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Pc3 pulsations during variable IMF conditions

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Abstract. Pc3 geomagnetic field fluctuations detected at low latitude (L'Aquila, Italy) during the passage of a high velocity solar wind stream, characterized by variable interplanetary magnetic field conditions, are analyzed. Higher frequency resonant fluctuations and lower frequency phenomena are simultaneously observed; the intermittent appearance and the variable frequency of the longer period modes can be well interpreted in terms of the variable IMF elements; moreover their polarization characteristics are consistent with an origin related to external waves propagating in antisunward direction. A comparison with simultaneous observations performed at Terra Nova Bay (Antarctica) provides additional evidence for a clear relationship between the IMF and Pc3 pulsations also at very high latitudes.

Key words. Magnetospheric physics (MHD waves and instabilities; solar wind – magnetosphere interactions)

Introduction

The physical characteristics of geomagnetic micropulsations and their association with interplanetary and magnetospheric structures are important tools for a better understanding of the primary sources of such phenomena. In this sense, an empirical relationship between the dominant frequency of the dayside Pc3 pulsations (20 mHz $< f <$ 100 mHz) and the strength, B, of the interplanetary magnetic field (hereafter IMF) has been found in several investigations [f(mHz) $\sim$ 6B (nT), review by Troitskaya and Bolshakova, 1988]. This relationship has been interpreted as an important argument in favor of the model predicting that these pulsations could be directly related to ion cyclotron upstream waves generated in the foreshock region along IMF lines connected to the quasi-parallel bow shock (i.e. where the angle between the IMF and the bow shock normal, θ_{BN}, is less than 45°, Yumoto, 1986). As a consequence, given the average spiral orientation of the IMF lines, these Pc3 pulsations should be preferentially expected in the morning side of the magnetosphere. Moreover small values of the cone angle (the angle θ_{XB} between the IMF and the Sun-Earth direction) have been shown to provide favorable conditions for a better transmission of upstream phenomena into the Earth's magnetosphere (Greenstadt *et al.*, 1980; Russell *et al.*, 1983; Odera, 1986). According to Russell *et al.* (1983), the cone angle control of the ground activity might be dependent on latitude of the observing station and more efficient at lower latitudes. They conducted, indeed, a statistical analysis of the experimental observations between $L = 2.4$ and $L = 4.3$, and found that for small cone angles ($\theta_{XB} < 15°$) the normalized rate of occurrence of Pc3 and Pc4 pulsations increases with decreasing latitudes. Recently, Le and Russell (1996) found that the cone angle can also play a role in determining the frequency of upstream waves, although the IMF strength is the most important parameter that controls this frequency.

Several papers have been so far devoted to the analysis of individual events and short time intervals. In this sense, Webb and Orr (1976) found a distinct correspondence between the enhancements in the radial IMF component and the amplitude of Pc3 pulsations at $2.6 < L < 3.6$; nevertheless, the correlation coefficient between these two parameters was only of the order of 0.135 over time intervals of 16 h. Greenstadt and Olson (1976) also found, at middle latitudes, a clear tendency for signal enhancement for $\theta_{XB} < 50°$, although with an appreciable variability in individual cases. More recently, Chi *et al.* (1994), who analyzed the geomagnetic field observations from a chain of stations ($2.7 < L < 6.3$) during a 12 h interval in which the cone angle was

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smaller than 45°, confirmed a global control of the wave occurrence by the IMF orientation, in that the ground activity abruptly ceased when the cone angle increased to large angles; nevertheless, within this interval, they also found temporal variations of Pc3 and Pc4 pulsations which were not associated with corresponding variations of the IMF orientation. At lower latitudes ($L = 1.6$) Villante *et al.* (1992) examined three different days in 1985 during which the solar wind velocity remained high and approximately constant and showed that the ground power of Pc3 pulsations was clearly switched by variations of the cone angle.

