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ULF fluctuations at Terra Nova Bay (Antarctica)

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Abstract
ULF geomagnetic field measurements in Antarctica are a very important tool for better understanding the dynamics of the Earth's magnetosphere and its response to the variable solar wind conditions. We review the results obtained in the last few years at the Italian observatory at Terra Nova Bay.

Key words *Antarctica – magnetosphere – geomagnetic field*

1. Introduction

The experimental results provided by spacecraft and ground stations in recent decades have made it increasingly evident that there exist close correlations among a large variety of physical phenomena occurring on the Sun, in the interplanetary medium and in the Earth's magnetosphere. In this sense, many physical phenomena which have been observed on the Earth for a long time have progressively assumed a wider significance in the context of a better understanding of the physical relationships which connect the Earth's environment with the Solar Wind (SW) plasma. Geomagnetic micropulsations (fluctuations of the magnetic field on the surface of the Earth and in the magnetosphere in the approximate ranges 0.001-10 Hz of frequency and 0.1-1000 nT of amplitude, typically increasing with decreasing frequency) are one of such phenomena.

Like other magnetospheric phenomena, pulsations obtain their energy from the SW. In particular, hydromagnetic instabilities driven by the SW along the flanks of the magnetosphere (such as the Kelvin-Helmoltz Instability, KHI), SW discontinuities impinging on the magnetopause and waves associated with particles reflected by the bow shock are currently interpreted as important exogenic sources for most daytime pulsations in the low and mid frequency bands (< 0.1 Hz). Highest frequency continuous pulsations are currently thought to be generated by ion cyclotron instabilities occurring within the Earth's magnetosphere.

The idea that the long regular periods of ground micropulsations could be interpreted in terms of standing Alfven waves excited along the geomagnetic field lines was originally proposed by Dungey (1954). Briefly (see Villante and Vellante, 1997, and papers therein referenced), in a highly simplified physical situation in which thermal pressure can be neglected with respect to magnetic pressure and the wave

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field is axisymmetric, decoupled poloidal (compressional) and toroidal (transversal) oscillation modes can propagate in a dipole magnetic field.

Toroidal modes, which propagate along the ambient field have the wave magnetic field and plasma velocity both in the azimuthal direction (shear mode) while the wave electric field is in the direction of the principal normal to the field line: in this case magnetic shells oscillate azimuthally independently of all others. Given the high conductivity of the ionosphere, the energy of this wave mode is basically confined in the region of space extending between ionospheres of opposite hemispheres. Standing oscillations can then be generated along field lines with eigenperiods which generally increase with increasing geomagnetic latitude. The good agreement between calculated eigenperiods and observed dominant pulsation periods has been considered in the past an outstanding argument to interpret *Pc*3-5 micropulsations in terms of oscillations of lines of force whose feet are rooted at conjugate points in opposite hemispheres. These resonant oscillations can be triggered by any disturbance propagating through the magnetosphere, in that a resonance occurs at a magnetic shell where the wave frequency matches one of the field line eigenfrequencies and the wave amplitude is enhanced.

Poloidal modes have the magnetic field and the velocity both in the meridian plane while the electric field is in the azimuthal direction: they propagate through the dipole field and the whole magnetosphere oscillates in phase (cavity mode). On the Earth's surface this mode would affect mostly the north-south (*H*) magnetic field component. Fundamental resonances for this mode (and their harmonics) are expected to be determined by the dimensions of internal cavities lying between boundaries such as the magnetopause, the plasmapause, the ionosphere, etc. So, in general, a large variety of periods in the micropulsation band can be expected also for cavity mode oscillations. According to Harrold and Samson (1992), who considered the Earth's bow shock as an outer reflecting boundary, trapped compressional modes could be expected at 1.3, 1.9, 2.5, 3.4 and 4.2 mHz. In general, these cavity modes are believed to be excited by impulsive events such as sudden compressions of the magnetosphere driven by impulsive variations of the SW dynamic pressure (Samson and Rankin, 1994).

