# An analysis of sudden impulses at geosynchronous orbit

U. Villante[1] and M. Piersanti[1]

Received 8 January 2008; revised 28 March 2008; accepted 8 April 2008; published 9 August 2008.

[1] An analysis of sudden impulses (SI) at geosynchronous orbit (2000–2004) confirms a general dependence of the SI amplitude on the variation of the square root of the solar wind pressure, together with an explicit LT dependence, with greater responses at satellites located closer to noon meridian. In the dayside hemisphere the magnetospheric response, which mostly influences the $B_z$ component, is well consistent with the magnetic field jump expected for changes of the magnetopause current alone, driven by changes of the solar wind pressure. In the dark hemisphere, where the changes of the $B_x$ component are often relevant, the competing contributions of several current systems (from the magnetopause, cross-tail current, ring current, Birkeland current) determine a large variety of responses that cannot be interpreted in a statistical sense. Depending on the solar wind conditions, different situations emerge for nightside events. We present a case in which a remarkable magnetospheric compression determined field variations which can be interpreted in terms of a strongly dominant contribution of the magnetopause current even in the midnight sector, while in other cases the observed features are consistent with the predictions of the global current system. We also speculated that additional elements (such as the geocentric distance of the hinging point, the separation point between closed and open field lines in the geomagnetic tail) might play a crucial role in determining the aspects of the magnetospheric response. The correspondence between model predictions and observations persists even in cases of moderate Southward orientations of the IMF.

**Citation:** Villante, U., and M. Piersanti (2008), An analysis of sudden impulses at geosynchronous orbit, *J. Geophys. Res.*, *113*, A08213, doi:10.1029/2008JA013028.

## 1. Introduction

[2] Sudden Impulses (SIs) are caused by sudden increases in the dynamic pressure of the solar wind (SW), generally associated with interplanetary shock waves, that compress the magnetosphere, increase the magnetopause and tail currents and possibly other magnetospheric current systems as well [*Smith et al.*, 1986; *Fowler and Russell*, 2001]; correspondingly, the magnetospheric field increases gradually over about a 2- to 15-min period.

[3] In agreement with theoretical predictions, spacecraft and ground observations [*Nishida*, 1978; *Smith et al.*, 1986] revealed a general dependence of the jump of the magnetic field (SI amplitude, $\Delta$B) on the increase of the square root of the SW pressure ($\Delta P^{1/2}$). At geosynchronous orbit, *Patel and Coleman* [1970] reported that SIs (13 events, 1967) in the nightside sector had smaller amplitude than in the dayside sector. *Kokubun* [1983] found that the SI response (81 events, 1978–1979) along the component parallel to the Earth's axis had a remarkable local time (LT) dependence, with highest values at local noon and very small values (or even negative, in some cases) near midnight. *Kuwashima and Fukunishi* [1985] examined 167 events (1976–1980) and confirmed a very small normalized amplitude near midnight. More recently, *Lee and Lyons* [2004, 35 events, 1997–2001] concluded that SW pressure enhancements generally lead to a magnetospheric compression at all time sectors with few exceptions in the nightside. *Borodkova et al.* [2005] found that 147 out of 261 changes of the SW pressure (positive and negative; 1996–1998) were associated with corresponding variations of the magnetospheric field ($B_z$ component in the GSM coordinate system); they also remarked that all the events without an explicit response were located either before 7:30 LT or after 16:30 LT.

[4] The magnetospheric response to sudden variations of the SW pressure has been currently interpreted in terms of an inward motion of the magnetopause, launching a compressive wave which propagates across the field lines [*Nishida*, 1978; *Smith et al.*, 1986, and papers referenced therein] and the experimental measurements have been examined using a variety of techniques. In the present paper we propose a new approach to the experimental observations which consists in comparing the observed field jumps with those predicted for the competing contributions of several current systems (from the magnetopause, cross-tail current, ring current, Birkeland current [*Tsyganenko*, 2002a, 2002b]) as determined by the varying interplanetary parameters: more particularly, we carefully examined the correspondence between observations and model predictions as

[1]Dipartimento di Fisica, Università and Area di Astrogeofisica, L'Aquila, Italy.


0148-0227/08/2008JA013028

determined for two states of the magnetosphere under different SW conditions. The results of the present analysis reveal that a realistic parameterization of the different contributions provides a good representation of the experimental measurements that allows a significant improvement in our understanding of the role of the different current systems. As a matter of fact we found that in the dayside hemisphere the magnetospheric response is well consistent with the one expected for changes of the magnetopause current alone, suggesting a negligible influence of the additional current systems (cross-tail current, ring current, Birkeland current) at geosynchronous orbit. In the nightside hemisphere (where the magnetospheric response is often negligible or even negative) the competing contributions of several current systems determine a large variety of responses which cannot be interpreted in a statistical sense. Depending on the SW conditions, different situations emerge for nightside events: we present, indeed, a case in which a remarkable magnetospheric compression determined field variations which can be interpreted in terms of a dominant contribution of the magnetopause current even in the midnight sector, while in other cases the observed behavior is better consistent with the global current system. We also speculated that additional elements (such as the geocentric distance of the hinging point, the separation point between closed and open field lines in the geomagnetic tail) might play a crucial role in determining the aspects of the magnetospheric response.

## 2. Data Analysis and Methods

[5] For the scope of the present investigation we preliminarily selected events at a ground low latitude station (L'Aquila, Italy, CGM $\lambda \approx 36°$, LT = UT + 1:37). We examined 1 min averages of the north–south component (H) for a 5-year interval (2000–2004) and selected the events associated with $\Delta$H increases $\geq$5 nT, occurring in less than 30 min. A careful inspection of the selected events (111) confirmed a clear identification of the SI characteristics for 90 cases (for example, we eliminated the events occurring during the main phase of geomagnetic storms, as well as those associated with geomagnetic bays, the low latitude manifestation of substorms); SW (WIND spacecraft) and magnetospheric observations (GOES 8, LT = UT- 5; GOES 10, LT = UT- 9; GSM coordinate system) were available for 71 events and in 55 cases allowed an unambiguous identification of the jump of the physical parameters both in the interplanetary medium and in the magnetosphere. In the following, $\Delta P = P_2 - P_1$, $\Delta P^{1/2} = P_2^{1/2} - P_1^{1/2}$ and $\Delta B_i = B_{2i} - B_{1i}$ identify the difference between 10 min averages of P, $P^{1/2}$, and $B_i$, evaluated on opposite sides of the main change when transient effects have died out.

[6] The theoretical values of the magnetic field elements at geosynchronous orbit are those predicted by the model by *Tsyganenko* [2002a, 2002b] (this model is usually referred as T01 in the scientific literature) in which the total magnetospheric field of external origin is represented in terms of the sum of the Chapman-Ferraro current at the magnetopause and of additional contributions from the cross-tail current, ring current, field-aligned currents. These additional contributions are evaluated taking also into account ($G_1$ and $G_2$ parameters in T01) several elements that influence the state of the magnetosphere (such as the orientation of the north/south component ($B_{z,IMF}$) of the interplanetary magnetic field (IMF), the SW electric field, etc.): in the present analysis we considered as additional elements the averages of the SW and IMF elements over the 1-h interval preceding the current observation as well as the Dst index. To take into account the delayed response of the magnetosphere, each data record was tagged by a trail of 5 min covering the preceding 1-h interval (however, different choices of the averaging interval and delay time did not influence significantly the results of the present analysis). In practice, the predicted jumps of the magnetospheric field elements (i.e., the difference between 10 min averages on the same time intervals considered for the experimental measurements) have been evaluated either in terms of the magnetopause current alone ($\Delta B_{CF,i}$) or in terms of the total current ($\Delta B_{T,i}$). Obviously, in this scheme we are implicitly assuming that the change of the magnetospheric field due to the arrival of a SW pressure jump is simply determined by the transition between two states of the magnetosphere under different SW conditions. Most of the events discussed in the present investigation occurred during "typical" SW conditions (P < 10 nPa, $-5$ nT< $B_{z,\ IMF}$ <5 nT in 46 out of 55 events), i. e. well within the limits proposed by *Tsyganenko* [2002a] for a confident estimate of the magnetospheric field configuration in different regions (namely, 0.25 nPa $\leq$ P $\leq$ 15 nPa, $-10$ nT$\leq$ $B_{z,\ IMF}$ $\leq$ 10 nT).

