A study of latitudinal dependence of Pc 3-4 amplitudes at 96° magnetic meridian stations in Africa

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Abstract. The study of latitudinal dependence of Pc 3-4 amplitudes at very low latitudes particularly near the dip equator is very important to identify the propagation mechanisms of the equatorial Pc 3-4 pulsations. Therefore, geomagnetic data simultaneously recorded at the MAGDAS African stations along the 96° Magnetic Meridian chain were analyzed to examine the latitudinal dependence of Pc 3-4 amplitudes at the equatorial and very low latitudes up to middle latitudes. During three and a half months between 4 October 2008 and 22 January 2009, 21 Pc 3 events and 25 Pc 4 events were selected for studying the latitudinal dependence of Pc 3-4 amplitudes. The latitudinal profile of the Pc 3 amplitude ratio indicates attenuation in the Pc 3 amplitudes at the dip equator. This attenuation may be due to the ionospheric shielding effect. On the other hand, the Pc 4 amplitude shows a peak at dip equator and decreased with increasing latitude up to middle latitudes as it revealed from the latitudinal profile of the Pc 4 amplitude ratio. According to the obtained results, the main source of the equatorial Pc 3 must be related to the compressional upstream waves, while the equatorial Pc 4 may be linked with the compressional upstream waves and/or the Pc 4 excited at higher latitudes.

Keywords: Latitudinal dependence, Equatorial Pc 3-4, Pc 3-4 amplitudes, Shielding effect.

Introduction

Geomagnetic pulsations, Ultra Low Frequency (ULF) waves, are naturally occurring magneto-hydrodynamic (MHD) waves in the Earth's magnetosphere. These ULF waves are classified as continuous (Pc) or irregular (Pi) pulsations. Each category is subdivided into period bands that roughly separate a specific type of pulsation. Pc 3-4 pulsations are continuous geomagnetic oscillations with a quasi-sinusoidal waveform. These two types of continuous pulsations are relatively low amplitude fluctuations of the geomagnetic field with periods of 10-45 s (Pc 3 range) and 45-150 s (Pc 4 range) [1-3]. The amplitude of the Pc 3-4 pulsations [peak to peak] ranges from fraction of a nano Tesla (nT) to a few nT. The characteristics of ULF waves observed on the ground contain information not only about the generation processes but also about the regions through which they have propagated [4].

Most of the ULF wave studies have relied on data obtained from middle or high latitudes, while the equatorial and very low latitudes have received a little attention [5]. Consequently, the source and propagation mechanisms of the equatorial and very low latitude pulsations are not fully understood and they might be related to either upstream waves or the mechanisms of pulsations at higher latitudes [2, 5]. A number of studies indicated an attenuation of the Pc 3 amplitude at the equatorial region [6-8]. On the other hand, some studies at the equatorial region showed an enhancement in the Pc 3 amplitudes at dip equator [9-11]. However for short period Pc 3 pulsations (< 20 s), the equatorial Pc 3 amplitude has been reported to suffer attenuation rather than amplification [9].

The study of the latitudinal dependence of geomagnetic pulsations at very low latitudes particularly near the dip equator is very important to identify the propagation mechanism of the low-latitude pulsations, i.e., a direct incidence of the compressional waves on the equatorial ionosphere or a leak of the ionospheric current caused by the pulsations at higher latitudes. The latitudinal dependence of the geomagnetic pulsations can be studied by a meridional array of stations. In the present study, we investigate the latitudinal dependence of Pc 3-4 amplitudes at equatorial to middle latitudes using simultaneous geomagnetic observations across the dip equator through the MAGnetic Data Acquisition System (MAGDAS) at African stations in order to identify the generation and propagation mechanisms of the equatorial Pc 3-4.

Instrumentation and data acquisition

MAGDAS Project effectively started in May 2005, with the installation of the first MAGDAS magnetometer in Hualien, Taiwan [12-13]. Since then, over 50 magnetometers have been installed around the world. They are distributed along three chains: (1) The 210° Magnetic Meridian (MM) chain, (2) The dip Equator chain, and (3) The 96° MM chain (African chain) as shown in Figure 1.