The study of geomagnetic pulsations in Antarctica is interesting in that local field lines penetrate magnetospheric regions close to the extreme magnetosphere boundary (the magnetopause) and the polar cusp (*i.e.* the funnel shaped area which separates the sunward from the tailward magnetospheric field lines), where several generation mechanisms for ULF waves are active. The Antarctic Italian geomagnetic observatory was installed in Terra Nova Bay (TNB, geographic coordinates: 74.7°S, 164.1°E; IGRF95 corrected geomagnetic coordinates 80.0°S, 307.7°E; LT = UT+13; magnetic local time, MLT = UT-8; altitude = 28 m a.s.l.) during the 1986/1987 austral summer; for a description of the instrumentation the reader is referred to Meloni *et al.* (1992). MLT is an important ordering parameter which controls many features of the Earth's magnetosphere, especially at high latitudes. Due to the Earth's rotation, TNB has a variable distance, through the day, from the cusp projection: during the major part of the day the station is located inside the polar cap (at the footprint of open field lines), while around the local geomagnetic noon it approaches closed field lines. In the first Antarctic surveys, TNB magnetic instrumentation included only proton precession and fluxgate magnetometers with a sampling rate of the magnetic field components between 2 min and 30 s. During the 1993/1994 campaign, a search-coil magnetometer was added to the instrumentation. The ULF experiment at TNB is a joint scientific venture of University of L'Aquila and Istituto Nazionale di Geofisica, two institutions which, among others, now cooperate in the Area di Astrogeofisica at L'Aquila.

The experimental results reviewed in the present paper have been obtained by a number of investigations conducted in the last few years. In several cases (see, for example, Section 4) a comparison between TNB and AQ observations (L'Aquila, Italy, IGRF95 corrected geomagnetic coordinates 36.2°N, 87.5°E) yielded interesting conclusions about the longitudinal and latitudinal extent of the observed phenomena, an aspect which is very important for better understanding the interaction between the SW and the Earth's magnetosphere.

For careful review papers of experimental and theoretical aspects of micropulsations the reader is referred to Samson (1991), Hughes (1994) and references therein. An overview of hydromagnetic wave studies in Antarctica has been presented by Arnoldy *et al.* (1988). The geomagnetic consequences of the Earth's passage of SW structures and the development of geomagnetic storms are summarized by Farrugia *et al.* (1997) and Kamide *et al.* (1998); the physical characteristics of coronal mass ejections and interplanetary magnetic clouds are discussed by Burlaga (1991).

2. The long period *Pc*5 fluctuations

A preliminary analysis of the geomagnetic field fluctuations at TNB in the Pc5 range was conducted by Ballatore *et al.* (1996) who found a higher level of activity during solar maximum years (1989-1990) and a good correlation between the power level of fluctuations and the SW velocity. In a more recent paper Villante *et al.* (1997) examined data from three austral summers (1988-1989) with interesting results. They found indeed (fig. 1), during daytime intervals, power enhancements in the *H* component at discrete frequencies of the order of ≈ 3.3, 3.9 and 4.5 mHz. These features became more evident during intervals characterized by higher SW speeds, when they were also accompanied by other enhancements at lower frequencies (≈ 1.2, 1.9 and 2.7 mHz). An interesting aspect of those observations is that the observed power enhancements appeared at frequencies close to those predicted by theoretical models for cavity modes and detected at auroral latitudes both in the *F* region drift velocities and in the local geomagnetic field measurements (Walker *et al.*, 1992; Samson *et al.*, 1992). At those latitudes these power enhancements were generally interpreted in terms of field line resonances set up by compressional cavity/waveguide modes of the whole magnetosphere which would act as a resonant cavity when excited by some external mechanism such as pressure pulses of the SW, KHI on the magnetopause or sporadic dayside reconnection of interplanetary and geomagnetic field lines. In this context, TNB observations lead to the conclusion that some evidence for these modes can be detected also at Antarctic latitudes.

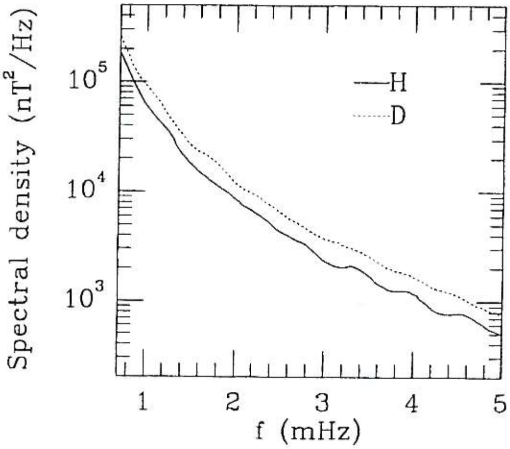

Fig. 1. Average power spectra of the *H* and *D* components.