### 2.1. LT Dependence of the Magnetospheric Response

[7] Figure 1 shows three examples of events with different characteristics. In panel a GOES 8 and GOES 10, on opposite sides of noon meridian, detect a sharp increase of the magnetospheric field associated with the SW pressure jump (heavy horizontal bars correspond to our estimates of the 10 min averages before and after the jump). Panel b shows an event that is clearly detected both in the midnight and dawn sector. In panel c a sharp magnetic field increase is identified in the dawn sector while night measurements do not reveal any clear SI signature: in similar cases the SI-related changes (if any) could hardly be distinguished from longer term trends, and their $\Delta B_i$ values were evaluated using 10 min averages for the same intervals as for the other spacecraft. As a matter of facts, most interplanetary events (51 out of 55) were characterized by $\approx$1 < $\Delta$P < $\approx$9 nPa ($\approx$0.5 < $\Delta P^{1/2}$ < $\approx$2 nPa$^{1/2}$); an extraordinary event was associated with $\Delta$P $\approx$22.7 nPa ($\Delta P^{1/2}$ $\approx$3.1 nPa$^{1/2}$). The jump of the magnetospheric field strength ($\Delta$B) ranged between $\approx -20$ and $\approx$60 nT.

[8] The normalized amplitude of the magnetospheric response has been evaluated considering the ratio $R_i = \Delta B_i/\Delta P^{1/2}$ for the field amplitude and components. As shown in Figure 2a (where the observations for the same event from the two spacecraft are connected by a line), $\Delta B/\Delta P^{1/2}$ shows a large spread of values in each time interval, suggesting that several elements contribute in determining the amplitude of the magnetospheric response. Nonetheless, in agreement with previous investigations [*Kokubun*, 1983; *Kuwashima and Fukunishi*, 1985; *Borodkova et al.*, 2005], we found an explicit LT dependence of that response with a general tendency for a greater value at satellite located closer to noon meridian. A remarkable exception in this sense is represented by an event characterized by a huge

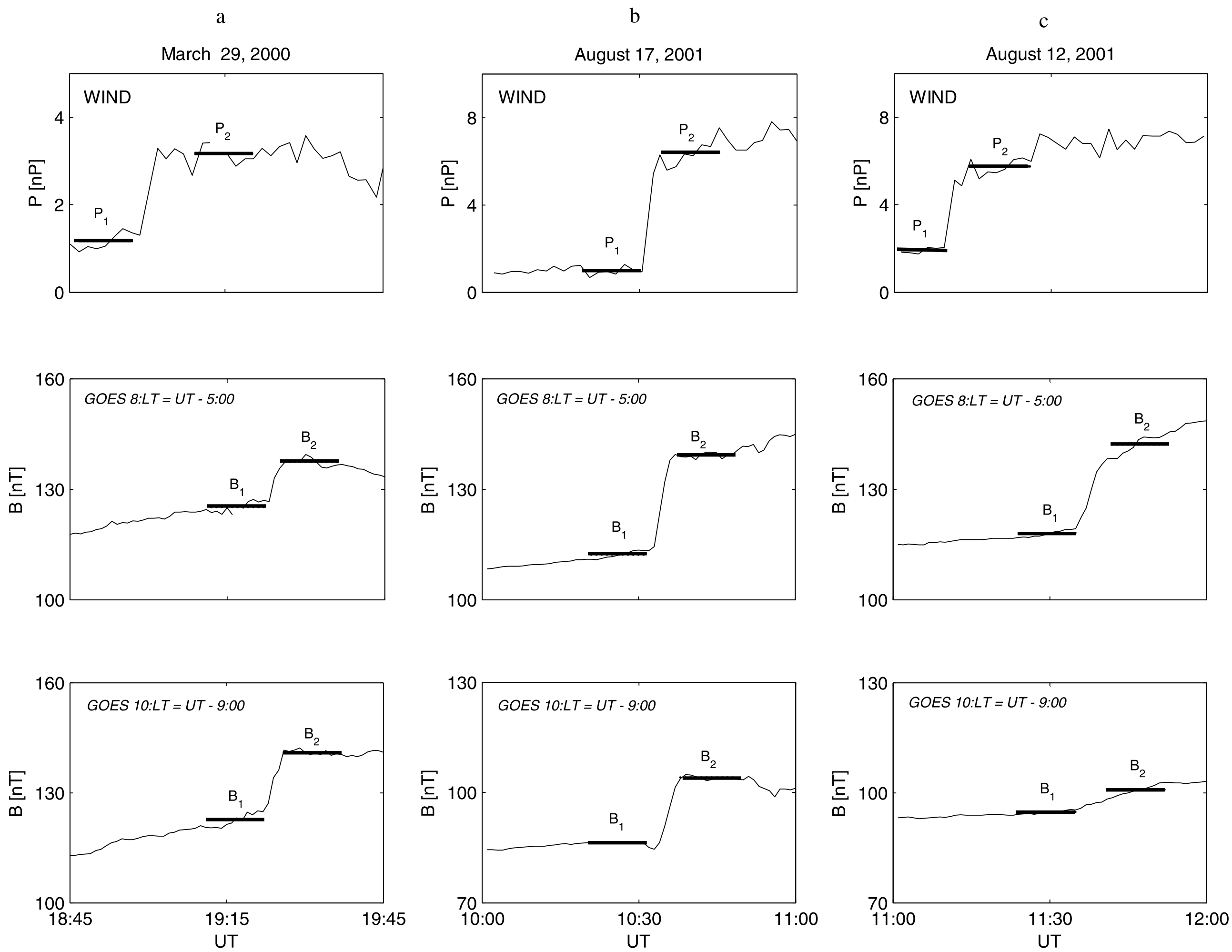


**Figure 1.** Three examples of SI events with different characteristics; (a) dayside region, (b) midnight and dawn sector, and (c) midnight and dawn sector. The SW dynamic pressure and the magnetic field amplitude at GOES 8 and GOES 10 are shown. The heavy horizontal bars correspond to the 10 min averages before and after the jump. The time delay between WIND and magnetospheric measurements corresponds to the transit time of the SW discontinuity to reach the geosynchronous orbit.

midnight response (event A in Figure 2a); conversely, the event associated with the extraordinary pressure jump shows a more pronounced response in the premidnight region and a LT behavior consistent with other observations (event B in Figure 2a). As we said, in some cases one sees only a gradual change of the magnetospheric field in response to the pressure jump (panel c in Figure 1); these events, identified by black circles in Figure 2a, are typically observed between ≈19:30–6:00 LT, where the normalized response is often quite small. Within the limits of the present statistics, separate analysis conducted for northward/southward IMF orientations do not reveal significant differences in the average response and only suggest some evidence for a larger spread of experimental values during negative $B_{z,IMF}$. A similar LT dependence is shown by $\Delta B_z/\Delta P^{1/2}$ (Figure 2b). Note that in this case neither event A nor event B reveal anomalous responses: indeed, as we discuss in the following, in both cases the remarkable increase of the field strength (Figure 2a) was mostly determined by an explicit jump of the $B_x$ component.

[9] Figure 3a compares the average values of $\Delta B_z/\Delta P^{1/2}$ in each 3-h interval with the theoretical profile expected for the magnetopause current alone. In this case the theoretical profile of $\Delta B_{CF,z}/\Delta P^{1/2}$ (which is practically independent on the SW pressure in the range of the observed values) has been determined for $\psi = 0$, $\psi$ being the tilt angle between the geomagnetic dipole and $Z_{GSM}$. In the noon sector, the experimental values lie close to the expected profile, suggesting average responses basically consistent with those predicted for changes of the magnetopause current. Far from noon meridian, the experimental values decrease faster then predicted, suggesting the progressive influence of additional contributions. Last, in the nightside sector, where significant negative contributions are expected to come from the tail current, the average responses are explicitly smaller than predicted for changes of the $B_{CF}$ field alone. The least squares approximation of the experimental observations suggests average peak values such as ≈26.4 nT/nPa$^{1/2}$ at ≈11:30 LT, and negligible/null values between ≈20:00–03:30 LT The results obtained for the field strength

