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Sudden Impulses in the Magnetosphere and at Ground

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1. Introduction

Sudden Impulses (SI) are rapid variations of the magnetospheric and geomagnetic field which are usually related to the Earth's arrival of sudden increases in the dynamic pressure of the solar wind (SW), generally associated with interplanetary shock waves or discontinuities. Such impulses often precede geomagnetic storms: in this case they are referred as Storm Sudden Commencements (SSC). Incoming SW pressure pulses compress the magnetosphere, increase the magnetopause and tail currents, and possibly other magnetospheric/ionospheric current systems as well; correspondingly, the magnetospheric and ground fields generally increase to a new state over about a two to fifteen minute period. The field variation associated to SI mostly occurs along the north/south component (B_z in the magnetosphere, H in the geomagnetic field). Additional contributions also come from the effects of the tail current (mostly in the nightside sector) and from those of the ring current (during more active magnetospheric conditions). The further development of field aligned currents (FAC) and ionospheric currents typically makes the SI manifestation at ground much more complex than in the magnetosphere: on the other hand, since earliest investigations (Matsushita, 1962; Nishida and Jacobs, 1962), it is well known that different transient waveforms are detected at different ground stations. Given their global simultaneous occurrence and clear onset time, SI provide a good opportunity for understanding the transient response of the magnetosphere and ionosphere to the SW variations.

In the present paper we review some aspects of the SI manifestations, as they are observed in the magnetosphere (basically at geosynchronous orbit, ≈6.6 Re, Re being the Earth radius) and at ground. For previous reviews of the experimental and theoretical aspects of SI events the reader is referred to Matsushita (1962), Nishida and Jacobs (1962), Siscoe et al. (1968), Nishida (1978), Smith et al. (1986), Araki (1994), Tsunomura (1998).

2. The SI manifestation at geosynchronous orbit

2.1 The general aspects and the local time dependence

Figure 1 (after Villante and Piersanti, 2011) shows the aspects of the SI manifestation at different LT (LT being the local time) along the geosynchronous orbit and the relationship between the magnetospheric field change (ΔB, B being the total field) and the increase of the

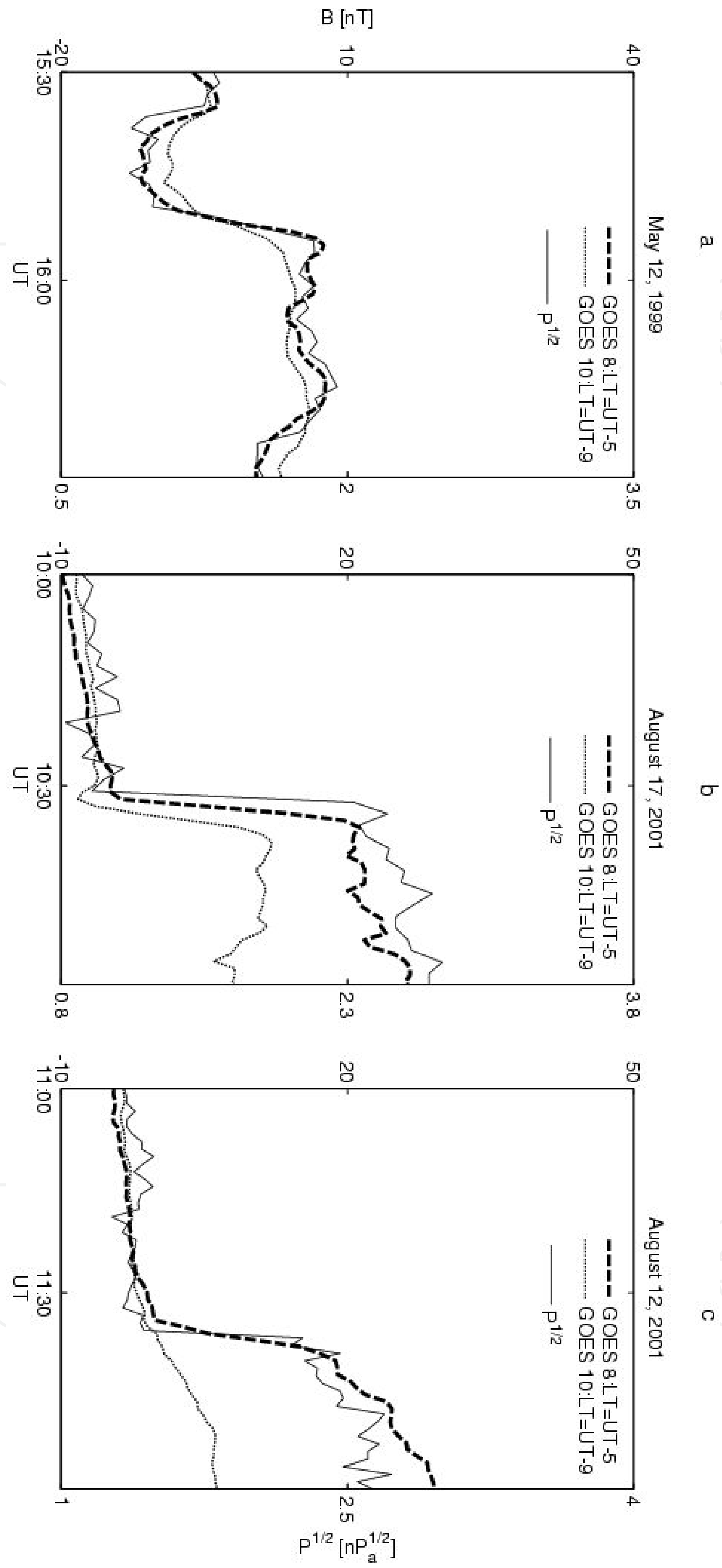

Fig. 1. (after Villante and Piersanti, 2011). Three examples of SI events at geosynchronous orbit. In each panel we show: the square root of the SW dynamic pressure (WIND spacecraft) and the magnetic field amplitude at GOES8 and GOES10. WIND data have been shifted to account for the SW propagation time

square root of the SW pressure $\Delta P^{1/2}$. As shown in panel *a*, the field jump is typically sharp in the entire dayside sector and basically reflects the behaviour of the change of the SW pressure, especially in the subsolar region. The ratio $R=\Delta B/\Delta P^{1/2}$ (hereafter referred as "relative response") at dawn is somewhat smaller (and smoother) than in the noon region ($R\approx21$ nT/nPa$^{1/2}$ and $R\approx25$ nT/nPa$^{1/2}$, respectively for the case in panel *a*). Such response attains smaller values in the dark hemisphere ($R\approx12$ nT/nPa$^{1/2}$ at ≈1:30 LT, $R\approx17$ nT/nPa$^{1/2}$ at ≈5:30 LT, for the case in panel *b*). Lastly, panel *c* shows that, in some cases, a continuous, small amplitude increase of the magnetospheric field is detected in the night sector, even in presence of a sharp change at dawn.

