Ring current space-time inhomogeneities in intense geomagnetic storms

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RESUMEN

El desarrollo de la corriente de anillo parcial durante la fase inicial de una tempestad geomagnética causa una asimetría longitudinal en el campo magnético en la superficie terrestre, en bajas y medias latitudes. Con la finalidad de lograr un mejor entendimiento de las inhomogeneidades espaciales y temporales así producidas, se estudió el comportamiento de la componente horizontal (H) del campo magnético medido por magnetómetros de suelo, para las tempestades geomagnéticas intensas que ocurrieron los días 14-15 de mayo de 1997, 24-25 de septiembre y 18-19 de octubre de 1998, respectivamente, mediante la utilización de gráficos de tipo UT-LT. Los datos fueron tomados a cada minuto, para seis estaciones de baja a media latitud con una distribución longitudinal aproximadamente uniforme. Siguiendo los pasos usados para la preparación del índice simétrico introducido por Iyemori (Dst), se calcularon los perfiles locales de la componente H del campo geomagnético y se construyeron mapas de contorno, para cada una de las tempestades analizadas. Contornos con reducción del campo geomagnético, centrados en el atardecer, se asocian con la existencia de una corriente de anillo parcial, en tanto que contornos con un incremento del campo magnético observados en la proximidad de la media noche se interpretan como debidos a la corriente de expansión de subtempestades geomagnéticas. Los mapas de contorno UT-LT son también comparados con los índices geomagnéticos, parámetros del viento solar y campo magnético interplanetario.

PALABRAS CLAVE: Anillo de corriente, tormenta geomagnética, UT-UL graphs.

ABSTRACT

Partial ring currents during the main phase of a geomagnetic storm cause a longitudinal asymmetry in the magnetic field at the earth's surface at low and mid latitudes. The horizontal component of the magnetic field obtained by ground magnetometers (H), for the magnetic storms on May 14-15, 1997, September 24-25, 1998 and October 18-19, 1998, was studied by means of UT LT diagrams at six magnetic observatories, with approximately uniform longitudinal distribution. Following the same steps used to generate Iyemori's symmetric index (Dst), local time minute by minute profiles of the H-component were obtained for each magnetic storm. An asymmetric disturbance associated with the presence of a partial ring current is identified in the UT-LT maps as contours of depleted magnitude in the H-component, centered around dusk. Increased H-magnitude around midnight is attributed to the substorm expansion current. The UT-LT maps are compared to geomagnetic indices, solar wind parameters and interplanetary magnetic fields.

KEY WORDS: Ring current, geomagnetic storm, UT-UL diagrams.

INTRODUCTION

The global strength of the ring current can be monitored on a worldwide network of ground-based magnetometers. The Dst index constructed from mid-latitude ground stations gives a primary measure of intensity of a geomagnetic storm, as an enhancement of the ring current. The characteristic signature of a magnetic storm is a depression in the Dst index as a result of the decrease in the field at the surface of the Earth (Kamide *et al.*, 1998).

The development of magnetic storms including the energy content on the ring current and the coupling to the solar wind has been successfully modeled in the past as a nonlinear input output system, with the solar wind VBz as the input and Dst as the output (Takahashi *et al.*, 1990; Gonzalez *et al.*, 1994; Clúa de Gonzalez *et al.*, 1998), where V is the x-component of the solar wind velocity and Bz is the z-component of the solar wind magnetic field. The solar wind-magnetosphere coupling is enhanced when the interplanetary magnetic field (IMF) convected by the solar wind to the dayside magnetosphere, is southward for several hours (Gonzalez *et al.*, 1994). This enhanced coupling may energize the magnetosphere-ionosphere system leading to an intensified ring current and a magnetic storm (Valdivia *et al.*,1999). This enhancement can be characterized by the variations of the horizontal component of the magnetic field at mid and low latitude ground stations.

Many authors (see *i.e.* Clauer and McPherron, 1980; Takahashi *et al.*, 1991; Grafe *et al.*, 1997) have extensively discussed the existence of longitudinal asymmetry in the geomagnetic disturbance field at low and mid-latitudes during magnetic storms. It is suggested that the asymmetric disturbance overlaps the symmetric field depression attributed to the presence of a symmetric ring current. The asymmetric development of the ring current is related to the main phase of a geomagnetic storm, with the greatest magnetic perturbation occurring in the dusk and evening sectors (Iyemori and Rao, 1996; Ebihara and Ejiri, 2000) being connected through field aligned currents to the auroral electrojet (Friedrich *et al.*, 1999; Takahashi *et al.*, 1991). During the recovery phase of the storm, the asymmetric component of the disturbance decays rapidly while the remaining symmetric magnetic depression decays in a time scale of several days.