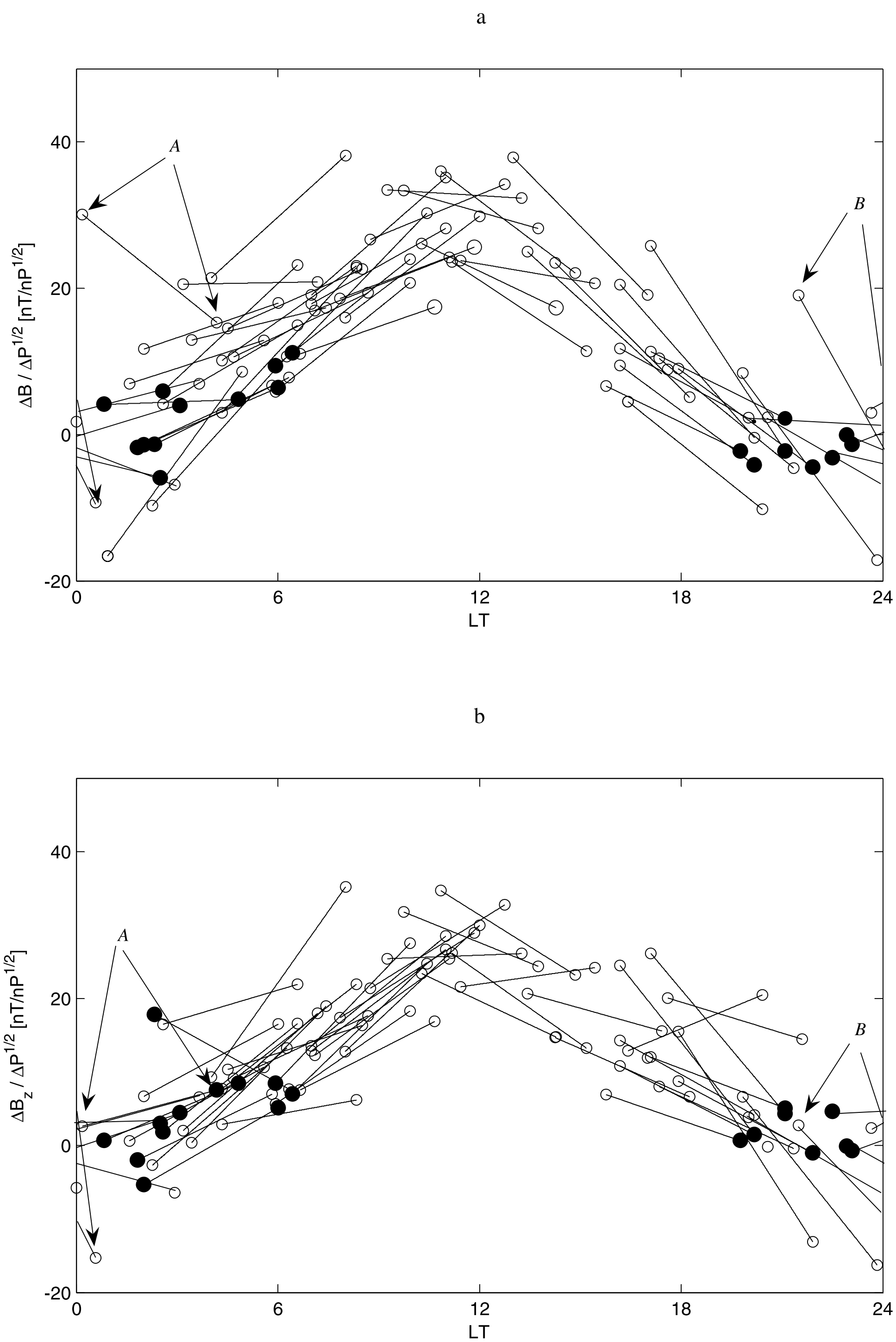


**Figure 2.** (a) The ratio $\Delta B/\Delta P^{1/2}$ versus local time (observations of the same event from the two spacecraft are connected by a line); (b) the ratio $\Delta B_z/\Delta P^{1/2}$ versus local time. Black circles identify events associated with gradual variations of the magnetospheric field at the SI occurrence.

(Figure 3b) suggest peak values of $\approx$29.5 nT/nPa$^{1/2}$. The general tendency for prenoon responses higher than postnoon values finds some correspondence in the daily modulation of the geosynchronous field that attains peak values before local noon [*Rufenach et al.*, 1992].

[10] Figures 4a and 4b more carefully examine the relationship between $\Delta B_z$ (and $\Delta B$) and $\Delta P^{1/2}$ for events occurring in the subsolar magnetosphere (10–14 LT): as can be seen, within the limits of the present statistics, the experimental results are well approximated in terms of linear relationships (r = 0.89 for the $B_z$ component, and r = 0.91 for the field strength, r being the correlation coefficient). It suggests normalized responses practically independent on the SW pressure, at least for $\Delta P^{1/2} < 2.5$ nPa$^{1/2}$ (with average values such as $\Delta B_z/\Delta P^{1/2} \approx 26.1$ and $\Delta B/\Delta P^{1/2} \approx 27.8$ nT/nPa$^{1/2}$, respectively). The relative variation

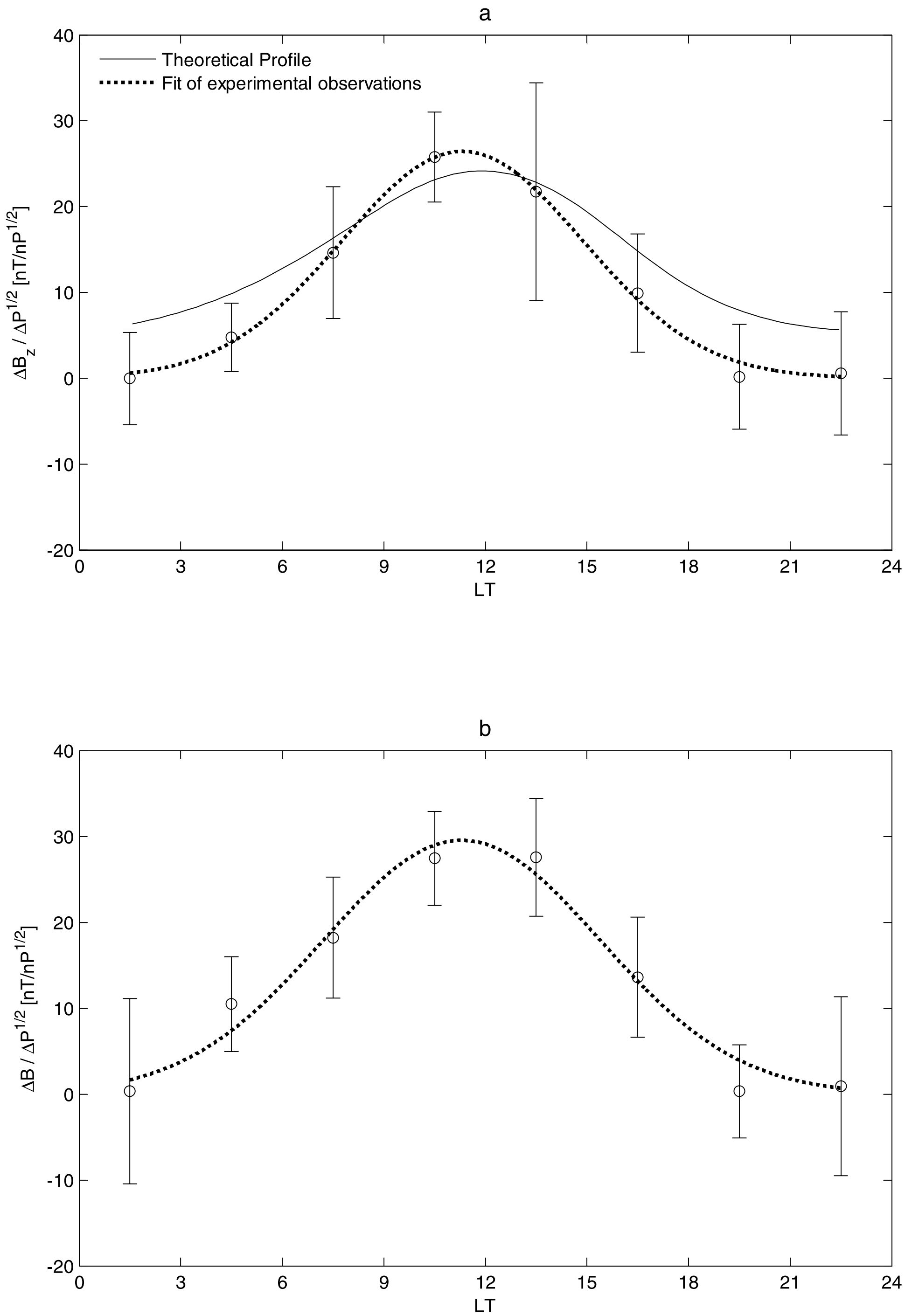


**Figure 3.** (a) A comparison between average values of $\Delta B_z/\Delta P^{1/2}$ in each 3-h interval and the theoretical profile (T01), determined considering the magnetic effects of the magnetopause current at geosynchronous orbit for $\psi = 0$. The dotted line represents the fit of experimental measurements; (b) the same as in Figure 3a for $\Delta B/\Delta P^{1/2}$.

$\Delta B_z/B_{z1}$ (and $\Delta B/B_1$, Figure 4c) also reveals a LT modulation, with noon values of $\approx$0.25. Figures 4d–4f show the LT dependence of the jump of the field components ($\Delta B_i/\Delta B$) as normalized to the jump of the field strength. The strong dominance of $\Delta B_z$ in the dayside sector suddenly decreases at the dawn/dusk meridians, becoming negligible around midnight: consistently, significant relative contributions of $\Delta B_x$ and $\Delta B_y$ appear in the dark sector.