The characterization of the polarization pattern in the horizontal plane of low frequency pulsations in a wide latitudinal and longitudinal extent is also an important tool for a better understanding of their generation and propagation mechanisms. Experimental results have shown that the sense of polarization of low frequency *Pc*5 pulsations exhibits a latitude dependence as well as a switch around local geomagnetic noon. The switch in the sense of polarization around local geomagnetic noon is consistent with hydromagnetic waves propagating westward in the morning and eastward in the afternoon, suggesting as an energy source the KHI at the magnetopause, as well as other «impulsive» excitations of the magnetosphere by variations in the SW pressure. Moreover, the field line resonance theory provides an explanation for the latitude dependence of the sense of polarization (Southwood, 1974); this theory relates the polarization pattern to the resonant coupling of a fast compressional wave mode, generated at the magnetopause, with the shear mode: in this case, for any given frequency, the theory predicts a first polarization reversal at the latitude of the amplitude minimum between the resonant field line and the magnetopause, and a second reversal across the latitude of the resonant field line (which has a local time dependence). The emerging overview would then suggest a complex pattern in which, depending on frequency, at any given latitude two or more polarization reversals at different MLTs might be expected. The results of a statistical analysis performed for an entire year (1995) by Lepidi *et al.* (1998a) for *Pc*5 pulsations at TNB are very interesting (fig. 2): indeed, in agreement with model predictions (Samson, 1972), the percentage of clockwise (CW) polarization dominates around local noon and in the early afternoon, then it decreases to ~ 50% at ~ 19 MLT, when a counterclockwise (CCW) polarization is predicted for a time interval of about two hours. Then the percentage of CW polarization again increases reaching highest values after local midnight while in the morning the polarization sense becomes definitely CCW between 6 and 10 MLT. These statistical results were also confirmed by the analysis of a long duration *Pc*5 event (Lepidi *et al.*, 1998b) driven by a SW pressure pulse: so, the results obtained at TNB can be considered well consistent with a poleward extension of the expected polarization pattern.

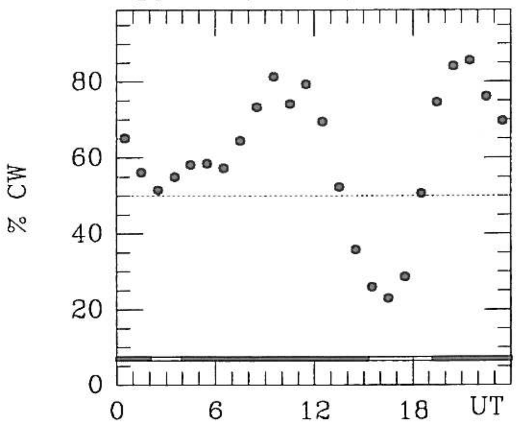

Fig. 2. Daily distribution of the percentage of intervals with CW polarization; times are shown in UT (lower margin) and MLT (upper margin). Light and solid bars indicate respectively the time periods in which, according to Samson (1972), CCW and CW polarizations are preferentially expected.

3. The *Pc*3-*Pc*4 pulsations

In the *Pc*3 range most of the daytime activity at mid latitudes is currently thought to be related to waves generated upstream of the bow shock by protons reflecting off the shock and creating conditions for wave generation as they interact with the incoming SW: in this sense, the observed empirical relationship between the dominant frequency, *f*, of the dayside *Pc*3 pulsations and the strength, B, of the interplanetary magnetic field (*f*(mHz) ~ 6B (nT)) 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 and penetrating deep into the magnetosphere.

In the mid frequency range TNB observations were investigated by Lepidi *et al.* (1996) and by De Sanctis *et al.* (1998). In particular, De Sanctis *et al.* (1998) analyzed data recorded continuously during the 1994-1995 austral summer and found clear evidence for a significant power enhancement around local magnetic noon (fig. 3) *i.e.* when the station is nearer to closed field lines. The results obtained (De Sanctis *et al.*, 1998) for the daily variation of correlation coefficient between the power of fluctuations and the SW velocity (fig. 4) are interesting in that they also reveal also at Antarctic latitudes a high SW control of the pulsation amplitude. They also show more explicitly in the *Pc*4 range two clear correlation maxima in the morning and afternoon hours, respectively. This feature can be considered consistent with a wave source still related to the KHI instability on the flanks of the magnetopause. This interpretation is confirmed by a polarization pattern which, as for the lower frequency modes discussed in the previous paragraph, shows a clear polarization reversal around the local magnetic noon, indicat-