Although comparisons among different investigations are made ambiguous by the different criteria adopted for the selection of events, for the definition of "magnetospheric response", and for the large variety in its amplitude (and characteristics) in any time sector, an explicit LT modulation of such response has been extensively reported in the scientific literature. On the other hand, since the magnetopause current is mostly enhanced in the dayside sector during the magnetospheric compression, while the enhancement of the tail current produces a negative variation of the magnetospheric field, a strong day/night asymmetry might be expected in the SI manifestation at geosynchronous orbit. Consistently, Patel and Coleman (1970) reported that SI events in the nightside had smaller amplitude than in the dayside. Kokubun (1983) and Kuwashima and Fukunishi (1985) found that the magnetospheric change had highest values at local noon and very small values, or even negative, near midnight. More recently, Lee and Lyons (2004) concluded that SW pressure enhancements generally lead to a magnetospheric compression at all time sectors (with few exceptions in the nightside): it is strongest near noon and decreases toward dawn and dusk. Borodkova et al. (2005, 2006) found that, in general, the changes of the SW pressure (positive and negative) were associated with corresponding variations of the magnetospheric field; they also remarked that all the events without an explicit response were located either before 7:30 LT or after 16:30 LT. Wang et al. (2007) confirmed that the field variation peaked near local noon and decreased toward dawn and dusk. Figure 2a (after Villante and Piersanti, 2011) compares the amplitude of the geostationary response for events simultaneously detected at different LT: it clearly confirms a large data spread of the relative response in any time sector, together with an explicit LT modulation, with greater values at satellite located closer to the noon meridian; as can be seen, negligible and even negative magnetospheric responses are often detected in the dark sector.

2.2 The role of the SW parameters

As for other aspects of the magnetospheric dynamics, particular attention has been dedicated to the possible role of the North/South component of the interplanetary magnetic field ($B_{z,IMF}$). As a matter of fact, Sanny et al. (2002) showed that the variability of the magnetospheric field strength near local noon was independent on the IMF orientation but strongly influenced by changes of the SW pressure. Consistently, Wang et al. (2007) concluded that the IMF orientation does not affect the geosynchronous response significantly (see also Figure 2a). Kuwashima and Fukunishi (1985) and, more recently, Lee and Lyons (2004) suggested that midnight events associated with southward IMF orientations were often characterized by a dipolarization-like change similar to that one occurring during substorms, while the dayside response was mostly compressional; for northward IMF, a compression of the entire magnetosphere was generally observed, with few

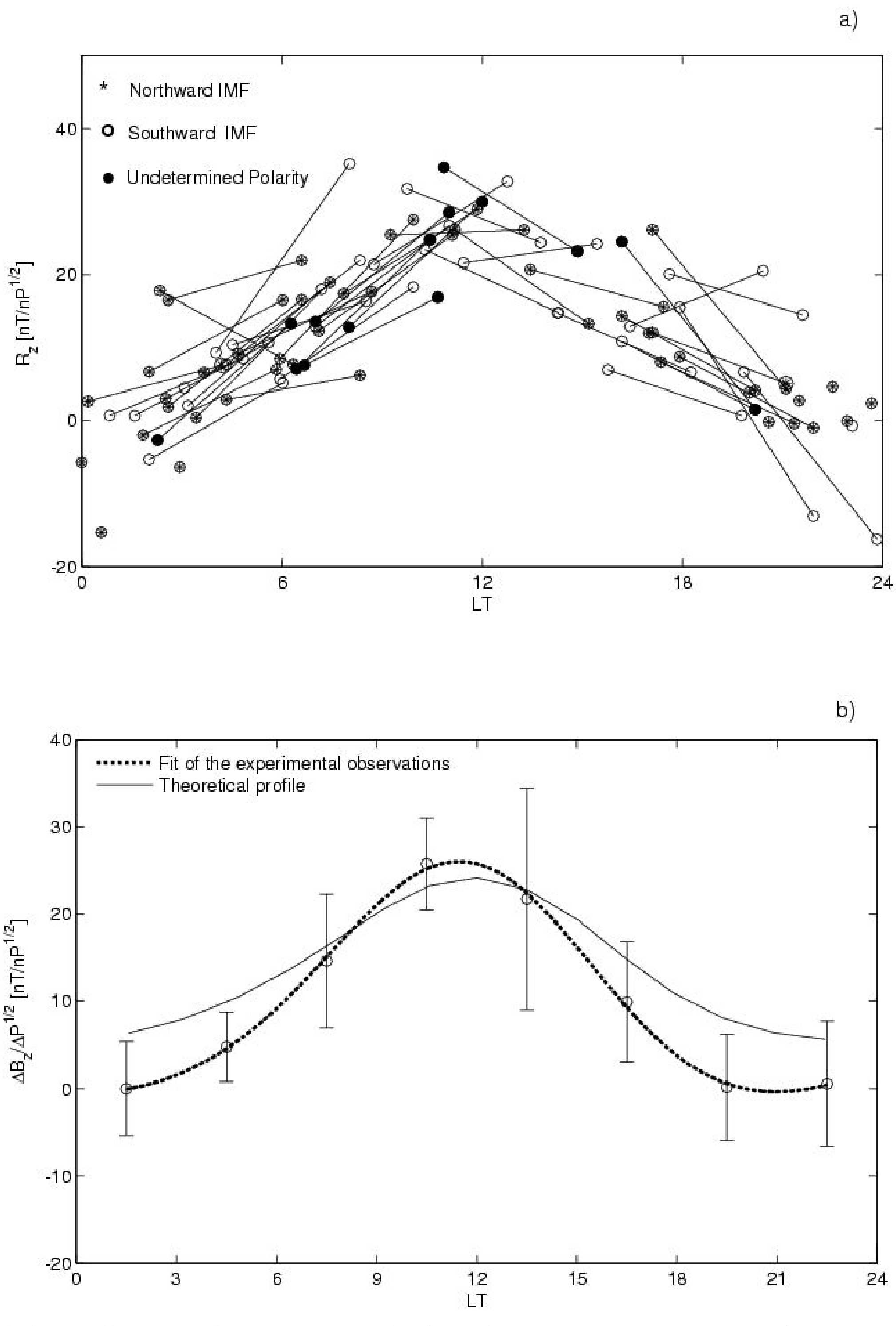

Fig. 2. a) (after Villante and Piersanti 2008) The relative response $R_z = \Delta B_z/\Delta P^{1/2}$ vs. local time (observation of the same event from two spacecraft are connected by a line. Empty circles identify events associated with Southward IMF; stars identify events associated with Northward IMF; black circles identify events associated with undetermined IMF polarity; b) (after Villante and Piersanti 2008) A comparison between average values of $\Delta B_z/\Delta P^{1/2}$ in each 3-h interval and the theoretical profile (solid line), determined considering the magnetic effects of the magnetopause current at geosynchronous orbit. The dotted line represents the fit of experimental measurements.

cases of depression near midnight. Lee and Lyons (2004) suggested that the magnetosphere is very sensitive to small SW pressure enhancements when the IMF is strongly southward for a long period of time. Focusing attention on the midnight sector, Wang et al. (2009) concluded that ≈75% of the negative responses were associated with southward IMF orientations. By contrast, Sun et al. (2011) revealed that the occurrence of positive or negative responses in the midnight sector had no obvious association with the sign of $B_{z,IMF}$, provided that no inversion of $B_{z,IMF}$ exists across the front of the impinging discontinuity.