On the other hand, deep into the magnetosphere, upstream waves are also expected to trigger eigenoscillations of the local field lines (Yumoto and Saito, 1983), if the source spectrum of external fluctuations contains the corresponding resonant frequencies: so, in general, both irregular wave forms (with periods related to the IMF magnitude) and more regular oscillations (with latitude dependent periods) are to be expected in ground observations. A previous statistical analysis in this sense, conducted by Vellante *et al.* (1996, see also Vellante *et al.*, 1989), demonstrated that during years of minimum solar activity the daytime pulsation activity at L'Aquila (Italy, AQ) is typically characterized by the occurrence of two dominant oscillation frequencies, at ~40 mHz and ~80 mHz, respectively interpreted in terms of the dominant upstream frequency and of the local fundamental field line eigenfrequency. The lower frequency peak is typically detected in both components while, in agreement with theory, the resonant peak much more sharply emerges in the H component and is clearly evidenced by the ratio between the H and D spectra. Approaching maximum solar activity, due to the simultaneous increase of the IMF strength and plasmaspheric ion density, the two peaks become progressively intermingled, and a single power enhancement in the Pc3 range is more typically observed at solar maximum.

In the present study we analyze the physical characteristics of individual Pc3 wave packets detected at low latitude on January 11, 1997, during variable IMF conditions. As in the statistical analysis conducted by Vellante *et al.* (1996), we find the simultaneous occurrence of higher frequency resonant fluctuations and lower frequency phenomena; the intermittent appearance and the variable frequency of the longer period modes can be well interpreted in terms of the variable IMF elements. We also analyzed simultaneous observations performed at an Antarctic station (Terra Nova Bay, TNB) and found that also at high latitudes Pc3 pulsations are clearly related to the IMF parameters (Engebretson *et al.*, 1986, 1991).

Data analysis and experimental observations

The micropulsation measuring systems at AQ and TNB basically consist of three high-sensitivity search-coil magnetometers. At AQ (IGRF95 geomagnetic latitude $\theta = 42.5°$, LT = UT+1, MLT = UT + 1:40) the output voltage signals, originally sampled at 16 Hz, are low-pass filtered and finally stored at a sampling rate of 1 Hz. At TNB ($\theta = -77.3°$, LT = UT+13, MLT = UT−8) the data, originally sampled at 10 Hz, are averaged and stored at 1 Hz; unfortunately, in the period of interest, only measurements of the D component were available. TNB, which during the major part of the day is located in the polar cap, progressively moves toward the polar cusp approaching local geomagnetic noon. Power spectra of the geomagnetic field components have been evaluated by means of the maximum entropy method.

As discussed by Villante *et al.* (1998), on January 10, 1997, the Earth's passage of a wide magnetic cloud triggered an intense geomagnetic activity at both the low latitude and the Antarctic station and different solar wind pressure variations found correspondence, after several minutes, in strong power enhancements at low frequencies (~0.8–5 mHz). Following the cloud, a solar wind stream, characterized by a velocity greater that 500 km/s, was detected from WIND (~85 R_e in the Earth-Sun direction) at ~0300 UT on January 11, 1997.

In Fig. 1 we compare for the time interval 0500–2400 UT (January 11, 1997), the 10 min running averages (with a step size of 2 min) of the IMF magnitude and direction with the running averages of the Pc3 power at AQ (H+D) and at TNB (D component). As can be seen, the IMF strength shows a rapid decrease from ~20 to ~8 nT until ~0800 UT followed by minor variations around ~6 nT; meanwhile the IMF maintains approximately its spiral orientation ($\phi \sim 135°$), except for two short intervals (~0520–0540 UT, 0740–0815 UT).

Several ground power enhancements are detected at AQ in the morning and noon sector (~0845–0930 UT, ~1000–1015 UT, ~1045–1130 UT): they are mostly observed to occur within intervals characterized, at WIND position, by small values of the cone angle ($\theta_{XB} < 45°$). In a single case (~0700–0730 UT), moreover, the ground power enhancement is somewhat delayed with respect to the occurrence of IMF variations which provided, for a short interval, minimum θ_{XB} values of the order of 55°. Actually, similar values of the cone angle (which are not accompanied by significant ground power enhancements) are also detected approximately between ~0730–0800 UT; however, as previously mentioned, they mostly correspond to large values of the ϕ angle (>200°) which, at the Earth position, would not provide IMF lines connected with the prenoon bow shock. According to Fig. 1, the Pc3 power enhancements at AQ reach approximately the same level, although associated with cone angle values which, on average, become progressively more favorable from the local dawn to the local noon. This feature suggests that the amplitude of the ground pulsations could also depend on the local time, as a consequence of the increasing longitudinal distance from the region where the upstream wave amplitude is expected to maximize (early morning sector for a spiral IMF orientation).