MAGDAS system is composed of two subsystems, which are MAGDAS-A and MAGDAS-B. MAGDAS-A consists of the magnetometer, data logger and data-transfer modules. Magnetic field digital data are obtained with the sampling rate of 1 second, and then the recorded data are transferred from the overseas stations to Space Environment Research Center (SERC), Japan in near real-time. Also, the data are recorded in compact flash memory cards in situ. MAGDAS-B is a subsystem of the MAGDAS to receive the data from MAGDAS-A, analyze the MAGDAS data and monitor the analyzed data as well as the status of each overseas station. The complete system of MAGDAS-B was installed at the SERC, Kyushu University in December 2004 [12].

The geomagnetic data used in this study were recorded using 2 types of magnetometers: MAGDAS and MAGDAS II magnetometers. MAGDAS system was manufactured by Meisei Electric Co., Ltd., while MAGDAS II system was developed by SERC, Kyushu University. Both types of magnetometer are ring core-type fluxgate magnetometers that can measure even small-amplitude geomagnetic fluctuations.

TABLE 1:
The geomagnetic stations selected for the present study.

Abbrev	Station	G. Lat	G. Long	GM. Lat	GM. Long
LAQ	L'Aquila	42.38	13.32	36.25	87.56
FYM	Fayum	29.3	30.88	21.13	102.38
ASW	Aswan	23.59	32.51	15.20	104.24
KRT	Khartoum	15.33	32.32	5.69	103.8
AAB	A Ababa	9.04	38.77	0.18	110.47
NAB	Nairobi	-1.16	36.48	-10.65	108.18
DES	Dar Es Salam	-6.47	39.12	-16.26	110.59
LSK	Lusaka	-15.23	28.20	-26.06	98.32
MPT	Maputo	-25.57	32.36	-35.98	99.57
DRB	Durban	-29.49	30.56	-39.21	96.1
HER	Hermanus	-34.34	19.24	-42.29	82.2

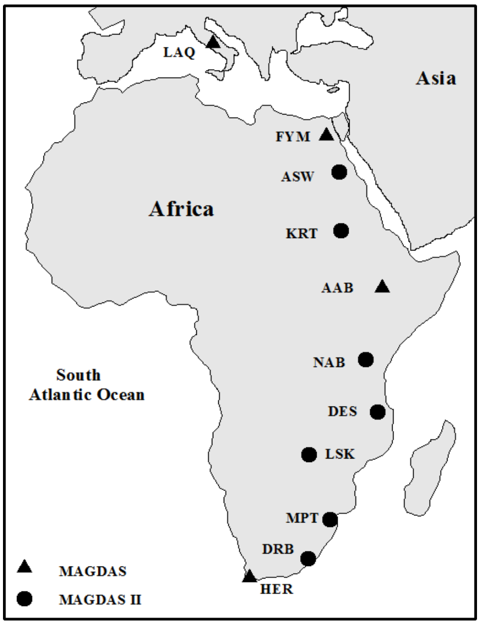

Fig. 1: African MAGDAS stations used in the present study.

The sensitivities of both types are almost the same with each other and also share the same sampling rate (1 s). Three observation ranges of ±2,000 nT, ±1,000 nT, and ± 300 nT can be selected for high, middle, and low-latitudestations, respectively. The resolutions of MAGDAS data are 0.061 nT/LSB and 0.031 nT/LSB, and 0.0091 nT/LSB for ± 2,000 nT, ± l,000 nT, and ± 300 nT range, respectively [2]. The noise level of the MAGDAS and MAGDAS II magnetometer is 0.02 nT.