2.3 The comparison with theoretical models

Kokubun (1983) evaluated the role of the magnetopause and tail currents and concluded that the geosynchronous responses were ≈30% smaller than expected. Figure 2b (after Villante and Piersanti, 2008), compares the 3-hr averages of R_z with the theoretical profiles evaluated assuming that the magnetic field change is determined by the transition between two steady states of the magnetosphere under different SW pressure conditions (i.e. different magnetopause currents, Tsyganenko, 2002a, 2002b). As a matter of facts, the observed average values reveal in the central part of the day a close correspondence with the predicted responses, a feature confirmed by an analysis of individual events (Villante and Piersanti, 2008). It suggests that, in this region, the field jumps are basically determined by the changes of the magnetopause current alone. The occurrence of negligible and negative responses makes the average values smaller than predicted in the dark region. It is worth noting, however, that, even in this region, the positive ΔB_z often show a substantial correspondence with the values predicted for the magnetopause current, especially for higher SW pressure jumps (Villante and Piersanti, 2011): it suggests that the dominant effects of the magnetopause current (i.e. the magnetospheric compression) might extend to a significant portion of the dark magnetosphere. On the other hand, the occurrence of negative variations in the nightside region (unpredictable in terms of the magnetopause current alone, solid line in Figure 2b) reveals, in several cases, a significant role of additional current systems. The interpretation of such events, however, requests a case by case analysis, paying attention to the SW and magnetospheric conditions in the period of interest (Villante and Piersanti, 2011). As a matter of facts, several approaches have been adopted to interpret the characteristics of the SI manifestation in the dark magnetosphere. Interesting results have been recently provided by Sun et al. (2011) who performed a MHD simulation of the nightside response to interplanetary shocks and concluded that when a shock sweeps over the magnetosphere, there exist mainly two regions: a positive response region caused by the compressive effect of the shock and a negative response region which is probably associated with the temporary enhancement of earthward convection in the nightside magnetosphere. In addition, according to their conclusions, a southward IMF would lead to a stronger and larger negative response region, and a higher shock speed would result in stronger negative and positive response region.

3. The SI manifestation at ground

3.1 The general aspects and the local time dependence

As previously underlined, the manifestation of ground SI is, in general, more complex than at geosynchronous orbit. This is because secondary effects like FAC and ionospheric currents contribute significantly in addition to the primary effect of the magnetopause current. On the other hand, it is now clear that FAC may modify the SI field even at middle and low latitudes (Kikuchi et al., 2001; Araki et al., 2006). As a matter of facts, shape and amplitude of the H waveform are strongly dependent on latitude and LT. Basically (Araki, 1994), at auroral latitudes, the waveform consists of two successive pulses with opposite sense (PI and MI, with typical duration of ≈1-2 min and ≈5-10 min, respectively). In the morning a positive pulse precedes and a negative pulse follows. The sense of the pulses is reversed in the afternoon and their amplitude decreases with decreasing latitude (Figure 3). Typically, SI manifestations are more simple at low latitudes, i.e. far from major high latitude and equatorial current systems. Here, the H behaviour becomes more step-like, but a two pulse structure with reduced amplitude is still identified. Figure 4 (after Villante and Piersanti, 2011) compares the aspects of ground events at λ≈36° (λ being the magnetic latitude) with the SW and geosynchronous observations. It confirms that, independently on LT, the low latitude response of the H component often consists of a simple monotonic increase with amplitude (ΔH) often comparable (although smaller) with the field jump observed at geosynchronous orbit. Interestingly, in any time sector, the H variations are accompanied by explicit negative variations of the D component (ΔD, perpendicular to H in the horizontal plane). In some cases, moreover, even at low latitudes, the main field jump is preceded by transient phenomena which do not appear in the magnetosphere: for example, the event in panel *c* is characterized by the occurrence of a preliminary positive impulse (PPI).

As for geosynchronous orbit, specific attention has been addressed to the LT dependence of the ground response. In a pioneering investigation, Ferraro and Unthank (1951) showed that, at low and middle latitudes, ΔH was larger near midnight than in daytime. More recently, Tsunomura (1998), who analysed events from low to middle latitudes (λ≈21°-43°), determined a smaller ΔH during local morning with respect to the rest of the day. Araki et al. (2006, 2009) examined the LT dependence of the average ΔH at λ≈35.4°, separately for summer and winter. They determined, in both seasons, a maximum near midnight, a minimum at 7-8 LT, and a secondary maximum on the dayside; in addition, the amplitude of the LT modulation was much larger in the summer (approximately by a factor ≈3). Russell et al. (1992, 1994a, b) reported that at low and middle latitudes ΔH is maximum around noon during northward IMF conditions; in addition, ΔH was found to decrease in the daytime sector and to enhance significantly in the night time sector in the case of southward IMF. At λ≈36°, Francia et al. (2001) revealed a LT dependence of the relative response, $R_H=\Delta H/\Delta P^{1/2}$, characterized by a depressed value in the morning (≈10 $nT/(nPa)^{1/2}$), a greater amplitude in the evening and night sector (≈14-17 $nT/(nPa)^{1/2}$), and a maximum after the local noon (≈20 $nT/(nPa)^{1/2}$). Similarly, at subauroral latitudes (λ≈54°-58°), the geomagnetic response showed strongly depressed values in the morning and enhanced values in the afternoon (≈30 $nT/(nPa)^{1/2}$; Russell and Ginskey, 1995). Recently, Shinbori et al. (2009) conducted a statistical analysis of the relative amplitude from middle (λ≈45°) to equatorial latitudes (λ≈15°) suggesting, between λ≈45° and λ≈36°, a strong dawn-dusk asymmetry, with minimum and maximum values in the morning (8–9 LT) and afternoon (15– 17 LT), respectively, and some evidence for a new enhancement in the night time sector (20–03 LT). They also showed that the amplitude of the relative response does not vary under specific IMF conditions (northward/southward), suggesting negligible effects from the ring and tail current. As a matter of fact, the emerging overview reveals a LT dependence of the ground response (with amplitude dependent on latitude and season) significantly different than in the magnetosphere, revealing explicit contributions from FAC and ionospheric currents: basically, from low to high latitudes, it is characterized by smaller (even negative, at higher latitudes) values in the morning and greater values in the post-noon and midnight sector, while, at equatorial latitudes, it shows a strong enhancement around 11 LT.