### 2.2. Comparison With Theoretical Models

[11] The correspondence between experimental results and theoretical predictions can be examined more carefully comparing each observed response (for each field element) with the value predicted considering $\psi$, satellite position, and the measured SW pressure. Figure 5a shows the results obtained in the dayside sector comparing the experimental observations ($\Delta B_i$) with the predictions of the magneto-

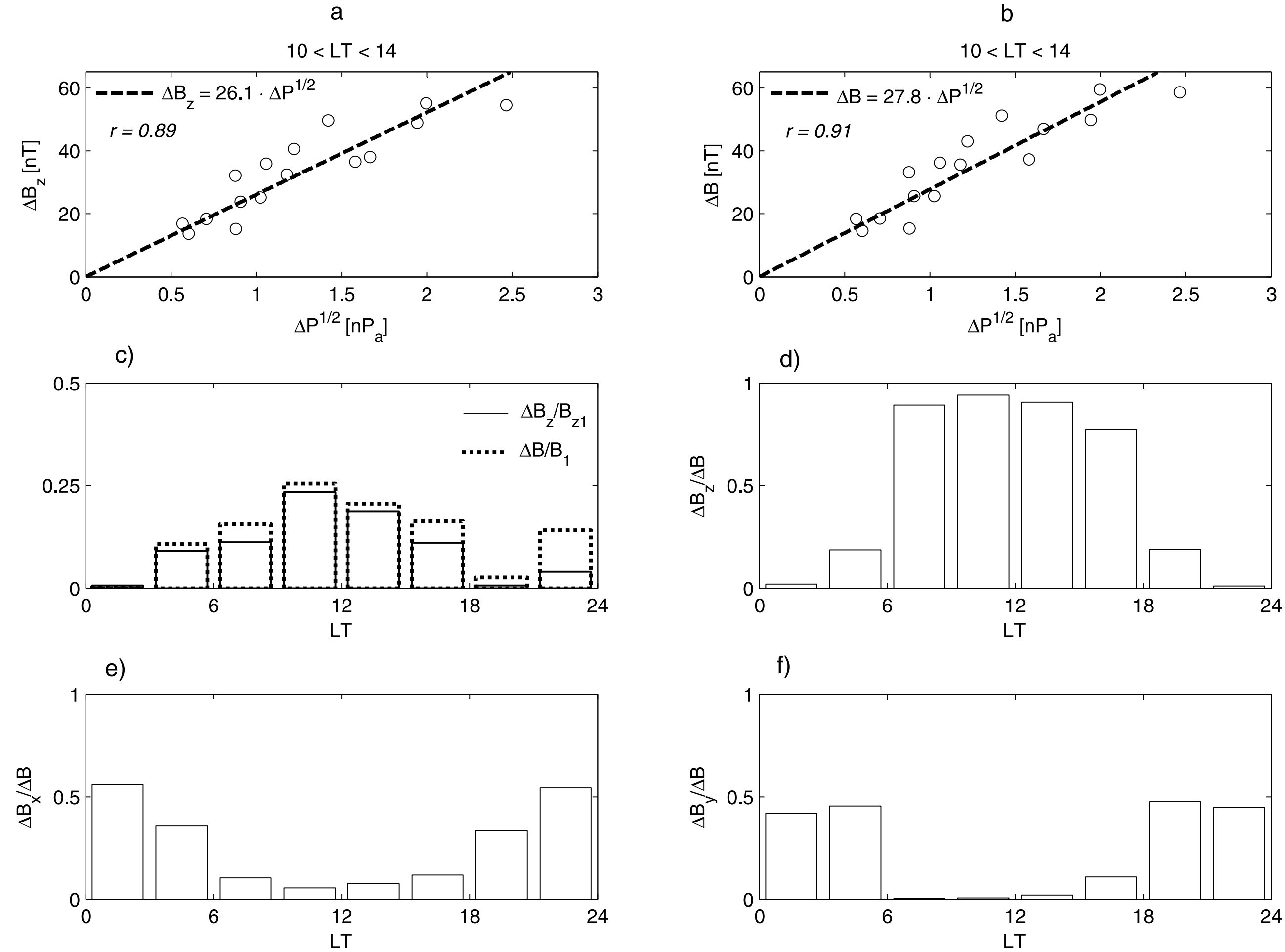


**Figure 4.** (a) $\Delta B_z$ versus $\Delta P^{1/2}$ for events occurring in the LT sector 10 < LT < 14, (b) $\Delta B$ versus $\Delta P^{1/2}$ for events occurring n the LT sector 10 < LT < 14, (c) a comparison between the 3-h averages of relative variations $\Delta B_z/B_{z1}$ and $\Delta B/B_1$ versus LT, (d) the normalized amplitudes $\Delta B_z/\Delta B$ versus LT, (e) the normalized amplitude $\Delta B_x/\Delta B$ versus LT, and (f) the behavior of the normalized amplitudes $\Delta B_y/\Delta B$ versus LT.

pause current alone ($\Delta B_{CF,i}$). As expected from theory, the dominant $\Delta B_z$ (and $\Delta B$) attains only positive variations, which are well correlated with model predictions (r = 0.88). The results of a least squares approximation ($\Delta B_z = m(\Delta B_{CF,z})$ +b; m = 0.96, b = 1.3; m = 1.01, for a fit through the origin) reveal that, in a statistical sense, the amplitudes of the observed responses are very well consistent with the predicted values. This is an interesting result that reveals that, in the dayside sector, the response of the dominant $B_z$ component is well represented in terms of changes of the magnetospheric field driven by jumps of the SW pressure (via the changes of the magnetopause current), when the effects of the $\psi$ angle are taken into account. Black circles in Figure 5a identify three events associated with negative values of $B_{z,IMF}$ beyond the limits ($-10$ nT < $B_{z,IMF}$ < 10 nT) proposed by *Tsyganenko* [2002a] for a confident estimate of the magnetospheric field configuration: as can be seen, in two cases the observed values are well consistent with the predicted ones; in one case the observed response is greater than predicted: however, similar situations occur also for events occurring during Northward $B_{z,IMF}$. The observed $\Delta B_x$ (which correspond to compression or stretching of the field lines in radial direction) are often consistent with theoretical predictions (although with r = 0.56). Conversely, the observed $\Delta B_y$, often much greater than expected, reveal distortions of the field lines which do not find correspondence in model predictions: it is worth noting in this sense that, in general, $B_y$ is the field component which shows the worst correlation between observed and model values, even during quiet magnetospheric conditions [*Tsyganenko*, 2002b]. The results obtained for the global current system (Figure 5b) provide, for the $B_z$ component, similar results, as expected for a minor influence of the additional current system at geostationary orbit: the larger spreads of data points in each field element (r = 0.75, for $B_z$) suggest that the additional currents do not improve the correspondence between the observed jumps and the expected values; however, it is worth noting the close agreement between model and observations for events associated with large negative $B_{z,IMF}$ (black circles in Figure 5b).

[12] The statistical analysis conducted for the nightside sector reveals that the experimental observations do not show any correspondence with the values predicted for