Data analysis and results

Since the main goal of the present study is to examine the latitudinal behavior of Pc 3-4 amplitudes, we analyzed one second geomagnetic data from 96° MM stations located from the dip equator to the middle latitudes. This profile extends from L' Aquila (LAQ) in Italy down to Hermanus (HER) in South Africa as shown in Figure1. Table 1 shows the geographic and geomagnetic coordinates (AACGM) of the MAGDAS stations along the studied profile. This profile includes 11 MAGDAS stations (four MAGDAS stations: LAQ, FYM, AAB and HER; seven MAGDAS II stations: ASW, KRT, NAB, DES, LSK, MPT and DRB). Geomagnetic data obtained from the MAGDAS magnetometer at LAQ station (Italy, Europe) were used to extend the latitudinal profile in the northern direction. The geomagnetic data used for this study were recorded from 4 October 2008 up to 22 January 2009.

The selection of the Pc 3-4 events involved comparing the daily dynamic power spectra of the H-component recorded at each station. The dynamic power spectra were performed in the period range 10-150 s by using MATLAB scripts in order to identify the Pc 3-4 events. Each day of geomagnetic data includes 86400 points, which subdivided in segments with 512 points. The dynamic spectra were calculated by the sliding Fast Fourier Transform (FFT) technique (512 points of 1-s resolution, sliding by 5 minutes). A clear peak in the dynamic power spectrum diagrams (visual inspection) in the same frequency range at each station and a continuous quasi-sinusoidal waveform in band-pass filtered (20-40 s for Pc 3 and 70–100 s for Pc 4) geomagnetic data recorded at each station were the selection criteria for the Pc 3-4 events. The selected Pc 3-4 events were observed along the selected profile with a good visual similarity (in dynamic power spectra) and coherence (in the waveform of the band-pass filtered data), except for DRB station where the data were too noisy and thus excluded from our results. Also KRT station was a bit noisy compared with other stations, but the difference in noise level was not too great to warrant exclusion. The ratio of noise level between KRT and AAB (KRT/AAB) stations was about 1.15. Figure 2 presents two hours (0800-1000 UT) dynamic power spectra (period range 10-150 s) of the H component recorded on 4 October 2008 at some African stations, where the H component shows an enhancement in the wave amplitude in the spectral band of 20-150 s and also the dynamic power spectra were visually similar along these stations.

Twenty one pulsation [Pc 3] events were selected for studying the Pc 3 amplitudes, and 25 [Pc 4] events were selected for the Pc 4 amplitudes along the same profile. The selected events occurred in the daytime from 0600 up to 1800 LT. The duration of the pulsation events was not constant; some events lasted for several minutes while other events lasted for one hour or more. In some pulsation events, it was difficult to find a good correlation between a number of the selected stations because some of these stations had momentarily noisy data (perhaps related to human activities near these stations). Therefore, we excluded such events from our results.

To examine the Pc 3 amplitudes for the selected events, the H (North-South) and D (East-West) components were digitally band-pass filtered in two period ranges: 20-30 s and 30-40 s (Pc 3 range). Figure 3 shows the filtered wave packets obtained after applying the two above-mentioned band-pass filters on one hour data of the H component from 0800-0900 UT on 4 October 2008 along a profile represented by stations code. Each event was divided into segments of 10 minutes length, and then the average peak-to-peak amplitude for each segment was determined. In the next step, the average Pc 3 amplitude was calculated for the whole pulsation event. After that, we calculated the Pc 3 amplitude ratio at each station in reference to AAB station (LAQ/AAB, FYM/AAB .... HER/AAB). Finally, we constructed the latitudinal profile of the Pc 3 amplitude ratios (Figure 4a and b). For the H component, there was a distinct latitudinal variation. The Pc 3 amplitude showed an enhancement at low latitude stations but with a depression at the dip equator (AAB station) and then it decreased steadily with increasing station latitude (up to ≈ ± 25°). At higher latitudes, it increased with increasing latitude. It is noteworthy that the attenuation of the shorter-period Pc 3 (20-30 s) amplitude at the dip equator is larger than the longer-period Pc 3 (30-40 s) as shown in Figure 4 a and b, respectively. On the other hand, the D component Pc 3 pulsations behaved differently. The amplitude was generally less than that of H component (i.e. the Pc 3 amplitude ratio D/H at AAB station was ranging between 0.25-0.3) and there was no systematic variation with latitude.