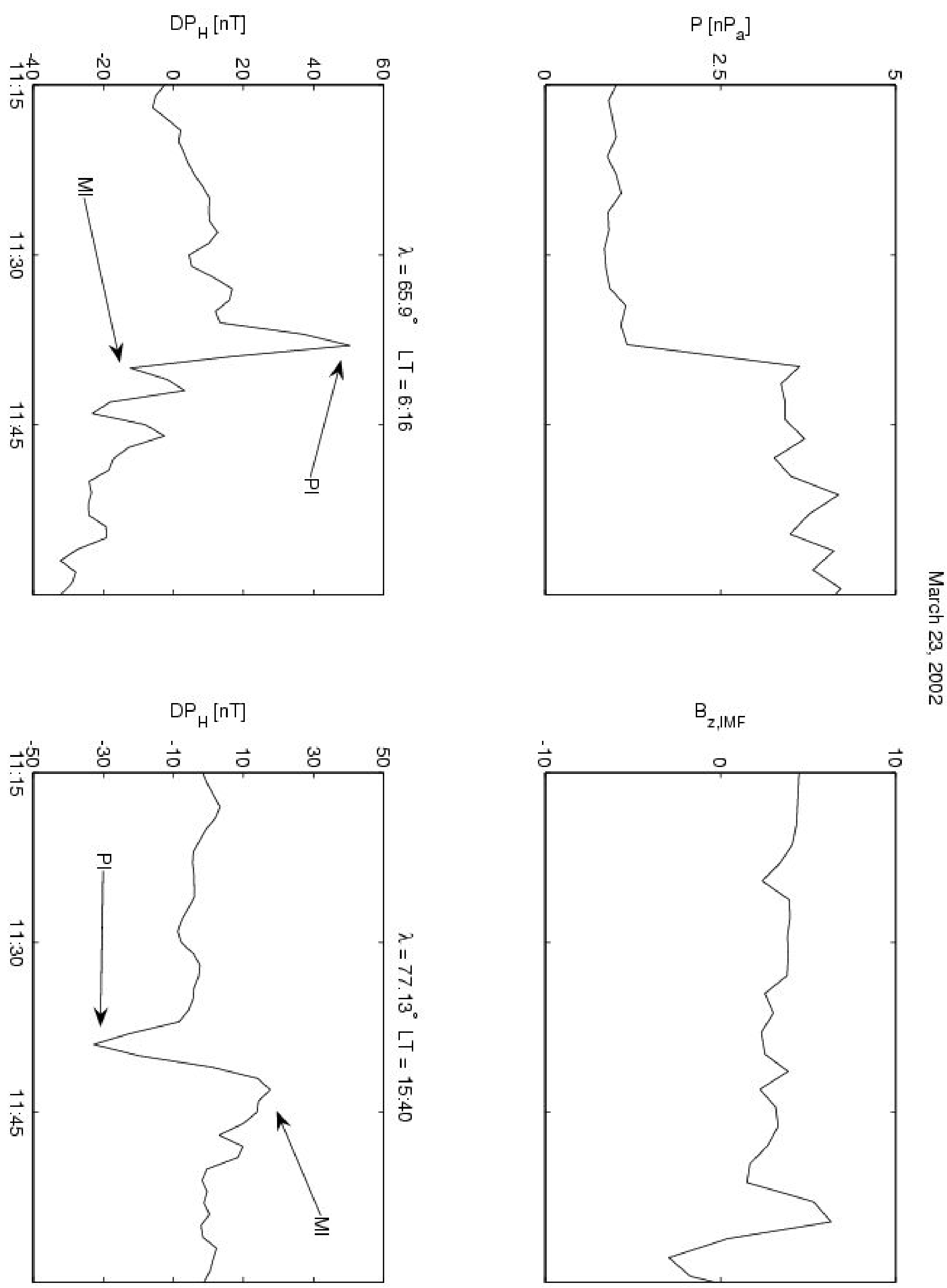

Fig. 3. Two examples of SI events at auroral latitudes in the local morning (right panel) and in local afternoon (left panel).