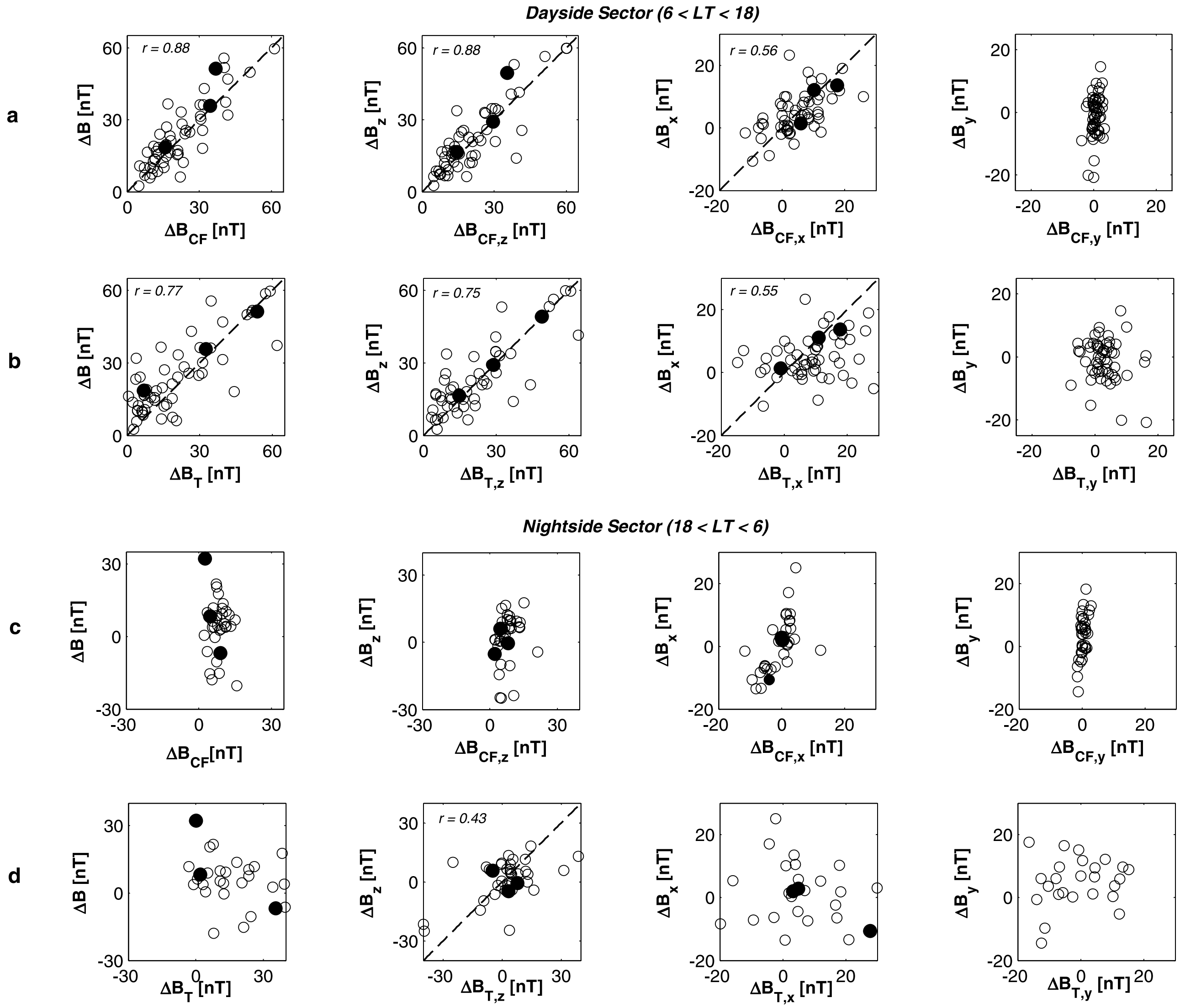


**Figure 5.** A comparison between the observed responses and model predictions (T01): (a) dayside sector for the magnetopause field alone ($\Delta B_{CF}$), (b) dayside sector for the total field ($\Delta B_T$), (c) nightside sector for the magnetopause field alone ($\Delta B_{CF}$), and (d) nightside sector total field ($\Delta B_T$). The dotted lines correspond to $\Delta B = \Delta B_{CF,i}$ and to $\Delta B = \Delta B_{T,i}$. *r* are the correlation coefficients. Black circles identify three events associated with negative values of $B_{z,IMF}$ beyond the limits proposed by *Tsyganenko* [2002a] for a confident estimate of the magnetospheric field configuration ($-10$ nT $\le B_{z,IMF} \le 10$ nT).

changes of the magnetopause current (Figure 5c; note, in particular, the large number of events with "unpredicted" negative $\Delta B_z$). By contrast, the observed response of the $B_z$ component is often consistent with that one predicted by the global current system (although with r = 0.43, Figure 5d). As in the daytime sector, the events related with negative $B_{z,IMF}$ reveal approximately the same characteristics observed for other events. More in general, the emerging overview suggests that the variable relative importance of the competing current systems does not allow, in the nightside sector, any meaningful comparison between experimental observations and model predictions, at least in a statistical sense.

### 2.3. An Analysis of Single Events

[13] To investigate further these aspects, we compared the theoretical profiles ($B_{CF}$ and $B_T$) with the observed behavior of the $B_z$ and $B_x$ components for several events. Three typical daytime examples are shown in Figure 6, where the external SW conditions are represented in terms of P and $B_{z,IMF}$. As a matter of facts in these cases GOES 10 was located in the noon quadrant (≈11:45–12:45 LT) while GOES 8 was located in the afternoon sector (≈15:45–16:45 LT). As shown in Figure 6, in each panel before the SI occurrence, $B_{CF}$ and $B_T$ practically predict the same field traces (very well consistent with the observed $B_z$ and $B_x$), confirming a minor influence of the additional current systems on the dayside field under quiet SW conditions. After the event, the $B_{CF}$ predictions and the experimental measurements show a close correspondence in the jump of the dominant $B_z$ component; by contrast, the $B_T$ field predicts for this component values appreciably smaller than observed. It is worth noting in this context that $B_{CF}$ and $B_T$ would predict very similar traces even in the postevent region, assuming

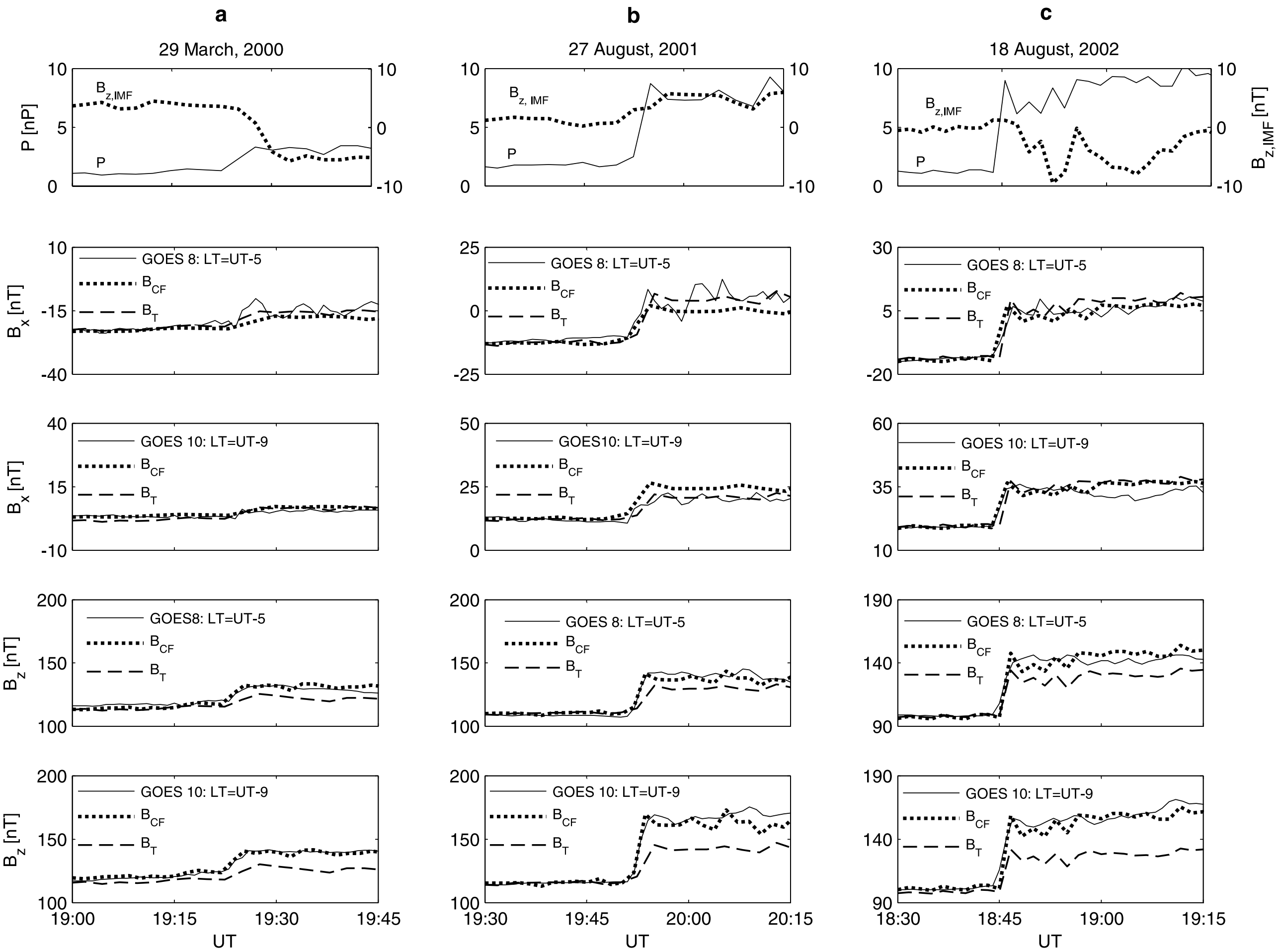


**Figure 6.** A comparison between experimental observations and theoretical models for three dayside events ($B_x$ and $B_z$ components). The external SW conditions are represented in terms of P and $B_{z,IMF}$ in the top. In the other panels, the dashed line represents the $B_T$ field; the dotted line represents the $B_{CF}$ field.

for the $G_1$ and $G_2$ parameters approximately the same values as in the pre-event region: it might suggest that external elements do not influence so rapidly the dayside magnetospheric field at geosynchronous orbit, at least in presence of rapid changes of the SW elements. This is an interesting aspect if we consider that event *a* and, more explicitly, event *b* were associated with Southward turning of $B_{z,IMF}$ at the SI occurrence: it confirms that, even in presence of a (moderate) southward component of the IMF, the experimental observations, soon after the event, can be well represented in terms of model predictions, assuming magnetospheric conditions basically determined by the pre-event values of the SW parameters. For the $B_x$ component, a closer agreement is observed between $B_{CF}$ and $B_T$ predictions (both consistent with the experimental observations) in the postevent region, revealing a smaller influence of the additional currents on the behavior of the radial component.