Ground observations of magnetic perturbations can be used to study the spatial and temporal development of magnetospheric disturbances, provided that the magnetic effects of the quiet time ionospheric currents (Sq) can be removed from the data. Clauer *et al.* (1980) have described the degree to which the quiet mid-latitude field can be removed from magnetic data to isolate disturbances of presumable magnetospheric origin.

The goal of the present paper is to study the possible formation of the partial ring current for three very intense geomagnetic storms that occurred in 1997 and 1998, by using the universal time-local time (UT-LT) map displays described by Clauer and McPherron (1974, 1980). These maps give the variation of the geomagnetic disturbance as a function of time (UT) and space (LT), and show at once the space-time variations of the geomagnetic disturbance, allowing one to identify the possible existence of the partial ring current. The partial ring current is associated to nested con-

tours of depressed field near dusk. On the other hand, substorms are associated with nested contours of enhanced field near local midnight.

ANALYSIS TECHNIQUE

The present analysis was based on the geomagnetic observations from six stations selected on basis to an homogeneous longitudinal distribution a worldwide configuration, being some of them currently used in the derivation of the geomagnetic Dst index (see Iyemori, 1990, and the booklets of the Data Analysis Center for Geomagnetism and Space Magnetism of the Kyoto University). These stations are listed in Table 1 along with the respective geographic and geomagnetic coordinates. Three events, characterized as very intense storms, were selected for the years 1997 through 1998, due to previous indication of partial ring current formation for them. The storms are May 14-15, 1997 (event I); September 24-25 (event II); October 18-19, 1998 (event III). For reasons of briefness only the results obtained for events I and III will be reproduced, although a completely similar analysis has been also done for event II.

For each of the studied events, the following steps were adopted. In first place, 1-min values of the horizontal component of the geomagnetic field were considered. Then, the 1-min averages of the horizontal components for the five most quiet days in the month were subtracted from the original data, in order to have the 1-min disturbed values, for each station. Figure 1a shows the one minute values of these differences in the horizontal geomagnetic field (in nT) for the six considered magnetic stations (see Table 1); during event I (May, 14-16, 1997). The vertical dashed lines show the specific times designated as P, A, and B in Figure 2a. Similarly, Figure 1b shows the disturbance for event III (October, 18-20, 1998), with the selected times P, A and B given in Figure 2b.

Table 1

Geographic and Geomagnetic coordinates of mid-to low-latitude observatories

Station name	ABB Code	Geographic Latitude	Geographic Longitude	Geomagnetic Latitude	Geomagnetic Longitude	Magnetic Local Time (*)
Alibag	ABG	18.6	72.9	9.9	145.8	18:55
Kakioka	KAK	36.2	140.2	26.6	207.8	15:04
Honolulu	HON	21.3	202.0	21.5	268.6	11:08
Boulder	BOU	40.1	254.8	48.7	319.0	07:21
San Juan	SJG	18.4	293.9	29.1	5.2	04.12
Hermanus	HER	-34.4	19.2	-33.7	82.7	23:48