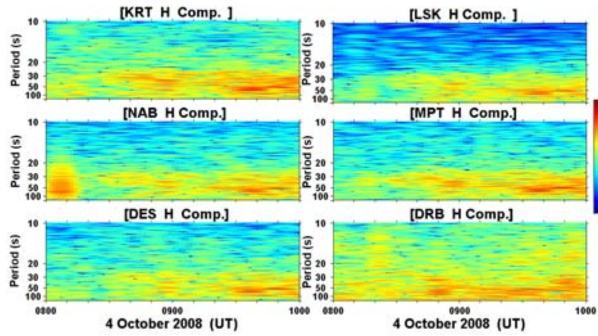

Fig. 2: Dynamic power spectra of two hours (0800-1000 UT) data of H component recorded at some MAGDAS African stations on 4 October 2008 [band pass filter 10-150 s].

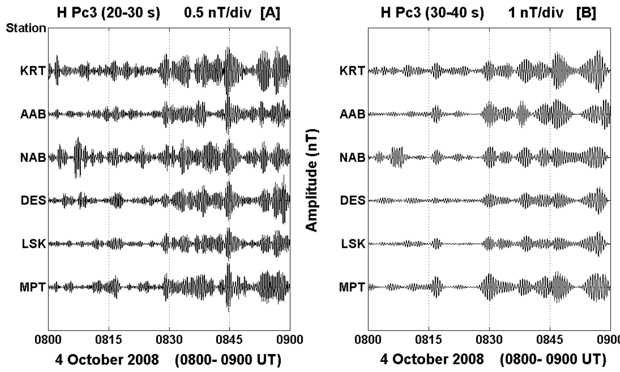

Fig. 3: A pulsation event in H component recorded at some African stations on 4 October 2008; the data have been digitally filtered in both 20-30 s and 30-40 s periods band, panels A and B respectively.

The band-pass filter in the period range 70-100 s was applied on the H and D components of the selected Pc 4 events. Figure 5 shows the filtered wave packets obtained after applying the band-pass filter (70-100 s) on two hours data of the H component from 0900-1100 UT on 4 October 2008 along a profile represented by stations code. The Pc 4 amplitudes were measured using the same technique previously used in the case of Pc 3. After that, we constructed the latitudinal profile of the Pc 4 amplitude ratios (by using the same procedure for calculating the amplitude ratio of the Pc 3 pulsations), which showed a peak at the dip equator and then decreased with increasing latitude (up to middle latitudes) as shown in Figure 6. Similarly to the Pc 3, the D component Pc 4 amplitudes were much smaller than the H component Pc 4 amplitudes (i.e. the Pc 4 amplitude ratio D/H at AAB station was around 0.35).

Discussion

Studies of the ULF waves at low latitudes show that significant hydromagnetic wave energy penetrates deep into the magnetosphere and the plasmasphere [14]. Generally, two models are proposed for the generation and the propagation mechanism of the Pc 3-4 at the equatorial region. The first model is the compressional upstream waves model (model 1). According to this model, the compressional waves propagating along the magnetosphere (direct transmission from the magnetosheath across the dayside magnetosphere) arrive at the equatorial ionosphere and couple with the magnetic perturbations on the ground through the ionosphere [15-17]. In this case, the field line resonances will be excited by the compersional waves; which are believed to be a main source of Pc3 pulsation observed at low latitudes [18-20]. The ionospheric current model (model 2) is the second model suggested to explain the propagation mechanism of the equatorial Pc 3-4. In this model, the surface waves generated by the Kelvin-Helmholtz instability at the dayside high-latitude magnetosphere boundary generate large-scale ionospheric current oscillations. These oscillations leak to the low latitude and generate Pc 3-4 pulsations near the dip equator [2,16]. In model 1, attenuation of the pulsations amplitude at the dip equator occurs as a result of the shielding effect, while an equatorial enhancement of the pulsations amplitude occurs due to the concentration of the ionospheric current to the magnetic equator in model 2 [21,16].