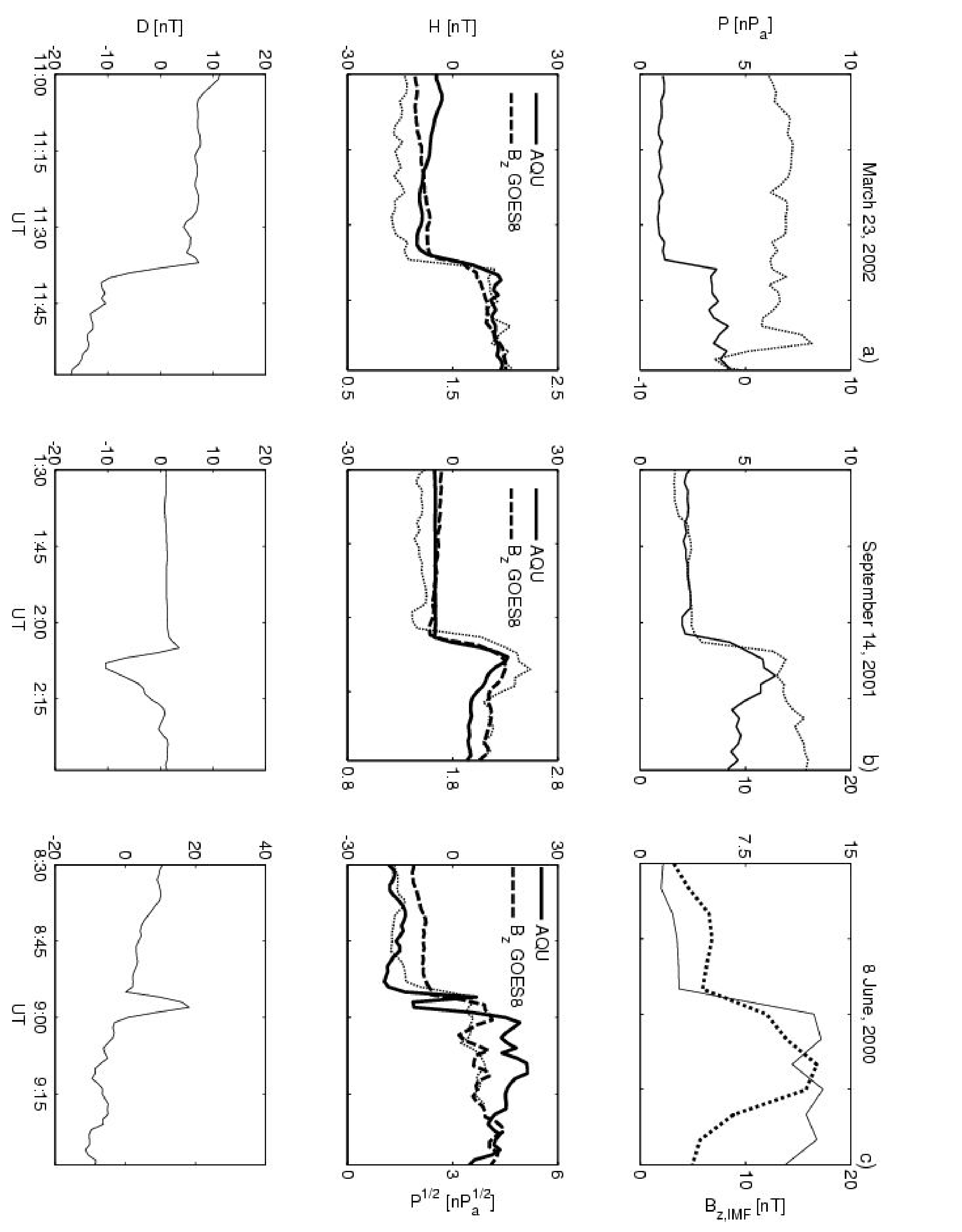

Fig. 4. (after Villante and Piersanti 2008) Three examples of SI events at low latitudes. Top panel: the SW dynamic pressure (solid line); the North/South component of the interplanetary magnetic field (dotted line). Central panel: the geomagnetic field component H at AQU; the magnetic field component B_Z at geosynchronous orbit; the square root of the SW pressure. Bottom panel: the geomagnetic field component D at AQU. WIND data have been shifted to account for the SW propagation time.

3.2 The comparison with theoretical models

The current understanding relates such complex scenario to the combined effects of the magnetospheric and ionospheric current systems. Namely, the total disturbance field (D_{SI}) of the H component is decomposed in different subfields (Araki, 1977, 1994; Araki et al., 1997, 2009):

$$D_{SI}=DL_{MI} + DP_{PI} + DP_{MI}$$

According to models, the direct effect of the increased magnetopause current propagates to low and middle latitudes as a compressive wave and produces a step like increase of the H component (DL_{MI} field, where L stands for low latitudes); its amplitude is largest at the equator and decreases with increasing latitude. A dusk-to-dawn electric field along the compressional wave front induces a twin ionospheric vortex system that produces a preliminary impulse of polar origin (DP_{PI}). The DP_{PI} field manifests as a preliminary reverse impulse (PRI) simultaneously observed at auroral latitudes in the afternoon and near the dip equator on the dayside, as well as a preliminary positive impulse (PPI) observed at auroral latitudes in the morning. On the other hand, if the increased pressure behind the SW discontinuity is kept up, the magnetospheric convection has to adjust itself to the compressed state of the magnetosphere: as a final result, it produces a twin polar vortex system (DP_{MI}) which is opposite to the DP_{PI} field and corresponds to the MI. Such DP_{MI} field is basically driven by an electric field originated in the polar region and transmitted from the outer magnetosphere through FAC which flow into the ionosphere in the morning side and away in the afternoon side. In this scheme, the preliminary impulse is exclusively due to current systems of polar origin, DP_{PI}, whereas the main impulse is due to the combined effect of DL_{MI} and DP_{MI}. On the other hand, Kikuchi et al. (2001) found that preliminary positive pulses tend to appear in the afternoon middle latitudes, and proposed that the generation mechanism is the magnetic effect of the FAC which are accompanied with the dusk-to-dawn electric fields.

The comparison between measurements at ground with those obtained by low altitude satellites above the ionosphere provided important insights on the ionospheric currents. For example, Araki et al. (1984), comparing ground and MAGSAT observations, showed that both H and D components showed variations with opposite sense at satellite and ground, revealing the existence of ionospheric currents associated with SI (at least near dawn and dusk, due to the orbital configuration). Han et al. (2007) examined Oersted and ground data and observed, in the night sector, very similar waveforms above and below the ionosphere; they then concluded that the ionospheric currents do not contribute significantly to nightside SI which, according to their conclusions, were dominantly caused by the enhanced magnetopause currents. By contrast, the waveforms observed by Oersted on the dayside were apparently different from those observed on the ground, reflecting the role of ionospheric currents. Corresponding to the PRI and the MI observed in the H component at the dayside dip equator, Oersted always observed an increase and a clear decrease in the magnetic field, respectively. These observational results suggest that the PRI at the dayside dip equator corresponds to a westward ionospheric current, and an eastward current is excited after the PRI. More recently, a comprehensive analysis of events simultaneously observed at ground and by CHAMP (Luhr et al., 2009) confirmed that night time events at ground are not (or minimally) affected by ionospheric currents. More in general, this analysis also showed that at latitudes smaller than $\lambda\approx40°$ the amplitude of the field variation was practically the same at ground and satellite; a progressive latitudinal increase of the SI amplitude was determined at higher latitudes both on the ground and at satellite, suggesting the effects of FAC rather than those of currents flowing in the ionosphere.

Figure 5a (after Villante and Piersanti, 2011) shows the 3-hr average values of the ground relative responses $<R_H>$ at $\lambda \approx 36°$: as can be seen, the LT modulation is much less pronounced than at geostationary orbit. The average responses in Figure 5a are compared with the theoretical profiles expected for the magnetopause current alone (R_{CF}) and for the global magnetospheric current system (from the magnetopause, tail and ring current, B_T), as evaluated at the winter and summer solstice. Such comparison shows that the observed $<R_H>$ fall, in general, within the limits of the expected profiles from approximately premidnight up to noon (an aspect confirmed by an analysis of single events), suggesting a poor contribution from FAC and ionospheric currents on this component. In the post-noon region, the observed responses overcome the theoretical profiles on average by ≈50% (and occasionally by a factor ≈2-3 in individual cases, Villante and Piersanti, 2011), revealing explicit effects from the additional ionospheric currents in this time sector. Consistently, Shinbori et al. (2009) interpreted such LT (and latitudinal) dependence as the manifestation of superimposed ionospheric currents: in particular, at low and middle latitudes, the observed pattern would be related to currents (producing negative and positive variations of the H component in the dawn and dusk sector, respectively) generated by the enhanced dawn-to-dusk electric field (accompanying FAC) due to the compression of the magnetosphere. Note, in addition, that, the negative responses of the D component ($<R_D>$, figure 5b) are far from the theoretical profiles, suggesting an explicit influence (through the entire day) on this component of the additional current systems.

4. The ULF waves occurrence

SI manifestations are occasionally accompanied by trains of almost monochromatic ULF waves (f≈1-10 mHz, usually referred as "Pc5 pulsations", Villante, 2007) which manifest soon after the main variation and persist for few cycles. According to Zhang et al. (2009), at geosynchronous orbit, the magnitude of ULF waves associated to variations of the SW pressure is larger around noon than at dawn and dusk. Amata et al. (1986) showed that magnetospheric oscillations excited by a SW shock have a complicated structure: a magnetosonic wave propagating from the dayside to the nightside sector suddenly appears and resonant shear Alfvén waves are generated during the propagation of this magnetosonic wave. As regard to ground observations, Ziesolleck and Chamalaun (1993) found wave amplitudes increasing with latitude, while their frequency was not dependent on either latitude or longitude.

