser (1985). These findings do not agree with the results reported by Kuwashima et al. (1978). However, in general the average frequency tends to decrease slightly
throughout the day in local winter at Hanle and Pondicherry, which is similar to the results reported by Ansari and Fraser (1985) and Barker (1977). This trend has also been seen at synchronous orbit in Pc3 harmonic structure by Takahashi and McPherron (1982) [Ansari et al., 2009(a)].

In the study of dependence of occurrence of Pc4 pulsations on solar wind velocity, the majority of Pc4 pulsation occurrence was found in between 300 km/s to 700 km/s Vsw velocity values. The maximum values of duration of pulsation events at all the stations are found corresponding to 300 km/s - 400 km/s Vsw values. However the secondary maxima of occurrence was found nearly between 600 km/s to 700 km/s. The occurrence of events was observed up to the IMF magnitude 22 nT but majority of events occurrence was seen when the value of IMF magnitude was in between 2-10 nT with maximum occurrence found with the magnitude of IMF in between 4– 6 nT [Ansari & Nafees, 2012(a)].

The results of present study are in agreement with the observed characteristics of ULF upstream waves by Vellante et al. (2004) and Heilig et al. (2007) who discussed that the upstream waves are the main cause of the observed ground magnetic pulsations and supported with their results, a partial but direct propagation of compressional waves from the sub-solar magnetopause through the magnetosphere towards the earth, as proposed by Yumoto et al. (1984). The results of dependence of occurrence of these pulsations on solar wind velocity are in agreement with the study of Ansari (2008), who has demonstrated that the occurrence probability of low latitude ULF Pc3 pulsations depends on solar wind velocity with a threshold at about 300 km/s and ranging up to 700 km/s and discussed that it is likely the bow-shock associated waves, originating from the direct interaction between the
solar wind and the magnetosphere, exciting the Pc3 pulsations. In the light of discussed excitation mechanisms and the observed results of the diurnal and seasonal variation of low latitude Pc4 pulsations and their dependence on solar wind velocity and IMF magnitude, it is suggested that the upstream waves are a major source of Pc4 pulsations detected on 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. In last, simultaneous studies of space data of different regions and also data from different ground magnetometer stations are required for complete view of whole process and for clear prediction of generation and propagation mechanism [Ansari & Nafees, 2012(a)]. As the stations array was spread over a latitudinal range of 21° only in my study, 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 [Ansari et al., 2009(a)].