An attenuation of the Pc 3 amplitude at the equatorial region due to the shielding effect was reported through many studies [6-7]. On the other hand, some studies indicated an equatorial enhancement of Pc 3-4 amplitudes [9,11]. [9] observed an equatorial enhancement of Pc 3-4 with periods greater than 30 s. Also, they indicated attenuation in the Pc 3 amplitude at the dip equator with periods less than 20 s. They related such attenuation to the effect of the equatorial ionosphere, where the ionosphere has a major role in the modification of the pulsation properties during their propagation through the magnetosphere-ionosphere system. However, their results did not refer to the behavior of the Pc 3 amplitude in the period range 20-30 s at the dip equator. Moreover, their results depended on data obtained from two stations only.

In the current study we analyzed data obtained from a meridional magnetometer array distributed over a wide range of latitudes; from dip equator up to middle latitudes. From the obtained results concerning the Pc 3, we found that the Pc 3 amplitudes show a peak at low-latitude stations with a depression at AAB station (the dip equator). Moreover, the attenuation in the Pc 3 amplitude is larger in the period range 20-30 s (typical range for the upstream waves) than that in the period range 30-40 s as shown in Figure 4.

This attenuation of the Pc 3 amplitude can be linked with the ionospheric conductivity above the dip equator. The very low latitude region is characterized by high zonal ionospheric conductivity close to the dip equator and the induced ionospheric currents are mainly controlled by the intensity of the ionospheric conductivity.

We consider that the equatorial Pc 3s observed on the ground are generated by model 1, in this case, the propagating compressional waves (that originally generated in the region upstream of the bow shock) are prevented from passing to the atmosphere by the induced ionospheric currents, i.e. these currents act as an obstacle in the way of the propagating compressional waves.

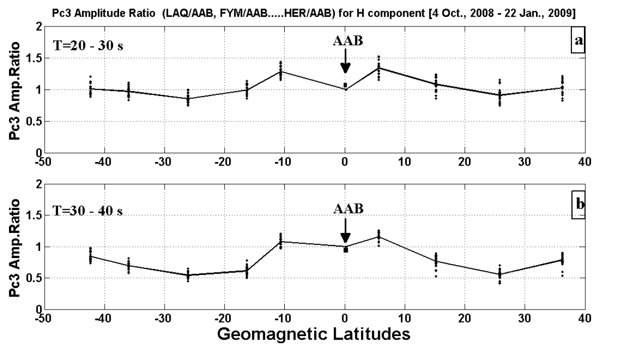

Fig. 4: The latitudinal profile of the Pc 3 amplitude ratios (the solid curve represents the average amplitude ratios of the Pc 3 for the selected events). Panel (a) is for the Pc 3 (20-30 s) and panel (b) is for the Pc 3 (30-40 s).

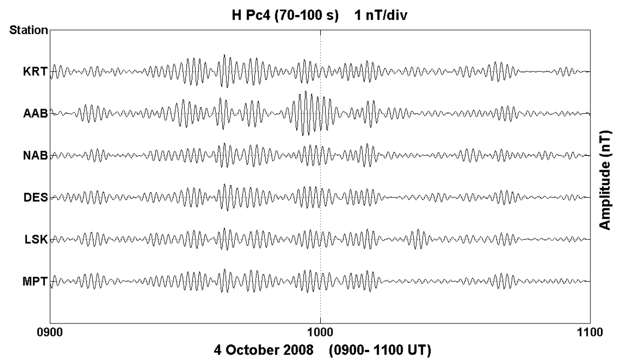

Fig. 5: A pulsation event in H component recorded at some African stations on 4 October 2008, the data have been digitally filtered in the (70-100 s) period band.