A spectacular example of SI-related waves is shown in Figure 6 (after Piersanti et al., 2012) in which, at GOES 8 position (≈04:15 LT), the SI manifestation itself practically consists in the onset of a large amplitude wave mode at f=3.3 mHz; by contrast, GOES 10 (≈00:15 LT) did not observe any similar wave activity in the midnight sector. Waves at the same frequency were detected at all ground stations (Figure 7 and Figure 8; after Piersanti et al., 2012), suggesting an interpretation in terms of a global oscillation mode of the whole magnetospheric cavity. Moreover, the characteristics of the wave amplitude and the behaviour of the polarization pattern suggest that, due to the variable length of the field line through the day, the magnetospheric wave leaked energy to field line resonance at $\lambda \sim 66°$ in the morning sector and at $\lambda \sim 71°$ in the noon sector.

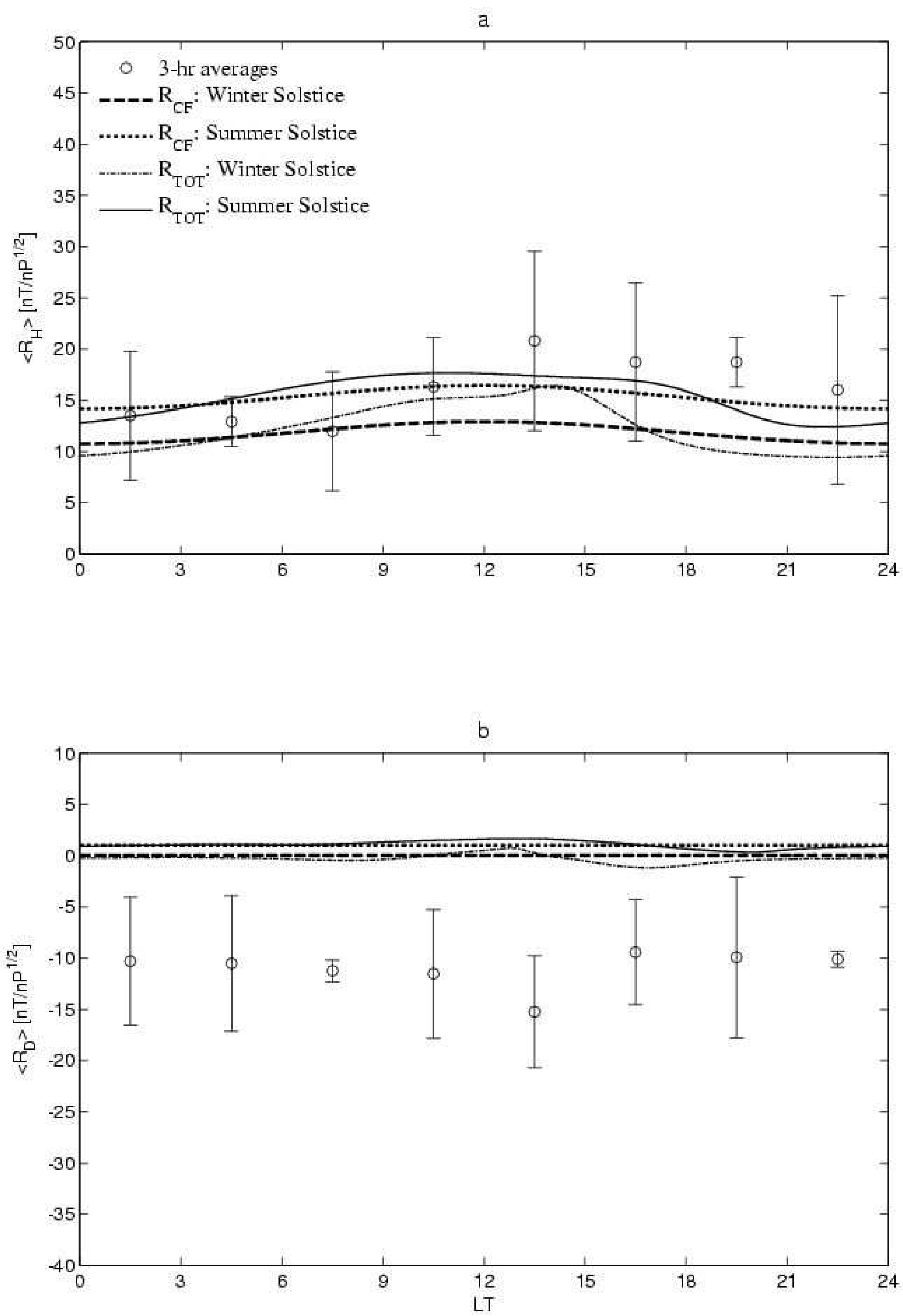

Fig. 5. (after Villante and Piersanti 2008) A comparison between averages values <R_H> in 3-hr intervals and the theoretical profiles determined considering the ground effects of the magnetopause current (B_{CF}-field) and those of the total current system (B_{TOT}-field). Both profiles have been evaluated at winter and summer solstice. b) The same for <R_D.