[14] Interesting results are obtained in the dark sector by an analysis of significant events with different characteristics. Figure 7 shows the results obtained for the event characterized by the extraordinary pressure jump ($\Delta P \approx 22.7$ nPa, event B in Figure 2). Note that in this case the high SW pressure (well beyond the limits proposed by *Tsyganenko* [2002a]) likely determined an inward motion of the magnetopause up to geosynchronous orbit. The observing spacecraft were located on opposite sides of the local midnight and at large $\psi$ angles ($\psi \approx -25°$). As a matter of fact, the sharp decrease of the $B_x$ component (observed at both satellite positions) was accompanied by a $B_z$ decrease at ≈01:30 LT (GOES 8) and by a $B_z$ increase at ≈21:30 LT (GOES 10). In this case, the comparison between observed and predicted values suggests conclusions similar to those obtained for daytime events. Indeed, before the SI occurrence, the predictions for the magnetopause current alone ($B_{CF}$) and those for the total field ($B_T$) provide approximately the same traces, which appear very well consistent with the experimental observations. By contrast, after the event, the experimental observations appear well represented only in terms of $B_{CF}$; the $B_T$ field would indeed predict a magnetic field behavior which is odd with respect to the observed one (i.e., a $B_z$ decrease at GOES 10 and a $B_x$ increase at GOES 8). It suggests that in this case the extreme jump of the magnetopause current is the key element (strongly dominant with respect to other current systems) in determining the magnetospheric re-

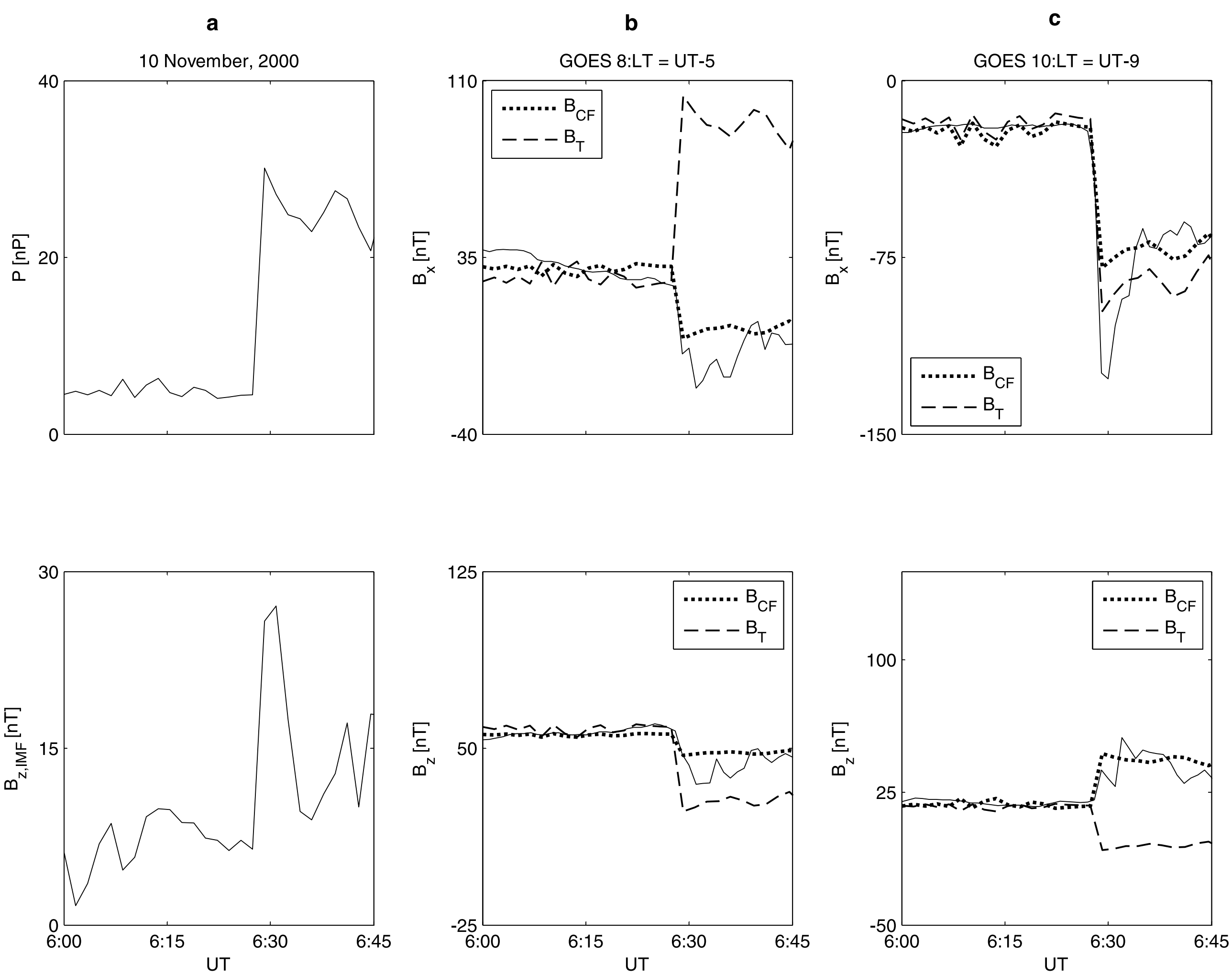


**Figure 7.** A comparison between experimental observations and theoretical models for the event characterized by the extraordinary pressure jump (10 November 2000). (a) the external SW conditions are represented in terms of P and $B_{z,IMF}$, (b) the behavior of $B_x$ and $B_z$ component at GOES 8, and (c) the behavior of $B_x$ and $B_z$ component at GOES 10. The dashed line represents the $B_T$ field; the dotted line represents the $B_{CF}$ field.

sponse also in the dark sector; it also interprets the large relative response $\Delta B/\Delta P^{1/2}$ in terms of a remarkable variation of the $B_x$ component (event B in Figure 2). It reveals, in addition, that the model predictions can interpret the experimental observations even in presence of extreme SW conditions.

[15] Figure 8 shows the results obtained for the event characterized by the large $\Delta B/\Delta P^{1/2}$ at local midnight (event A in Figure 2). Consider GOES 10 observations ($\approx$00:15 LT, $\psi \approx 5°$, panel b). Here, this event is basically characterized by a huge jump of the $B_x$ component while the $B_z$ component experiences a smaller amplitude change. In this case, the $B_{CF}$ field, which well reproduces both the magnetic field components before the event and well interprets the $B_z$ variation, is unable to reproduce the behavior of the $B_x$ component: in particular, the predicted trace does not show any evidence for the observed $B_x$ jump. On the other hand, the $B_T$ field predicts a positive $B_x$ change qualitatively consistent with the observed behavior, suggesting an explicit influence of the tail current in the nightside magnetosphere. By contrast, the predicted change of $B_{T,z}$ is opposite to the observed one. It is worth noting in this sense that the correspondence between observed and predicted values for both components remarkably improves ($B_{T1}$ traces in panel b) assuming a $\approx$10% smaller hinging distance (the separation point between closed and open field lines assumed at $\approx$9 Re in T01). Such condition might be related to the sharp increase of the positive $B_{z,IMF}$ component in the period of interest, with a consequent dipolarization of the field lines in the extended tail. As a matter of fact, when combined with a $\approx$30% thinner current sheet ($\approx$2.4 Re in T01), the smaller hinging distance would determine a general enhancement of the magnetospheric field and a significant stretching of the field line in antisolar direction which appear consistent with the experimental observations [*Lui*, 1993; *Collier et al.*, 1998; *Huttunen et al.*, 2005; *Thompson et al.*, 2005]. The large change of the $B_x$ component allows in this case to interpret the extreme