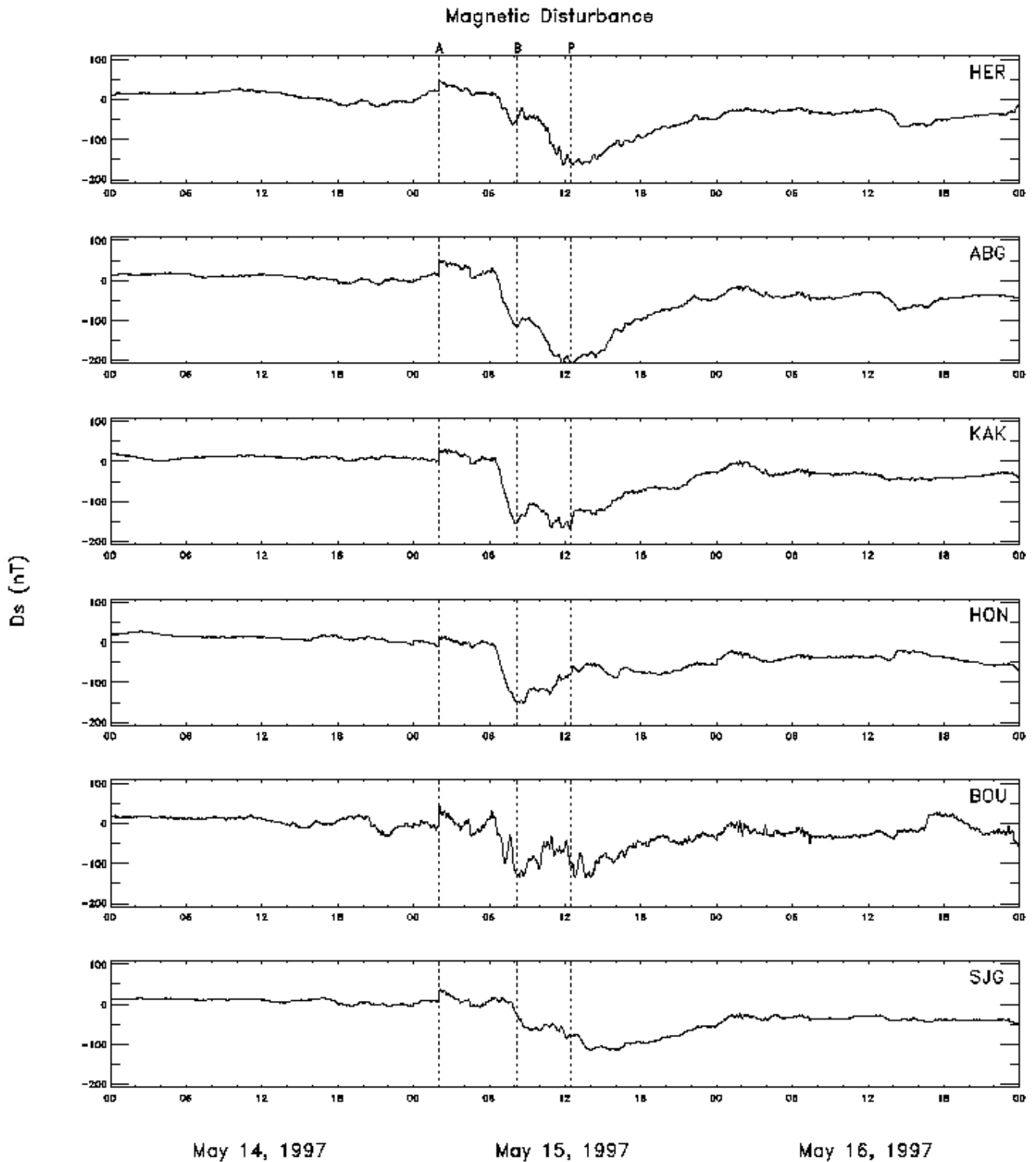(*) From: http://nssdc.gsfc.nasa.gov/space/cgm/cgm.html