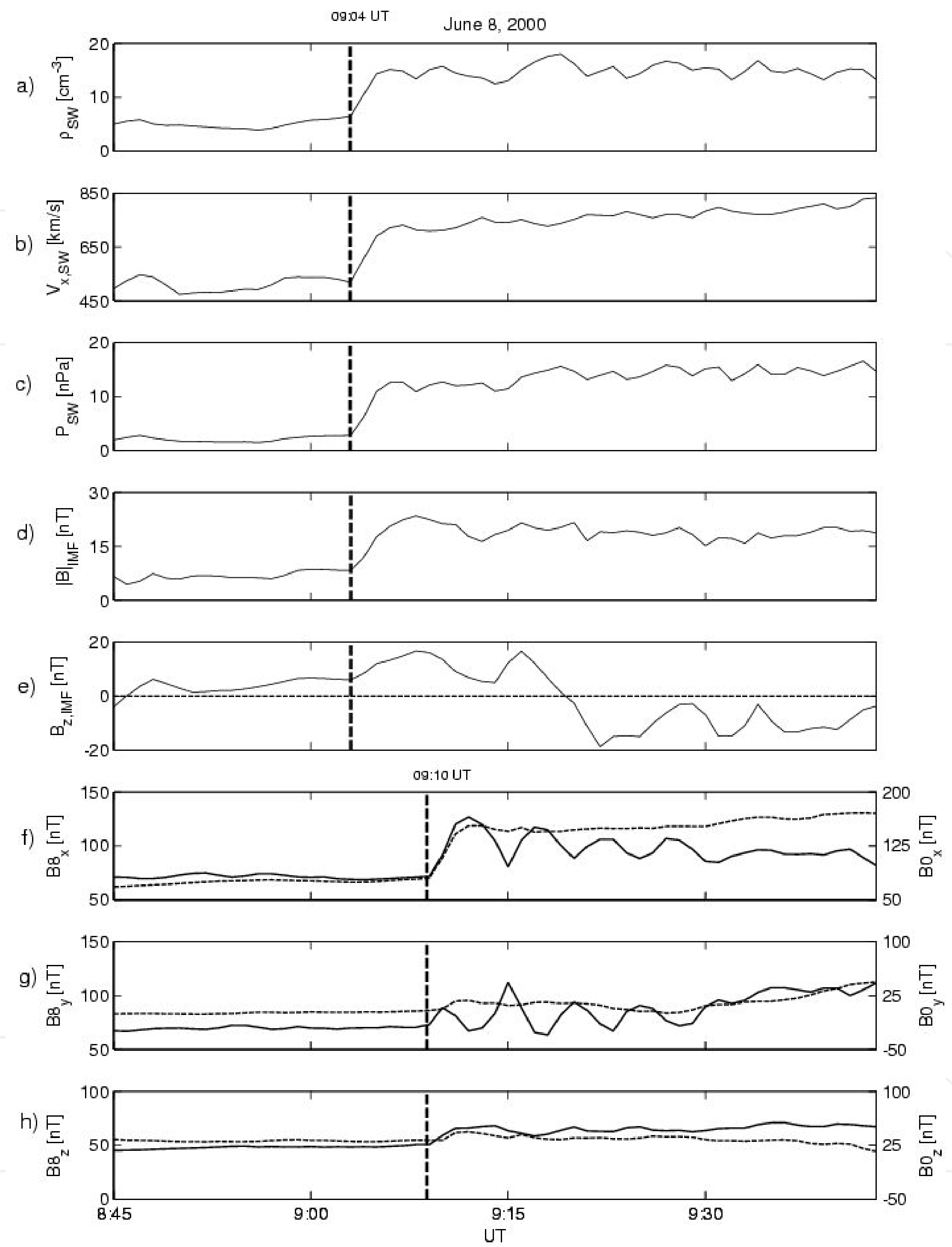

Fig. 6. (after Piersanti et al., 2011) The solar wind (WIND) and the magnetospheric observations (GOES) for the SI event occurred on June 8, 2000: a) the SW density; b) the SW velocity; c) the SW dynamic pressure; d) the IMF |B|; e) the IMF Bz component; f) The B_X component of the magnetospheric field measured by GOES8 (solid line) and GOES10 (dashed line); g) the B_Y component of the magnetospheric field measured by GOES8 (solid line) and GOES10 (dashed line); The B_Z component of the magnetospheric field measured by GOES8 (solid line) and GOES10 (dashed line). The vertical dashed lines identify the SW pressure jump and the SI occurrence.

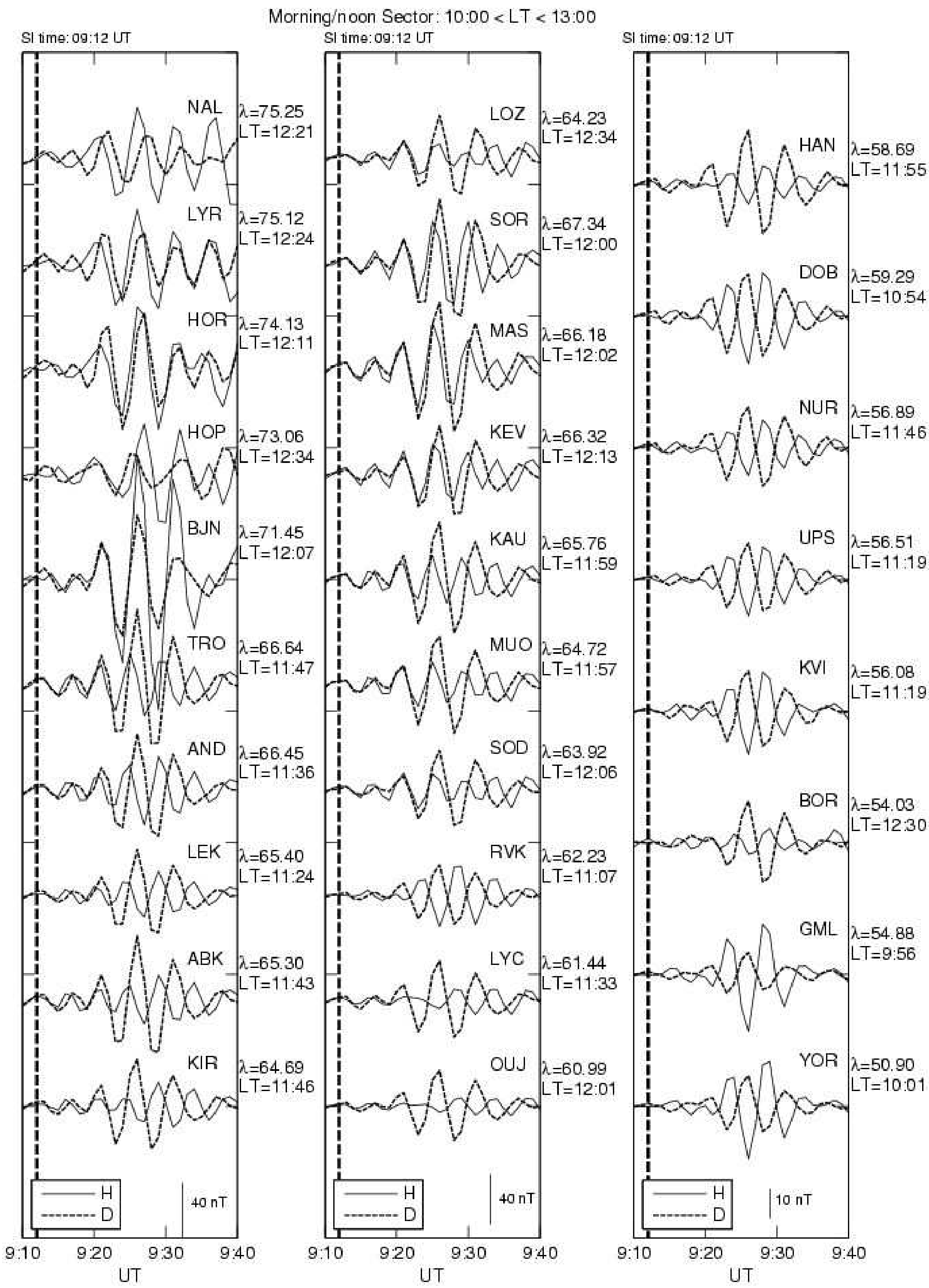

Fig. 7. (after Piersanti et al., 2011) The H (solid) and D (dotted) components of the geomagnetic field at ground stations location in the morning/noon sector (10:00 < LT <13:00) on June 8, 2000 (0910÷0940 UT). The data are filtered at f = 3.3 mHz.