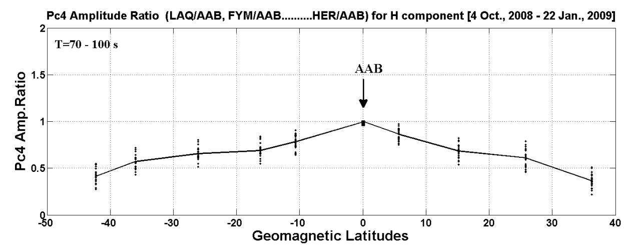

Fig. 6: The amplitude ratio profile of Pc 4 (70-100 s) pulsations (the solid curve represents the average amplitude ratio of the Pc 4 for the selected events).

As a result, we can observe attenuation of the pulsation amplitudes. Besides, the observed attenuation of the Pc 3 amplitude was larger in the period range 20-30 s, which is the typical range for the compressional upstream waves. So the concept of shielding effect of the high-conducting equatorial ionosphere is an acceptable theoretical concept to interpret the attenuation of the Pc 3 amplitude at the dip equator [6-7].

In our opinion, the reason that the attenuation of Pc 3s amplitude in the period range 20-30 s is larger than that in the period range 30-40 s (see Figure 4), may be due to the superposition of the Equatorial Electrojet (EEJ) effect on the shielding effect. The EEJ, an eastward electric current in the day time equatorial region of the Earth's ionosphere, has a considerable influence on geomagnetic variations over a wide range of periods [9]. The EEJ effect can cause an enhancement in the signal amplitudes of the Pc 3-4 close to the dip equator [22]. [8] reported that the lower frequencies of magnetic pulsation undergo larger equatorial amplification due to the EEJ effect, but for a certain frequency range (18-24 s) the pulsation signal is found to attenuate rather than exhibit the general enhancement. However no specific explanation was given for such attenuation in their study.

Therefore, we propose that the daytime equatorial Pc 3s observed at the African sector are propagated from the upstream region by the compressional wave model. In addition, it is difficult to explain the occurrence of very low-latitude Pc 3 on the ground as a result of the surface waves (model 2) at the day side high-latitude magnetopause because of the high damping rate of these wave in the Pc 3 frequency range in the radial direction (for more details see [23,2]). Furthermore, [24] demonstrated a high coherence between the compressional component in space and the H component on the ground after they performed a coherence analysis of a Pc 3 event observed both in space (by a satellite) and on the ground.

On the other hand, the Pc 4 amplitudes showed a peak at dip equator and decreased with increasing latitude up to middle latitudes. As for the equatorial Pc 4, there are not so many studies related to the Pc 4 at the equatorial region because most researchers concentrated on mid to high latitudes. In our results concerning the equatorial Pc 4, we found a peak at the dip equator in contrast to the Pc 3. However, the source of the equatorial Pc 4 is not fully understood, but the two above-mentioned models can be used to explain the generation mechanism of the equatorial Pc 4. If we consider the compressional upstream waves as a source of the equatorial Pc 4; In this case, the Pc 4 amplitude at the dip equator will not attenuated due to shielding effect because the shielding effect attenuation mainly occurs in the shorter-period pulsations (Pc 3 range). On the other, if we consider the source of the equatorial Pc 4 is the leak of the ionospheric currents caused by the Pc 4 pulsations at higher latitudes (model 2), we can observe an enhancement in the Pc 4 amplitudes at the dip equator as it reported by [16]. Many studies showed that there is enhancement of equatorial Pc 5 whose main source is at high latitudes [25-26], so maybe we can expect a similar mechanism for generating the equatorial Pc 4 pulsation. In our opinion, more detailed studies are required in order to examine that exact source of the equatorial Pc4 (including the phase difference, coherence, polarization etc).