Fig. 1a. The six plots give respectively the disturbance in the horizontal geomagnetic-field component for each of the six observatories listed in Table I, during the intense storm of May 14-15, 1997 (event I). These curves are obtained by subtracting the 1-min mean for the 5 most quiet days in the month, from observed value of the horizontal component at each observatory.
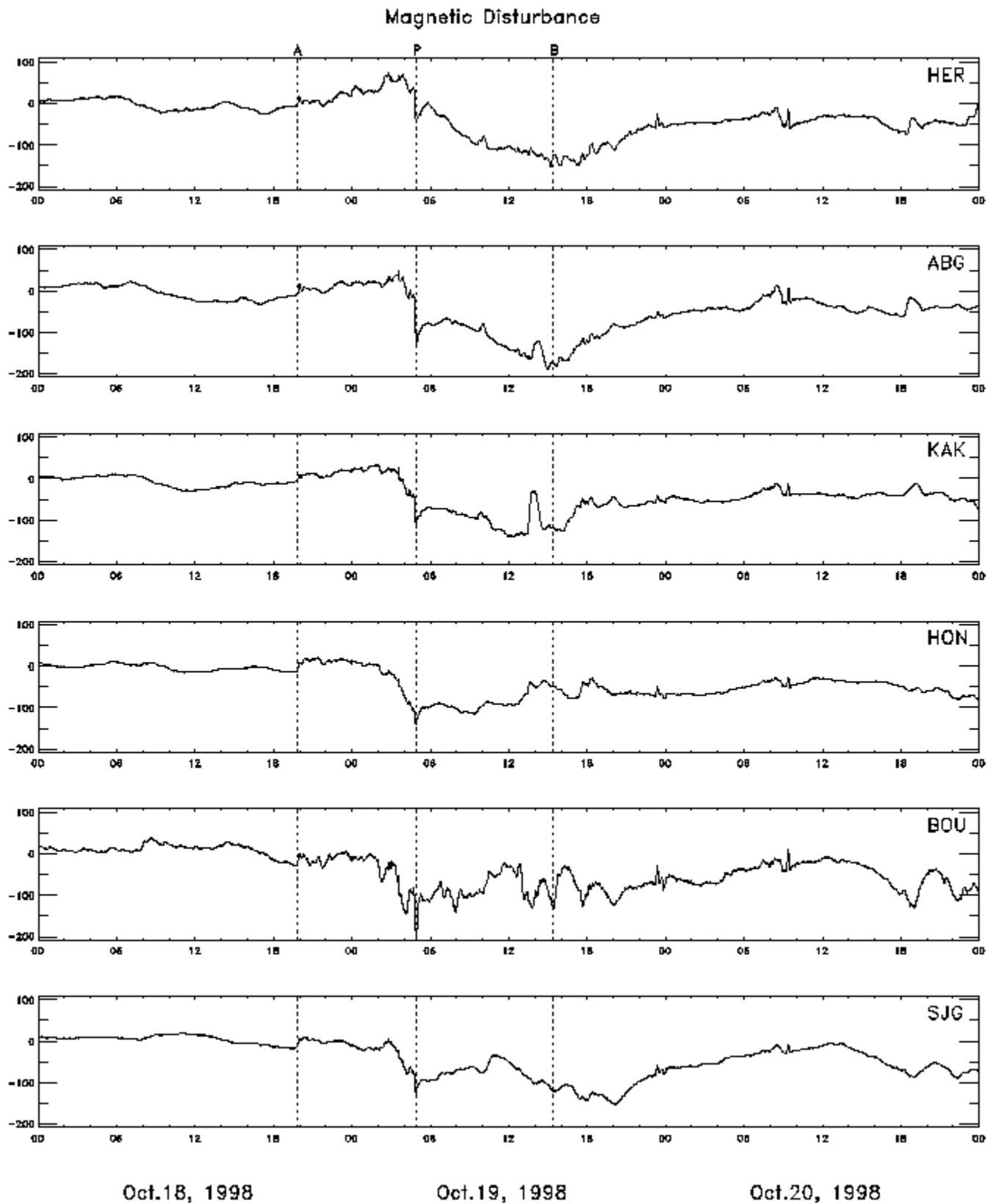
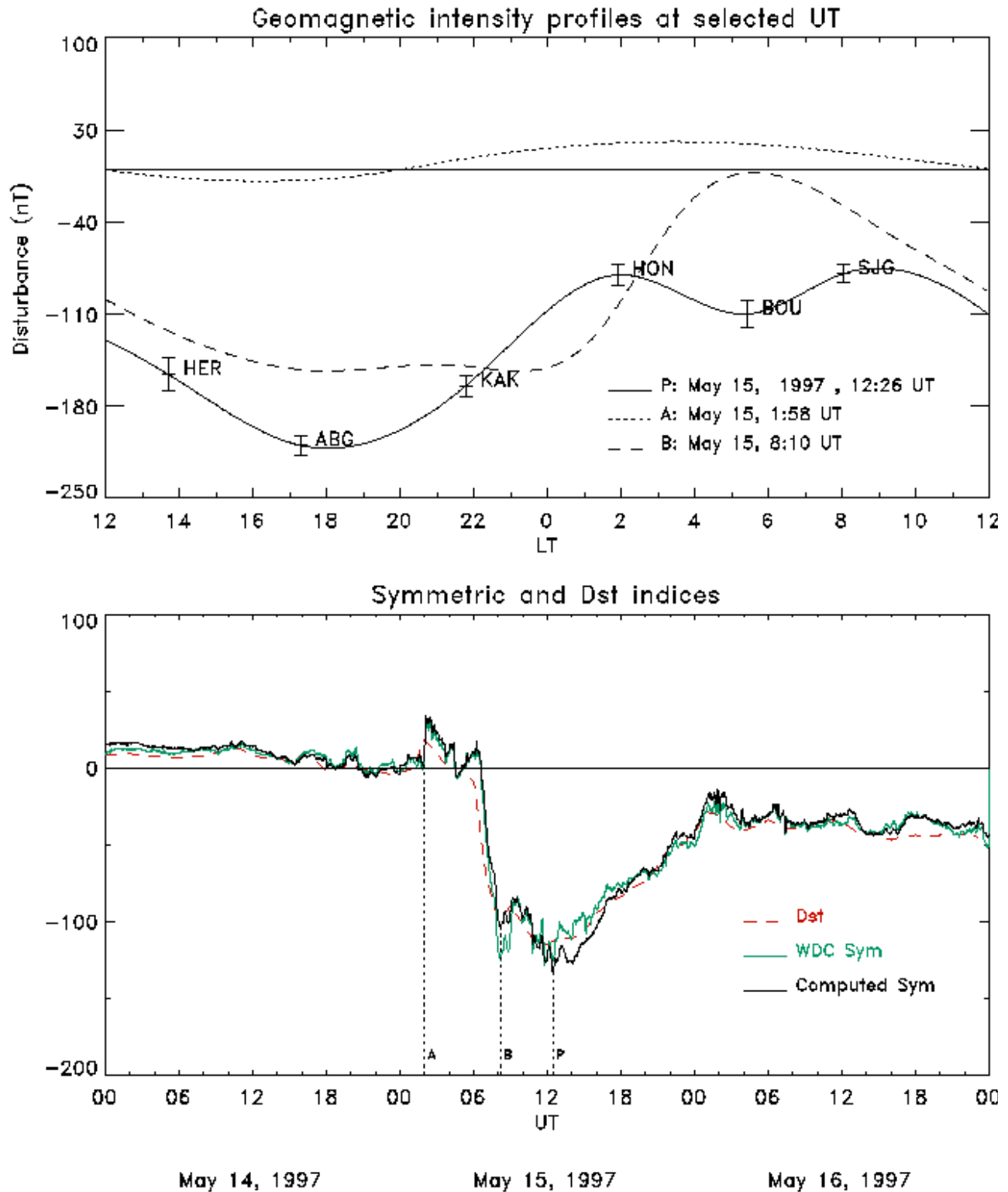Fig. 1b. Similar to Figure 1a, for the intense storm of October 18-19, 1998 (event III).