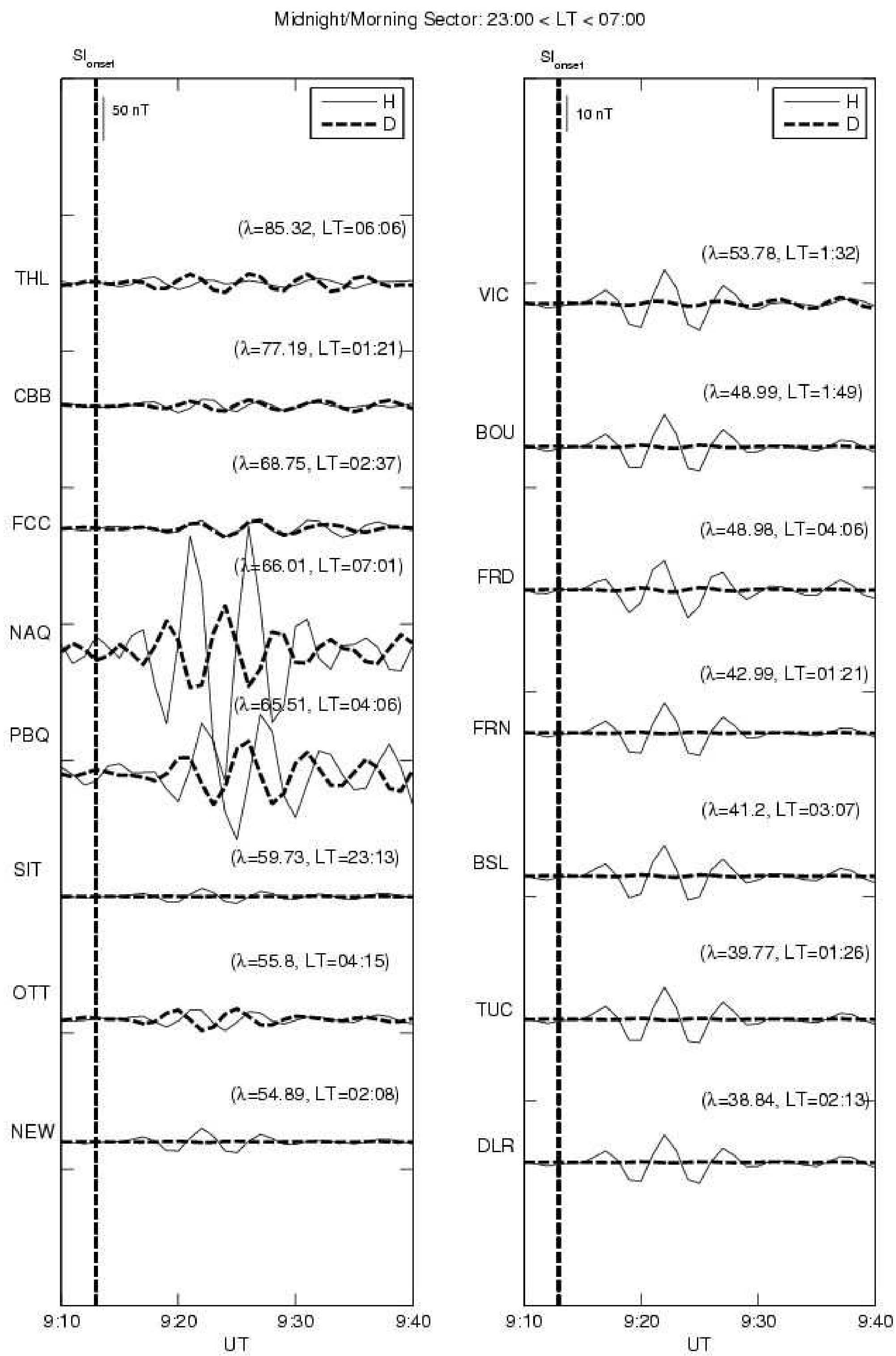

Fig. 8. (after Piersanti et al., 2011) The H (solid) and D (dotted) components of the geomagnetic field at ground stations location in the midnight/morning sector (23:00 < LT < 07:00) on June 8, 2000 (0910÷0940 UT). The data are filtered at $f = 3.3$ mHz.

5. Summary

The impinging on the Earth's magnetosphere of sudden increase of the SW pressure, related to the arrival of shock waves or other discontinuities, typically causes rapid increases of the magnetospheric and geomagnetic field, called sudden impulses (SI). Such pressure pulses, indeed, compress the magnetosphere, increase the magnetopause and tail currents, and possibly other magnetospheric/ionospheric current systems as well.

On the other hand, since the magnetopause current is mostly enhanced in the dayside sector, while the enhancement of the tail current produces a negative variation of the magnetospheric field, a strong day/night asymmetry might be expected in the SI manifestation: consistently, the experimental observations at geosynchronous orbit reveal an explicit LT modulation, with greater responses at satellite located closer to the noon meridian. The comparison between experimental observations and theoretical models reveals that the positive jumps are basically determined by the changes of the magnetopause current alone, in the dayside and in a large portion of the dark magnetosphere. On the other hand, the occurrence of negligible and negative responses in the nightside reveals a significant role of the tail (and ring) current.

At ground, the SI manifestation is more complex than at geosynchronous orbit since secondary effects like FAC and ionospheric currents contribute significantly in addition to the primary effects of the magnetospheric currents. The ground responses show a clear latitudinal dependence and a LT modulation (with smaller values in the morning and higher values in the postnoon region), a behaviour which can be interpreted as the manifestation of the superimposed ionospheric currents.

SI manifestations are occasionally accompanied by trains of almost monochromatic ULF waves which manifest soon after the main variation and persist for few cycles. In some cases they can be interpreted in terms of global oscillation modes of the whole magnetospheric cavity.

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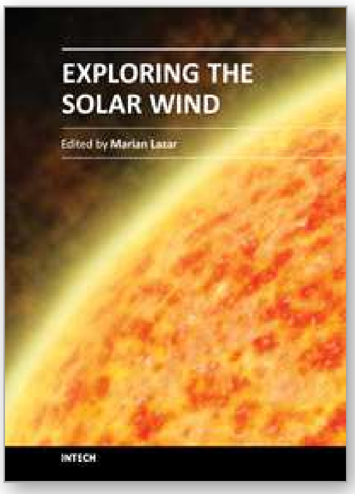

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This book consists of a selection of original papers of the leading scientists in the fields of Space and Planetary Physics, Solar and Space Plasma Physics with important contributions to the theory, modeling and experimental techniques of the solar wind exploration. Its purpose is to provide the means for interested readers to become familiar with the current knowledge of the solar wind formation and elemental composition, the interplanetary dynamical evolution and acceleration of the charged plasma particles, and the guiding magnetic field that connects to the magnetospheric field lines and adjusts the effects of the solar wind on Earth. I am convinced that most of the research scientists actively working in these fields will find in this book many new and interesting ideas.

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