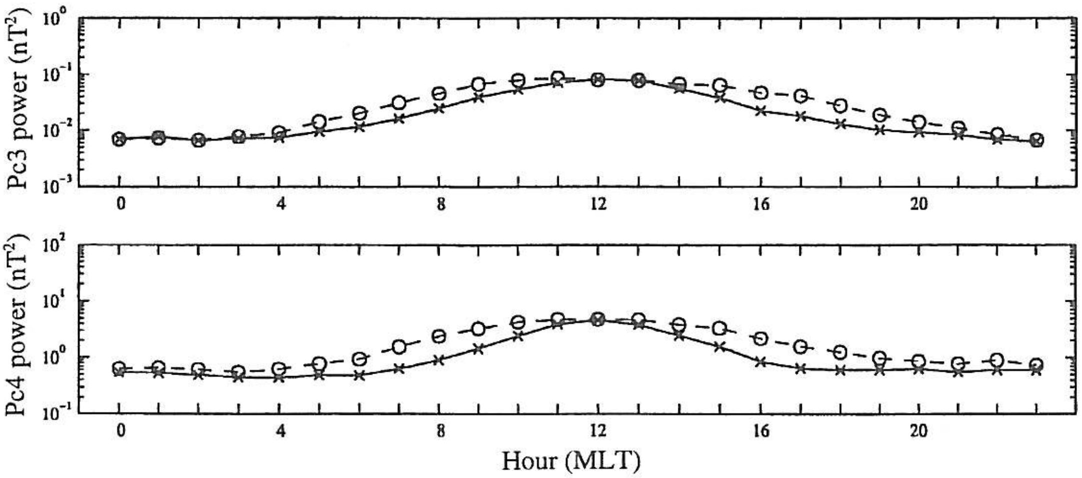

Fig. 3. Daily distributions of the average power integrated in the *Pc*3 and *Pc*4 frequency ranges. Crosses and circles refer to the *H* and *D* components, respectively.

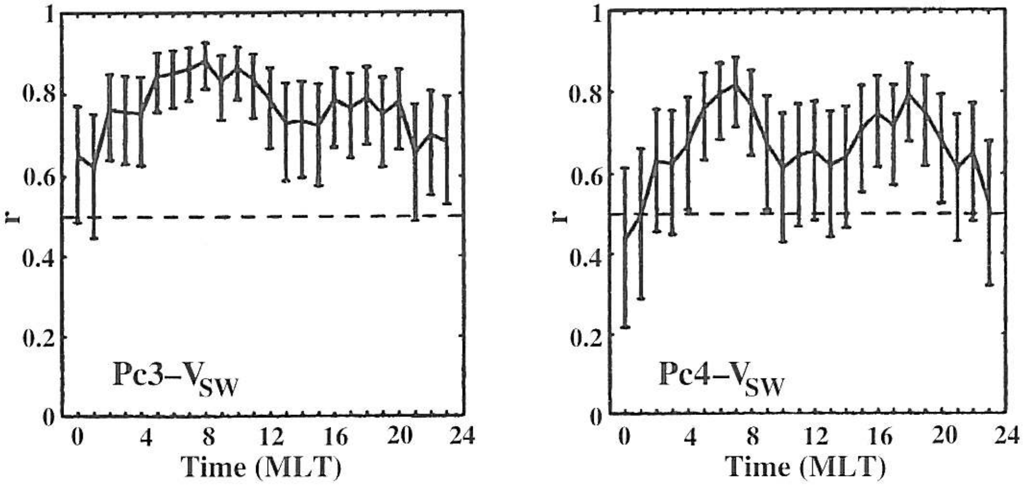

Fig. 4. Daily variation of the correlation coefficient *r* between the SW velocity V_{SW} and the *Pc*3 and *Pc*4 power; each correlation coefficient has been calculated from about 80 data points; error bars represent the 95% confidence intervals.

ing an antisunward propagation. In the *Pc*3 range the strong correlation between the pulsation power and the SW velocity, which is clearer during the morning hours, indicates that the *Pc*3 source can be identified in the upstream waves; indeed these waves are preferentially generated in the morning side and their amplitude is expected to be related to the SW velocity.