Fig. 2a. Top panel. Smoothed curves obtained by a cubic spline of the disturbances in the horizontal magnetic field shown in Figure 1a (event I), for three selected UT values. The solid line, P, corresponds to the time of the peak of the storm (May 15, 1997, 12:26 UT). In this curve, the error bars from the spline fitting at the six selected stations are also given. Curve A (dotted line) corresponds to the storm onset, occurring around 1:58 UT, and curve B (dashed line) to the first peak of the storm, occurring around 8:10 UT. Bottom panel. Gives a comparison among the symmetric indices and the Dst index. The heavy solid line gives the symmetric index defined as the average of the six curves shown in Figure 1a. The light solid line corresponds to the symmetric index reported by the World Data Center and the dashed line to the 1-hour Dst variation (http://swdcdb.kugi.kyoto-u.ac.jp/). The vertical dotted lines indicated the three selected UT values shown on the top panel.
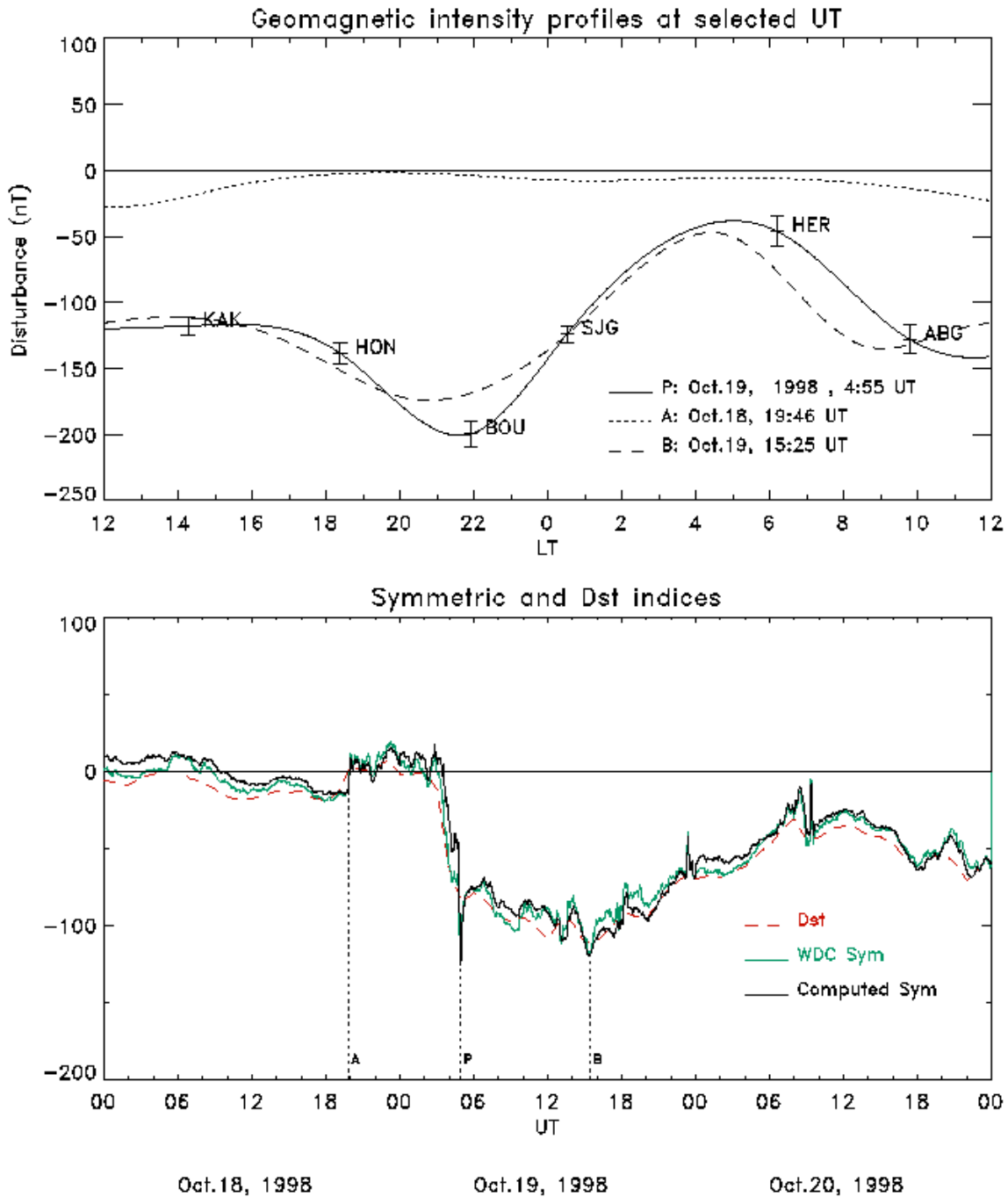
Fig. 2b. Similar to Figure 2a, for event III. The selected UT values, P, A and B, are given on the top panel, and respectively correspond to the peak, the onset and a secondary peak of the storm.