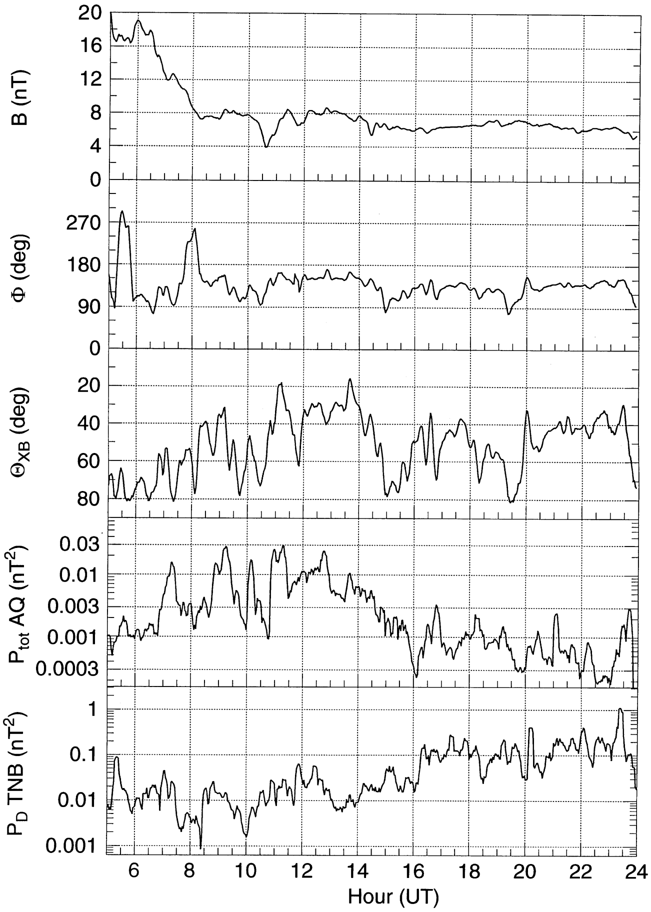

Fig. 1. Interplanetary magnetic field parameters (*from the top:* magnitude, longitude and cone angle), Pc3 power at AQ (H + D) and TNB (D component) for the time 0500–2400 UT on January 11, 1997. Powers have been computed by taking into account instrument transfer functions

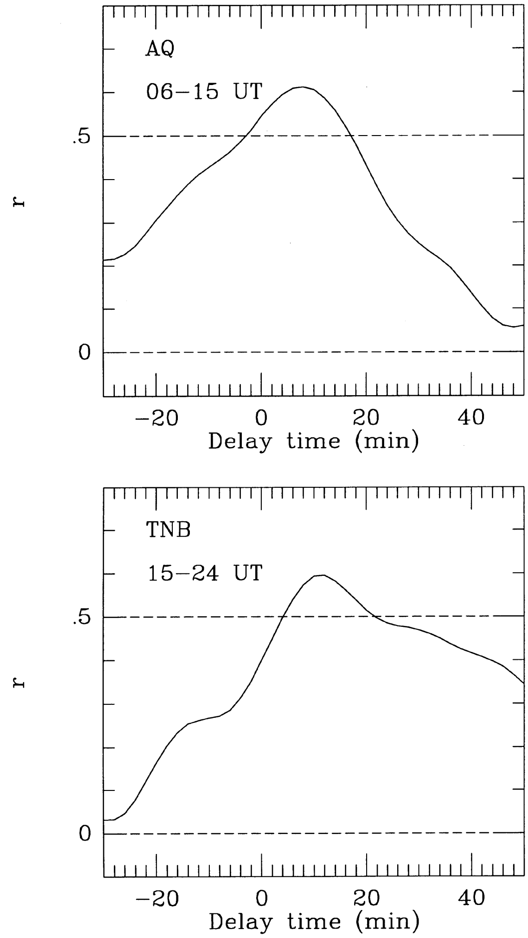

Fig. 2. Normalized cross-correlation function between $\cos(\theta_{XB})$ and the logarithm of the Pc3 power at AQ (*upper panel*) and TNB (*lower panel*)

Consistently, during early afternoon the pulsation activity progressively decays even in presence of favorable cone angle values (~ 1200–1430 UT); it persists, however, some correspondence between minor power enhancements and highly favorable θ_{XB} values (~ 1340 UT, ~ 1645 UT). During local late afternoon and night the pulsation activity becomes negligible.