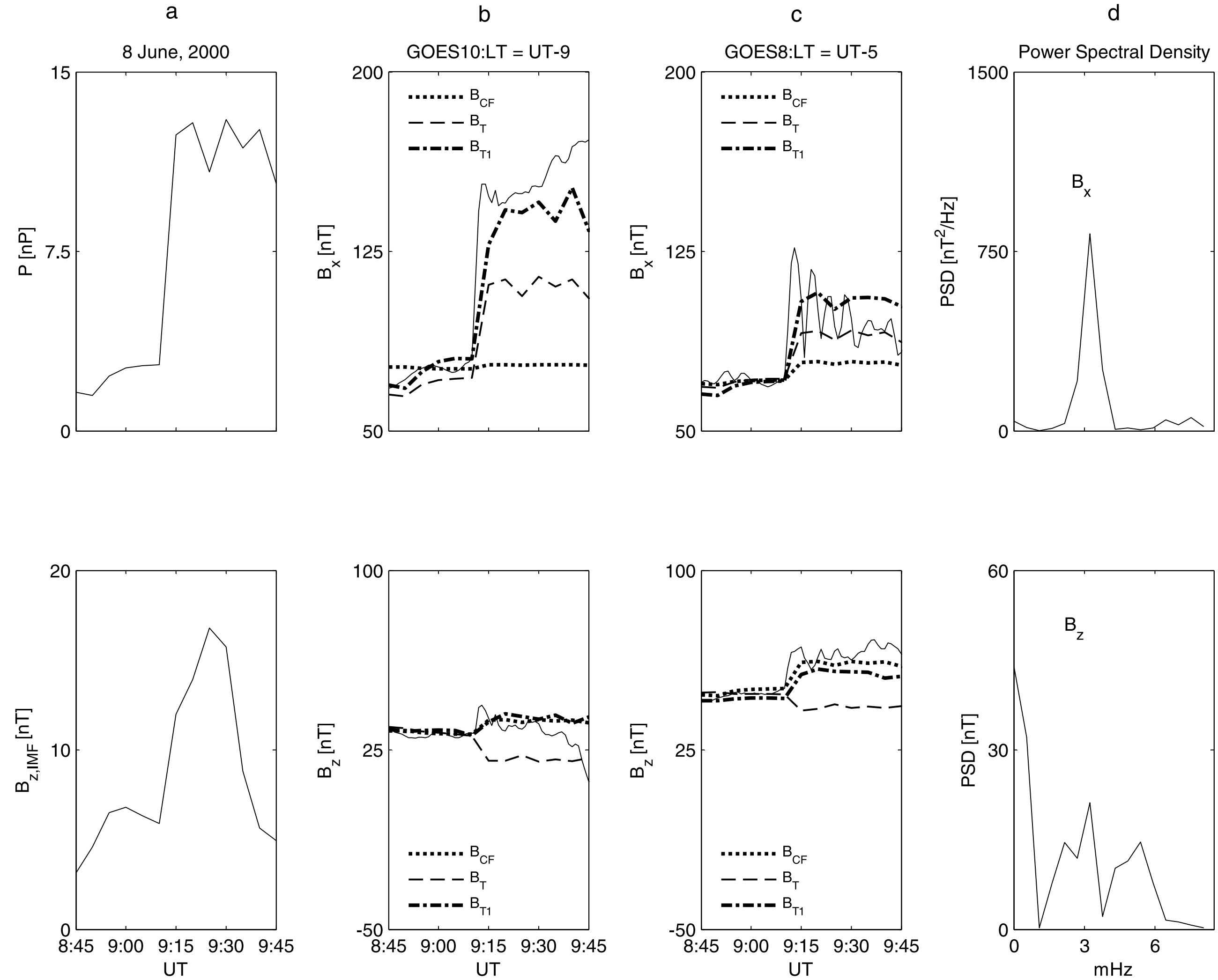


**Figure 8.** A comparison between experimental observations and theoretical models. (a) The external SW conditions are represented in terms of P and $B_{z,IMF}$; (b) the behavior of $B_x$ and $B_z$ component at GOES 10; (c) the behavior of $B_x$ and $B_z$ component at GOES 8; the dotted line represents the $B_{CF}$ field; the dashed line represents the $B_T$ field; the dash–dotted line represents the $B_{T1}$ field, in which a ≈10% smaller hinging distance and a ≈30% thinner current sheet are assumed; (d) power spectra of the field components at GOES 8.

response in the midnight sector (event A in Figure 2) as a direct consequence of the enhanced tail current. Interestingly, the $B_{T1}$ traces qualitatively interpret the average changes of the field elements also at dawn position (GOES 8; ≈04:15 LT, panel c). However, the most striking aspect is here represented by the onset of large amplitude, almost monochromatic waves at ≈3.2 mHz (panel d) which persist for several cycles in the $B_x$ component (and $B_y$, not shown). The large SW velocity (≈790 km/s) might suggest a generation process related to the Kelvin-Helmholtz instability at the dawn flank of the magnetopause. Interestingly, moreover, the observed frequency attains to the set of "discrete" frequencies extensively detected in ground observations and tentatively interpreted in terms of global cavity/waveguide modes of the entire magnetosphere (f ≈ 1.3, 1.9, 2.6–2.7 and 3.2–3.4, 4.0–4.2 mHz [*Samson et al.*, 1991, 1992; *Walker et al.*, 1992; *Ziesolleck and McDiarmid*, 1994; *Mathie et al.*, 1999; *Villante et al.*, 2001]).

## 3. Discussion

[16] SI are important for several aspects of Solar-Terrestrial Physics and Space Weather such as the acceleration and transport of energetic particles, the onset and development of magnetospheric storms, etc. Accordingly, the magnetospheric response has been subject to a large number of investigations using a variety of data sets and technique. In the present paper we propose a new approach to the analysis of the magnetospheric response to sudden variations of the SW pressure that consists in examining the correspondence between the field jumps detected in different LT sectors at geostationary orbit and those expected for transitions between two states of the magnetosphere. Our results reveal

that a realistic parameterization of the different current contributions, as determined by empirical models, provides a good representation of the experimental measurements. On the other hand, a definite interpretation of the major aspects related with the SI manifestation in the magnetosphere might also be useful for a better understanding of the additional ionospheric processes which determine the aspects of the SI manifestation at ground (the separation between preliminary impulse and main impulse, their latitudinal and LT dependence, etc. [*Araki*, 1994]).

[17] The results of the present analysis confirm [*Kokubun*, 1983; *Kuwashima and Fukunishi*, 1985; *Borodkova et al.*, 2005] an explicit LT dependence of the magnetospheric response at geosynchronous orbit, with greater values at satellites located closer to noon meridian and peak values of $\approx$29.5 nT/(nPa)$^{1/2}$. *Russell et al.* [1992] who examined ground SI at geomagnetic latitudes between $\approx 15°-30°$ proposed noon peak values of $\approx$18.5 nT/(nPa)$^{1/2}$. It leads to estimate, for the present case, an average relative amplitude (i.e., the geosynchronous response normalized to the ground response at low latitudes) of $\approx$1.6, which appears consistent with previous findings ($\approx$1.5–1.8 [*Kokubun*, 1983]). On the other hand, a large spread of individual values is typically detected in each time sector. In addition to the occurrence of events related to extreme jumps of the SW pressure, enhanced tail currents, and to the possible erosion of the magnetospheric field caused by Southward orientations of the IMF, this aspect might be partially interpreted in terms of the variable tilt angle: indeed, the results of a numerical simulation shows that the variability of the $\psi$ angle through the year might provide a seasonal modulation of $\approx$20% in the response of the $B_z$ component as well as explicit contributions of the $B_x$ component. In addition, we speculate that other elements (such as the orientation of the shock front and the position of the observing spacecraft with respect to the impact point at the magnetopause) may be important in determining the amplitude of the observed responses.

[18] In the dayside hemisphere the magnetopause current (and the magnetospheric field) suddenly responds to rapid changes of the SW pressure. This is an interesting aspect if we consider that a time interval of the order of $\approx$5 min is usually assumed as the minimal timescale for the magnetosphere to respond to changes in the external SW pressure [*Araki*, 1994; *Collier et al.*, 1998; *Huttunen et al.*, 2005; *Tsyganenko*, 2002b]. By contrast, the effects of the additional current systems (even in presence of a moderate southward component of the IMF) do not influence so rapidly (or so significantly) the dayside magnetospheric field at geosynchronous orbit: it suggests that the onset and development of the additional currents, and the propagation of their effects to the dayside magnetosphere might easily imply significant delay times with respect to the sudden manifestation of the changes of the magnetopause current.