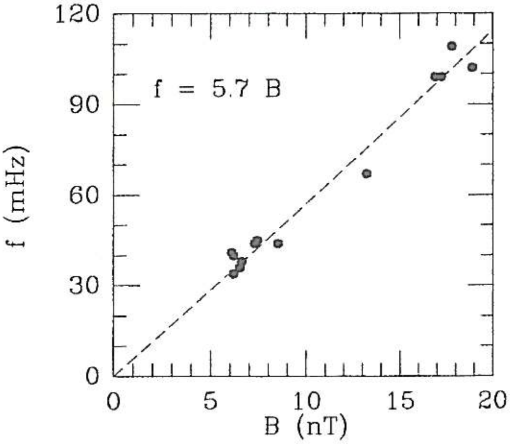

Fig. 5. Dependence of the frequency f of selected $Pc3$ wave packets on IMF strength B. The dashed line is the linear regression.

Interesting results have recently been provided at TNB by Villante *et al.* (1998a) who examined ground observations obtained during variable interplanetary magnetic field conditions and found a strong correlation between the frequency of Antarctic pulsations on the D component and the interplanetary magnetic field magnitude (fig. 5), a result which obviously suggests that $Pc3$ events, at high latitude too, can still be strictly related to the upstream wave activity. Moreover, although the $Pc3$ activity is enhanced when TNB is located in the dayside magnetic hemisphere, SW controlled $Pc3$ pulsations have also been observed during nighttime hours, supporting the idea of an additional high latitude entry of the upstream ULF wave energy (Engebretson *et al.*, 1991).

4. The geomagnetic response to SW events

A very important aspect of the relationship occurring between the Sun and the Earth is what is now becoming identified as the Space Weather Program. Space Weather encompasses many activities which are necessary for a timely specification and forecast of natural conditions on the space environment, with a peculiar emphasis on those aspects which might be related to impacts on technical systems. Extremely critical for Space Weather is the availability of simultaneous measurements in the interplanetary space, in the magnetosphere and at widely spaced ground stations. The comparison between TNB and AQ observations has progressively providing interesting insights on the latitudinal and longitudinal extent of geomagnetic disturbances and low frequency fluctuations.

In the Space Weather context particular attention has recently been devoted to the interaction of the magnetosphere with peculiar structures, called «magnetic clouds», which often accompany massive emissions from the solar corona which are known as «coronal mass ejections» and extend over distances of significant fractions of the Sun-Earth distance. Magnetic clouds are typically characterized by strong magnetic field intensities and smooth rotations of the magnetic field direction over large angles. Southward turning of the interplanetary magnetic field orientation is the major factor which controls (through reconnection with magnetospheric field lines) the onset and development of geomagnetic storms.

On January 10, 1997 the arrival of a magnetic cloud was detected from WIND spacecraft at a geocentric distance of ~ 85 Earth radii in the Earth-Sun direction. A study of the geomagnetic field variations at TNB and AQ associated with the passage of the cloud was conducted by Villante *et al.* (1998b). Figure 6 plots the H and D components at AQ and TNB together with the interplanetary parameters observed during a time interval of 60 h. As can be seen, on January 10, at 0053 UT a shock wave was detected from WIND. A new SW regime appeared at ~ 0500 UT; on appearing, it was characterized by extremely low density (2-3 cm^{-3}), and high B values and definitely southward interplanetary magnetic field orientation ($\theta \sim -80°$). These features seem to mark the front boundary of the magnetic cloud in which the Earth was embedded for the following 20 h. During this time interval B had an approximately constant value of ~ 15 nT and its direction smoothly rotated from southward to northward at the rear edge of the cloud. At the end of the cloud (January 11, at 0054 UT) WIND detected a