It is well known that the occurrence and intensity of geomagnetic pulsations are linked with the interplanetary magnetic field (IMF) and the solar wind velocity (V) as revealed from many geomagnetic observations (ex. [27]). Furthermore, the upstream waves are generally controlled by the solar wind parameters and the IMF. The transmission of upstream waves into the Earth's magnetosphere can be linked with the cone angle (the angle between the IMF and the Sun-Earth direction). Previous studies showed that, the transmission process will be better under small values of cone angel [27-28]. Hence, we examined the solar wind velocity, the IMF magnitude and the cone angle during the selected Pc 3-4 events in order to confirm the source of the equatorial Pc 3-4 pulsations. Figure 7 shows the comparison of the dynamic power spectrum of the H component recorded at AAB station (panel [a]), and the total magnitude of the IMF (panel [b]), the cone angle (panel [c]) and the solar wind velocity (panel [d]) in the upstream region during 13 October 2008 (UT). The IMF and Solar wind velocity data are obtained from the Advanced Composition Explorer (ACE). We found, about 85% of the Pc 3 events and 60% of the Pc 4 events occurred during solar wind velocity ranging between 400-650 km/s. Furthermore, we found that the shorter period of the magnetic pulsation (Pc 3) tend to occur during IMF magnitude ranging between 4-6 nT. While, the longer period (Pc 4) pulsations occur during low IMF magnitudes (less than 2.5 nT).

These observations agree with the formula proposed by [23] concerning the interrelation between the IMF magnitude and the frequency of the magnetic pulsations observed on the ground. In addition, 80% from the Pc 3-4 events occurred during cone angle less than 45°. From these results, the occurrence of the equatorial Pc 3s can be correlated with the upstream activities, which support model 1 to be the predominant source of the equatorial Pc 3. In addition, Pc 4s showed less correlation; in this case, models 1 and 2 almost have equal possibilities to be the source of the equatorial Pc 4.

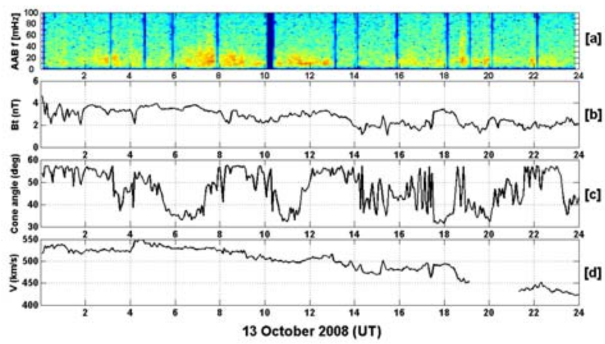

Fig. 7: The comparison of the dynamic power spectrum of the H component recorded at AAB station (panel [a]), and the total magnitude of the IMF in nT (panel [b]), the cone angle in degrees (panel [c]) and the solar wind velocity in km/s (panel [d]) at the upstream region during 13 October 2008 (UT).

Summary and conclusion

Based on 46 magnetic pulsation events (Pc 3-4) observed at selected MAGDAS African stations along 96° magnetic meridian array during three and a half months starting from 4 October 2008, we studied the behavior of Pc 3-4 amplitudes at equatorial and low latitude stations. We identified the Pc 3-4 pulsation events by constructing the dynamic power spectra for the data recorded at each station. The Pc 3-4 amplitudes were calculated after applying the band-pass filters for both H and D components. From the statistical analysis of our results, we obtained the latitudinal profiles of the Pc 3-4 amplitude ratios.

The latitudinal profile of the Pc 3 amplitude ratio indicates attenuation in the Pc 3 amplitudes at the dip equator. This attenuation may be due to the ionospheric shielding effect. On the other hand, the Pc 4 amplitude shows a peak at dip equator and decreased with increasing latitude up to mid latitudes as it revealed from the latitudinal profile of the Pc 4 amplitude ratio. According to the obtained results, the main source of the equatorial Pc 3 must be related to the compressional upstream waves, while the equatorial Pc 4 may be linked with the compressional upstream waves and/or the Pc 4 excited at higher latitudes. These results agree with the model of the excitation and propagation of MHD waves leading to Pc 3-4 activity on the Earth's surface proposed by [15].

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