[19] In the nightside sector the role of the additional current systems is obviously much more explicit and manifests more rapidly than in the dayside sector; however, during quiet conditions (i.e., before the events) the magnetospheric field elements are, in general, satisfactorily reproduced in terms of the magnetopause current alone also in the nightside sector. The large variety of the observed responses reflects, in our opinion, the variable relative importance of the current systems (in terms of their onset, amplitude, position, etc...) which compete in determining the magnetospheric response; consequently, in the nightside region, a definite prediction of the field changes is much more difficult than in the dayside region. On the other hand, this aspect was already pointed out by *Tsyganenko* [2002b] who remarked that the predictability of variations of the field elements associated with substorm events is typically much poorer than the more accurate matching of the field variations associated with dayside compression. Consistently, different situations emerge in the dark sector. Indeed, we found a case in which an extreme magnetospheric compression determined field variations which can be interpreted in terms of a strongly dominant contribution of the magnetopause current even in the midnight sector. On the other hand, an explicit correspondence between SI observations in the nightside hemisphere and external SW pressure changes was already remarked by *Villante and Di Giuseppe* [2004], who examined the geomagnetic field observations at low and middle latitudes during a time interval characterized by a significant SW pressure change and identified in the dusk and night sectors a correlation between interplanetary and ground measurements much better than in other sectors. In other cases the observed features are better consistent with the predictions of the global current system and the external conditions (and, in particular, the IMF orientation) may occasionally drive changes in the tail configuration and dynamics (for example in terms of the position of the hinging point and on the thickness of the plasma sheet) which significantly influence the magnetospheric response. In this sense it is worth noting that *Lee et al.* [2005], who examined the geosynchronous energetic particle response to solar wind pressure enhancements, suggested that, during northward IMF conditions, simple compression effects are observed in the dayside and nightside, while, during southward IMF conditions, a dipolarization of the geomagnetic field associated with current wedge formation is observed on the nightside and a simple compression is detected on the dayside. On the other hand *Pulkkinen* [1991], who modeled a substorm growth phase, provided an essentially time-dependent representation of the tail field, introducing temporally varying changes to the Tsyganenko model such as the thinning of the current sheet.

[20] **Acknowledgments.** The authors thank N.A. Tsyganenko (Institute of Physics, University of Saint-Petersburg, Russia) and A.T.Y. Lui (Johns Hopkins University, Applied Physics Laboratory, Laurel, Maryland) for their useful cooperation. The GOES magnetic field data were provided by H. Singer (National Oceanic and Atmospheric Administration's Space Environment Center, Asheville, NC). The solar wind and magnetic field data of WIND were obtained from the NASA's cdaweb site. This research activity was supported by MIUR and ASI.

[21] Zuyin Pu thanks Larry Lyons and another reviewer for their assistance in evaluating this paper.

## References

Araki, T. (1994), A physical model of the geomagnetic sudden commencement, in *Solar Wind Sources of Magnetospheric Ultra-Low-Frequency Waves*, *Geophys. Monogr. Ser.*, *81*, 183.

Borodkova, N., G. N. Zastenker, M. Riazantseva, and J. D. Richardson (2005), Large and sharp solar wind dynamic pressure variations as a source of geomagnetic field disturbances in the outer magnetosphere (at the geosynchronous orbit), *Planet. Space Sci.*, *53*, 3.

Collier, M. R., J. A. Slavin, R. P. Lepping, K. Ogilvie, A. Szabo, H. Laakso, and S. Taguchi (1998), Multispacecraft observations of sudden impulses in the magnetotail caused by solar wind pressure discontinuities: WIND and IMP 8, *J. Geophys. Res.*, *103*, 17,293.

Fowler, G. J., and C. T. Russell (2001), Geomagnetic field response along the Polar orbit to rapid changes in the solar wind dynamic pressure, *J. Geophys. Res.*, *106*(A9), 18,943.

Huttunen, K. E. J., J. Slavin, M. Collier, H. E. J. Koskinen, A. Szabo, E. Tanskane, A. Balogh, E. Lucek, and H. Rème (2005), Cluster observations of sudden impulses in the magnetotail caused by interplanetary shocks and pressure increases, *Ann. Geophys.*, *23*, 609.

Kokubun, S. (1983), Characteristics of storm sudden commencement at geostationary orbit, *J. Geophys. Res.*, *88*, 10,025.

Kuwashima, M., and H. Fukunishi (1985), SSC-associated magnetic variations at the geosynchronous altitude, *J. Atmos. Sol. Terr. Phys.*, *47*, 451.

Lee, D.-Y., and L. R. Lyons (2004), Geosynchronous magnetic field response to solar wind dynamic pressure pulse, *J. Geophys. Res.*, *109*, A04201, doi:10.1029/2003JA010076.

Lee, D.-Y., L. R. Lyons, and G. D. Reeves (2005), Comparison of geosynchronous energetic particle flux responses to solar wind dynamic pressure enhancements and substorms, *J. Geophys. Res.*, *110*, A09213, doi:10.1029/2005JA011091.

Lui, A. T. Y. (1993), Inferring global characteristics of current sheet from local measurements, *J. Geophys. Res.*, *98*, 13,423.

Mathie, R. A., I. R. Mann, F. W. Menk, and D. Orr (1999), Pc5 ULF pulsations associated with waveguide modes observed with the IMAGE magnetometer array, *J. Geophys. Res.*, *104*, 7025.

Nishida, A. (1978), Geomagnetic diagnosis of the magnetosphere, in *Physics and Chemistry in Space*, vol. 9, Springer, New York.

Patel, V. L., and P. J. Coleman Jr. (1970), Sudden impulses in the magnetosphere observed at synchronous orbit, *J. Geophys. Res.*, *75*, 7255.

Pulkkinen, T. I. (1991), A study of magnetic field and current configurations in the magnetotail at the time of a substorm onset, *Planet. Space Sci.*, *39*, 833.

Rufenach, C. L., J. Schaper, and R. L. McPherron (1992), The quiet geomagnetic field at geosynchronous orbit and its dependence on solar wind dynamic pressure, *J. Geophys. Res.*, *97*, 25.

Russell, C. T., M. Ginskey, S. Petrinec, and G. Le (1992), The effect of solar wind dynamic pressure changes on low and mid-latitude magnetic records, *Geophys. Res. Lett.*, *19*, 1227.

Samson, J. C., R. A. Greenwald, J. M. Ruohoniemi, T. J. Hughes, and D. D. Wallis (1991), Magnetometer and radar observations of MHD cavity modes in the Earth's magnetosphere, *Can. J. Phys.*, *69*, 929.

Samson, J. C., B. G. Harrold, J. M. Ruohoniemi, R. A. Greenwald, and A. D. M. Walker (1992), Field line resonances associated with MHD waveguides in the magnetosphere, *Geophys. Res. Lett.*, *19*, 441.

Smith, E. J., J. A. Slavin, D. G. Sibeck, D. N. Baker, R. D. Zwickl, S.-I. Akasofu, and R. P. Lepping (1986), Solar wind-magnetosphere coupling and the distant Magnetotail, in *Solar Wind-Magnetosphere Coupling*, edited by Y. Kamide and J. A. Slavin, 717 pp., Terra-Reidel, Tokyo.

Thompson, S. M., M. G. Kivelson, K. K. Khurana, R. L. McPherron, J. M. Weygand, A. Balogh, H. Rème, and L. M. Kistler (2005), Dynamic Harris current sheet thickness from Cluster current density and plasma measurements, *J. Geophys. Res.*, *110*, A02212, doi:10.1029/2004JA010714.

Tsyganenko, N. A. (2002a), A model of the near magnetosphere with a dawn-dusk asymmetry: 1. Mathematical structure, *J. Geophys. Res.*, *107*(A8), 1179, doi:10.1029/2001JA000219.

Tsyganenko, N. A. (2002b), A model of the near magnetosphere with a dawn-dusk asymmetry: 2. Parameterization and fitting to observations, *J. Geophys. Res.*, *107*(A8), 1179, doi:10.1029/2001JA000220.

Villante, U., and P. DiGiuseppe (2004), Some aspects of the geomagnetic response to solar wind pressure variations: A case study at low and middle latitudes, *Ann. Geophys.*, *22*, 2053.

Villante, U., P. Francia, and S. Lepidi (2001), Pc5 geomagnetic field fluctuations at discrete frequencies at a low latitude station, *Ann. Geophys.*, *19*, 321.

Walker, A. D. M., J. M. Ruohoniemi, K. B. Baker, R. A. Greenwald, and J. C. Samson (1992), Spatial and temporal behaviour of ULF pulsations observed by the Goose Bay HF radar, *J. Geophys. Res.*, *97*, 12,187.

Ziesolleck, C. W. S., and D. R. McDiarmid (1994), Auroral latitude Pc5 field line resonances: Quantized frequencies, spatial characteristics and diurnal variations, *J. Geophys. Res.*, *99*, 5817–5830.

M. Piersanti and U. Villante, Dipartimento di Fisica, Università and Area di Astrogeofisica, Via Vetoio 6, Coppito (AQ) L'Aquila, 67100, Italy. (umberto.villante@aquila.infn.it; mirko.piersanti@aquila.infn.it)