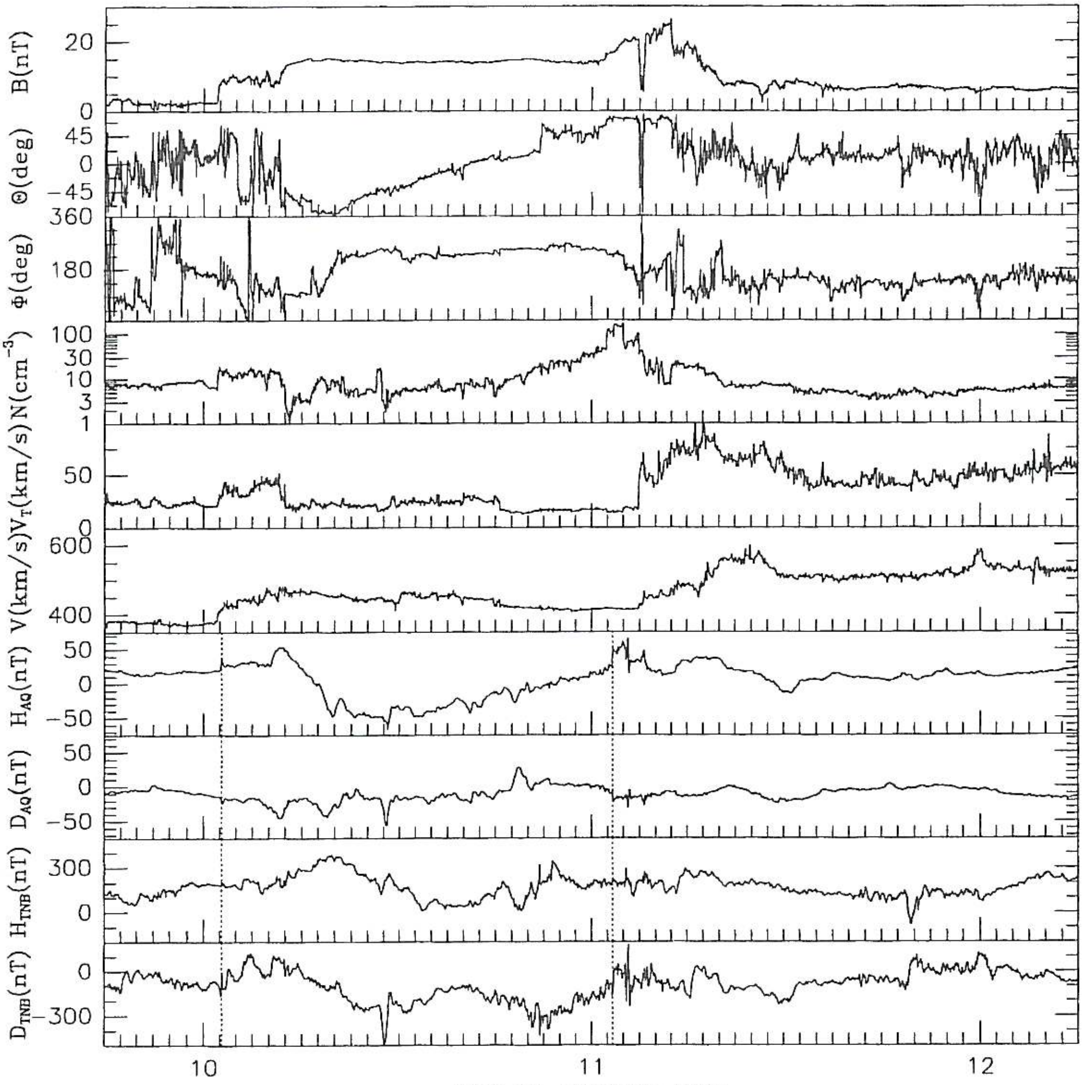

Fig. 6. WIND and ground observations from January 9, 1997, 1800 UT until January 12, 0600 UT. From top to bottom are shown the IMF strength and its latitude and longitude, the proton number density and thermal speed, the SW flow speed and the geomagnetic field components *H* and *D* at AQ and TNB. Dashed lines indicate the SI's discussed in the text.

strong density enhancement with peak values of ~ 150 cm^{-3}.

The passage of the interplanetary event triggered intense geomagnetic activity. Namely, in correspondence with the 0053 UT shock, a positive SI (which more clearly emerges at AQ) was observed simultaneously (January 10, 0106 UT) at both stations, with an amplitude of the *H* component of ~ 15 nT at AQ and ~ 20 nT at TNB. Similarly, the strong density enhancement detected on January 11, 0054 UT caused at 0118 UT a sharp SI with an amplitude of ~ 30 nT at AQ and ~ 45 nT at TNB. In both cases, the time delay (13 and 24 min, respectively) well corresponds to the expected transit time between WIND and Earth of the SW structures.

The prolonged southward interplanetary magnetic field orientation produced at AQ, in the *H* component, the typical signatures of a geomagnetic storm with a main phase characterized by a ~ 100 nT decrease during a time interval of ~ 10 h; as expected, at cusp latitudes these features were less evident. In correspondence with the different pressure variations ULF wave power enhancements were observed at both stations. In particular, during the major intensification of the fluctuation activity, after the arrival of the highest density SW region at about 01 UT on January 11, waves appeared simultaneously at the two stations approximately at the same discrete frequencies for both components (fig. 7a). The highest coherence (> 0.9) between the two stations for both components corresponds to the 1.8 mHz mode. Figure 7b shows the corresponding filtered data; it is evident that simultaneous wave packets appear at both stations on both components; moreover their polarization pattern is consistent with an antisunward propagation, as expected for any magnetospheric perturbation driven by the solar wind.