The bottom panel in Fig. 1 shows that also at TNB the Pc3 activity is significantly enhanced when the station is located in the dayside magnetic hemisphere (1600–2400 UT, Lepidi *et al.*, 1996). It is interesting to note that also at these high latitudes several power peaks (for example at ~ 2010 UT and ~ 2320 UT) are observed in correspondence with the smallest cone angle values.

To better analyze the correspondence between the cone angle and the pulsation power, we examined the behavior of the correlation coefficient r between the logarithm of ground Pc3 power and $\cos(\theta_{XB})$ for different delay times: the results of our analysis (Fig. 2) show that the best correspondence is obtained during magnetic daytime hours at both stations for a delay time of the order of 10 min (r = 0.61 between 0600 and 1500 UT at AQ; r = 0.60 between 1500 and 2400 UT at TNB). Moreover, only for TNB, we found that, also during night-time hours, there is some evidence for a dependence of the ground Pc3 power on $\cos(\theta_{XB})$, with approximately the same delay time (r = 0.38 between 0600 and 1500 UT). The observed delay time (~ 10 min) is comparable with the one estimated as the sum of the corotation delay from WIND to the subsolar point of the bow shock (~ 5 min, assuming the average IMF orientation in the period of interest) and the transmission delay from the bow shock to the ground (~ 6 min; Farrugia *et al.*, 1989).

The dynamic spectra in Fig. 3 clearly confirm the intermittent occurrence of the power enhancements at AQ (upper panels); they also show, more clearly in the D component, a progressive decrease in frequency (from ~ 90 mHz to ~ 40 mHz) which finds correspondence in the simultaneous decrease of the IMF strength (Fig. 1). In several cases a double peak structure appears in the H component (~ 0720 UT, ~ 0850–0940 UT, ~ 1010 UT, ~ 1120 UT); this feature can be well interpreted in terms of resonant oscillations of the local field line (Vellante *et al.*, 1989; 1996). An analysis of the behavior of the H/D spectral ratio (Baransky