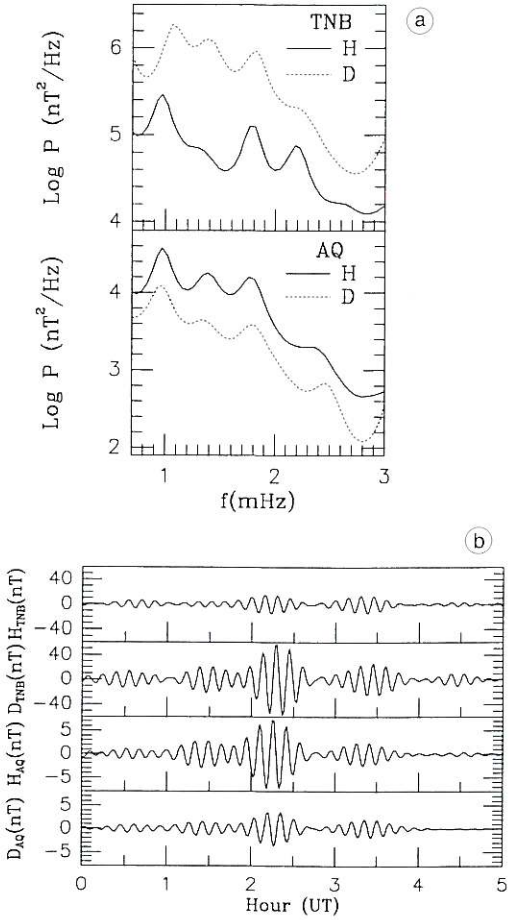

Fig. 7a,b. a) The January 11, 1997, 00-04 UT power spectra. b) The 1.8 mHz filtered signals.

Another example of a Sun-Earth connection event occurred on April 11, 1997, during the passage of a solar ejecta characterized by northward IMF conditions and variable SW pressure (fig. 8). Also in this case major SW pressure variations were followed both at AQ and TNB by simultaneous low frequency power enhancements (Lepidi *et al.*, 1999). Moreover, in correspondence with the major power enhancements, the coherence between fluctuations at the two stations attains very high values when TNB is close to the local geomagnetic noon and during closed magnetospheric conditions. In this sense it is interesting to remark that during northward IMF conditions the polar cusp is expected to move poleward with respect to its average position (Carbary and Meng, 1986); so, in the hours around local magnetic noon, we can expect TNB to be close or even at the footprints of closed field lines. These conditions are the most favourable for a high latitude station, usually located in the polar cap, to observe the same magnetospheric phenomena as a low latitude station. Indeed, despite the wide latitudinal and longitudinal separation, the observed coherent fluctuations have common frequencies and simultaneous wave packets appear on both horizontal components at both stations (fig. 9a,b)

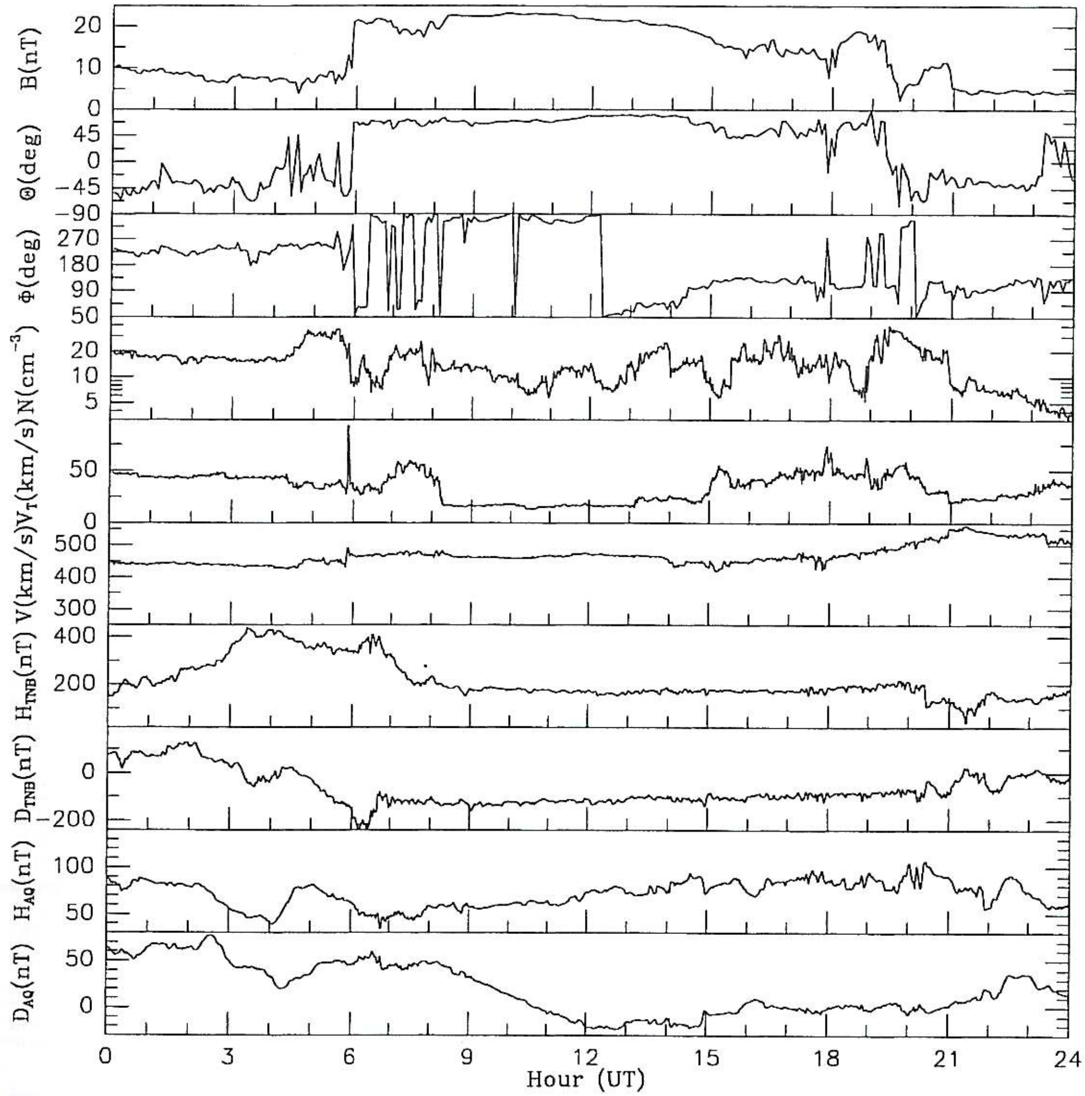

Fig. 8. WIND and ground observations on April 11, 1997. From top to bottom are shown the IMF strength and its latitude and longitude, the proton number density and thermal speed, the SW flow speed and the geomagnetic field components *H* and *D* at TNB and AQ.

and their polarization sense can be considered consistent with an antisunward propagation of a disturbance along the flanks of the magnetosphere. These features suggest that also in this case the observed fluctuations could be interpreted in terms of compressional oscillations of the whole magnetosphere generated by SW pressure pulses.

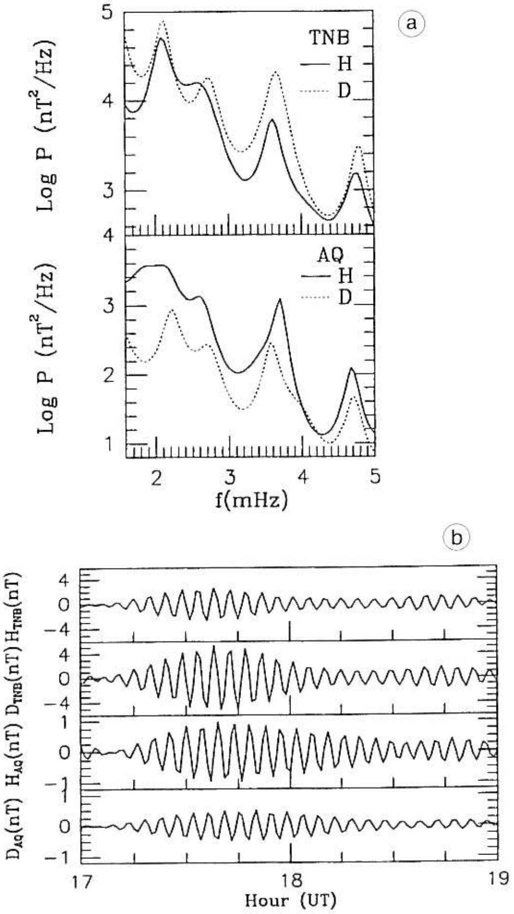

Fig. 9a,b. a) The April 11, 1997 17-19 UT power spectra. b) The 3.6 mHz filtered signals.

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