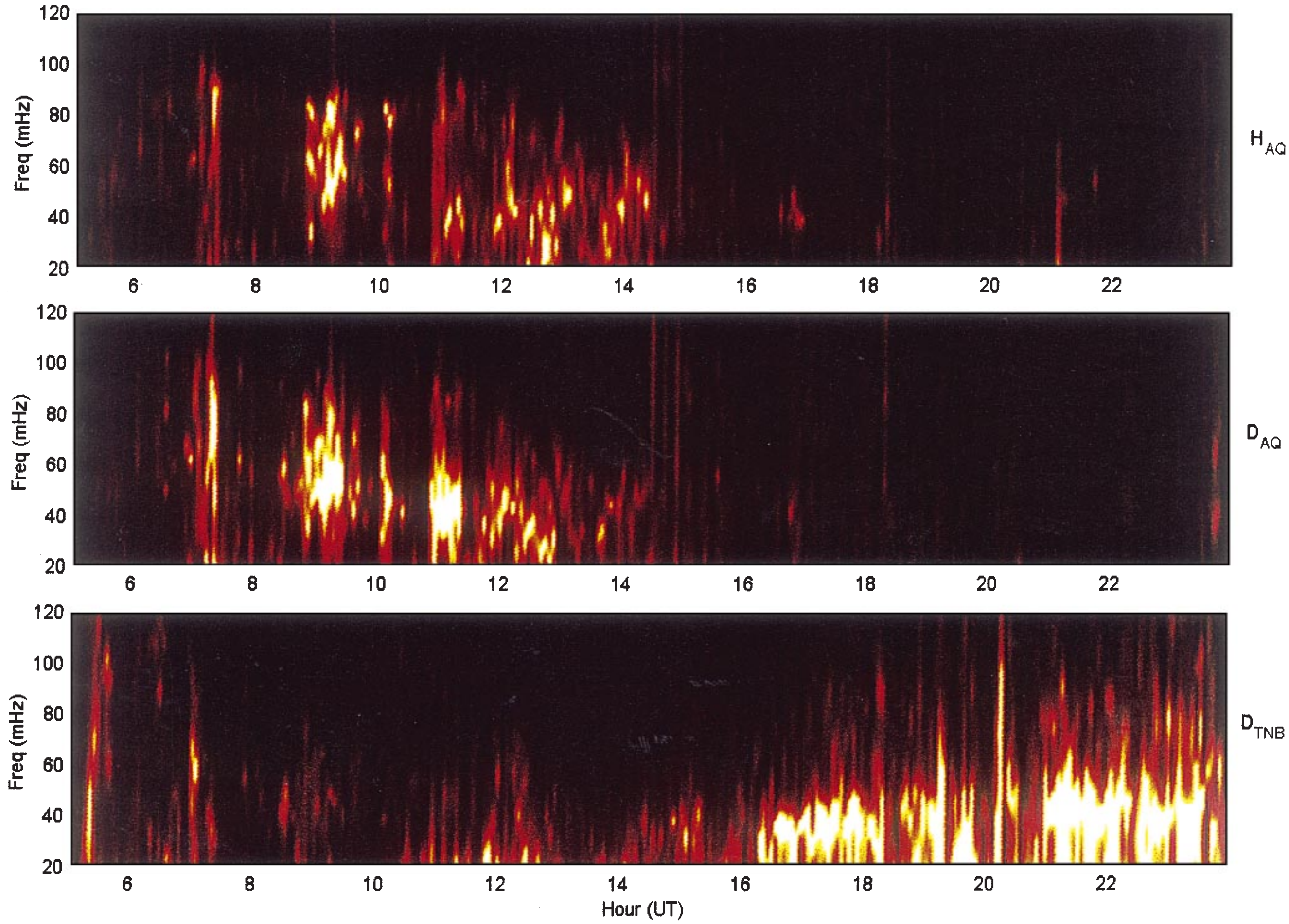

Fig. 3. Dynamic power spectra (obtained by computing power spectra over consecutive 4-min time intervals) of the H and D components at AQ (*upper panels*) and D component at TNB (*lower panel*) on January 11, 1997

et al., 1990; Vellante *et al*., 1993), shows that the resonant frequency is somewhat higher in the early morning (~90 mHz between 0700 and 0730 UT) and then decreases to values of the order of ~80 mHz in the following hours.

As regard TNB, the dynamic spectrum (Fig. 3, lower panel) reveals evidence for enhanced activity in the frequency range 20–60 mHz in the entire dayside magnetic hemisphere, with a slight increase of the dominant frequency until ~2000 UT, followed by a slight decrease. A similar feature can be observed during the same time interval in the IMF strength (Fig. 1). It is also worth noting some short living narrow-band events during local night-time interval which find correspondence in simultaneous similar features in the AQ spectra ($f \sim$ 80–90 mHz at ~0630 UT and $f \sim$ 60 mHz at ~0700 UT).

In order to better analyze the relationship between the Pc3 frequency and the IMF strength, we visually selected for both stations the clearest wave packets and estimated their frequency from the power spectra of the D component (which is less affected by resonant phenomena). Figure 4 shows the scatter plots of the selected frequencies versus the corresponding IMF strength (according to previous results, a delay time of 10 min has been assumed). It can be seen that at both stations the correlation between the two parameters is very good (r = 0.89 at AQ; r = 0.99 at TNB); linear regression at a 95% confidence level gives the empirical relationships: f (mHz) = (6.2 ± 0.4) B (nT) and f (mHz) = (5.7 ± 0.2) B (nT) at AQ and TNB, respectively. We also investigated a possible influence of the cone angle on the frequency of the observed Pc3 pulsations (Le and Russell, 1996). We found however only a poor correlation (r = 0.35 at AQ; r = 0.09 at TNB) between f/B and $\cos(\theta_{XB})$.

Finally, a polarization analysis for the selected wave packets at AQ shows highly polarized pulsations with a counterclockwise sense of polarization and polarization axis in the NW-SE direction in the local morning and early afternoon. In Fig. 5 (left side) we show, as an example, the low-pass filtered (0–100 mHz) data in the time interval 0909–0916 UT, together with the corresponding power spectra and hodogram for the signal filtered at the frequency of the main peak (51 ± 5 mHz). For comparison, we also show in

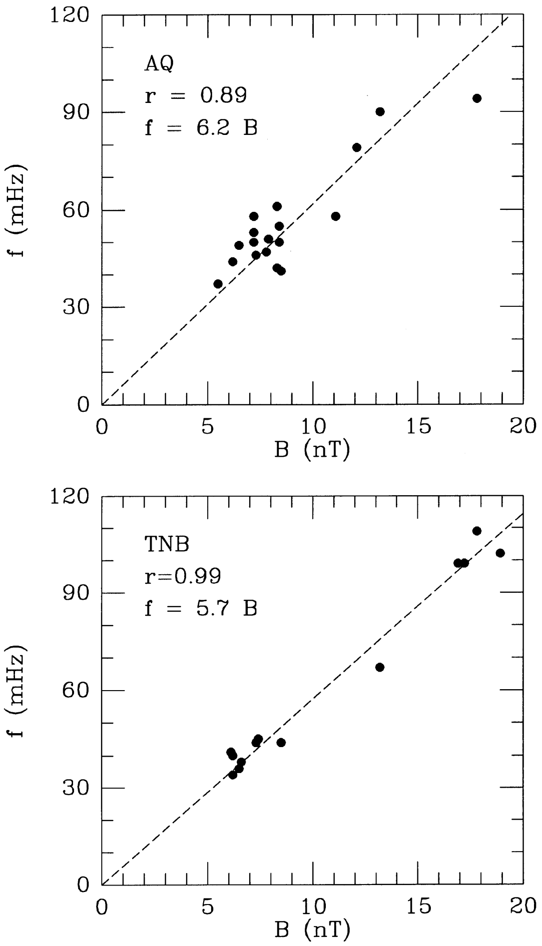

Fig. 4. Dependence of the frequency of selected Pc3 wave packets at AQ (*upper panel*) and TNB (*lower panel*) on the IMF strength. The *dashed lines* are the linear regressions

Fig. 5 (right side) the short, unique wave packet selected in the local late afternoon (1643–1646 UT); we found in this case a clockwise sense of polarization with a polarization axis switched to NE-SW direction. The observed ellipses orientation and polarization sense can be considered consistent with the predictions drawn for external source waves propagating westward in the morning and eastward in the afternoon hemisphere (Chen and Hasegawa, 1974).

Summary and discussion

In this study we analyzed the high resolution geomagnetic field measurements at low and high latitude during the Earth's passage of a high velocity solar wind stream characterized by variable IMF conditions.

At low latitudes, during local morning, Pc3 power intensifications were simultaneously observed in both components: the observed decrease of the dominant frequency in a wide range was well consistent with the corresponding decrease of the IMF strength, and the intermittent character of the pulsation activity was found to be related with the variable orientation of the IMF lines. These features both suggest that the ground wave packets can be well interpreted in terms of upstream ion cyclotron waves penetrating deep into the magnetosphere (Yumoto, 1986). Russell *et al.* (1983) suggested that low latitude ground pulsations are mostly generated close to the subsolar point and propagate nearly radially inwards. Our observations suggest that also upstream waves generated in the morning side of the bow shock (where for nominal IMF conditions the level of turbulence is higher) can reach low latitudes. On the other hand, similar results were also obtained by previous statistical analysis conducted at low latitudes by Yumoto *et al.* (1988) and Vellante *et al.* (1989) who found that the Pc3 activity in the D component (less affected by field line resonance, it more strictly reflects the upstream waves) maximizes during morning hours.

Pulsation measurements at TNB (Antarctica) show that Pc3 activity is enhanced when the station is located in the dayside magnetic hemisphere and modulated by the variable orientation of the IMF lines. In some cases, however, we found evidence for night-time Pc3 fluctuations which were simultaneous with similar dayside fluctuations at low latitudes. This result confirms that in the polar cap solar wind controlled pulsations can be observed also during night-time hours (Engebtretson *et al.*, 1989), supporting the idea of an additional high latitude entry of the upstream ULF wave energy (Engebretson *et al.*, 1991). In this sense we found that, in agreement with previous results (review by Troitskaya and Bolshakova, 1988), both at low and high latitude the dominant wave frequency depends on the strength of the IMF according to the relation f (mHz) $\sim$ 6 B (nT).

At AQ the polarization analysis of the observed Pc3 pulsations shows opposite sense of polarization and different direction of the polarization axis between morning and afternoon observations. These results are in agreement with those provided by previous investigations at low latitudes (Lanzerotti *et al.*, 1981; Yumoto *et al.*, 1985; Ansari and Fraser, 1986), and are consistent with the polarization pattern expected for waves propagating in the antisunward direction (Southwood, 1974; Chen and Hasegawa, 1974).

The observed fluctuations at AQ were typically accompanied by the simultaneous occurrence, at higher frequencies, of power enhancements which are clearly related to resonance phenomena of local geomagnetic field lines. Estimates of the resonant frequency confirm a tendency for higher values in the early morning hours (Green *et al.*, 1993, Waters *et al.*, 1994).

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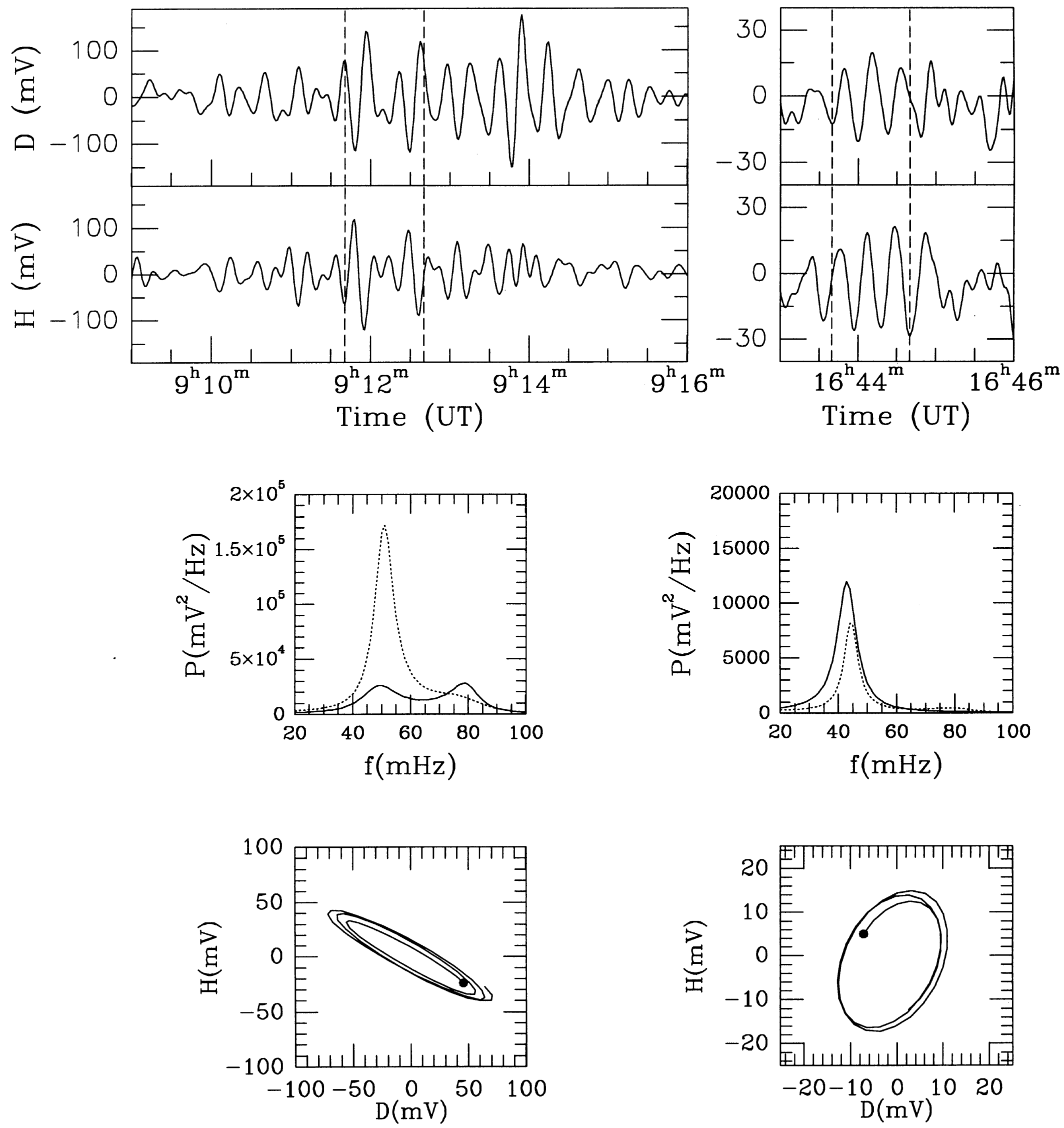

Fig. 5. Low-pass filtered (0–100 mHz) H and D data at AQ in the time intervals 0909–0916 UT (*left*) and 1643–1646 UT (*right*), together with the corresponding power spectra (H, solid line) and the hodograms for two selected wave packets (indicated in the corresponding *upper panel* by *dashed vertical lines*) filtered at the peak frequency (51 ± 5 mHz and 44 ± 5 mHz); the *black dot* indicates the initial point

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