The matrix containing the disturbance of the six stations for each UT minute, would allow one to construct the kind of UT-LT map described by Clauer and McPherron (1980). However, due to the small number of stations considered here, some interpolation needs to be done, in order to obtain a smoother variation in local time. This has been accomplished by interpolating the data at each 6 min of local time using the Spline subroutine of the IDL program, with *sigma*=1.0. In order to keep the circular symmetry in this interpolation, the values corresponding to the stations closest to noon were repeated at both sides of local noon. The top panels of Figures 2a and 2b, show the smoothed curves obtained in this way for the time corresponding to the peak of the storm (designed by P), for the time of the storm

onset (A) and also for the time of a secondary peak (B), for events I and III respectively. The error bars derived from the spline fitting, are also given for the curve corresponding to the peak (solid line).

The horizontal magnetic field disturbances for each of the six stations computed as described above (Figures 1a and 1b), were averaged to obtain a global symmetric index. This is shown by the darker solid line in the bottom panels of Figures 2a and 2b, for events I and III, respectively. This computed index is compared to the symmetric index published by the WDC (Iyemori, 1997, 1998), given by the lighter solid lines, and to the Dst index, shown by the dashed lines. The corresponding UT values for the three selected times P, A and B of the top panels, are indicated by the vertical dotted lines.

The matrices formed by the smoothed geomagnetic disturbance values, are the basis for the construction of the UT-LT maps shown in Figures 3a and 3b, for events I and III, respectively. The darker the color in these maps, the more intense the negative perturbation is, as shown by the adjacent color bars. The selected times P, A and B, are indicated by arrows at the respective UT values.

Figures 4a and 4b show some other variables of interest for events I and III, respectively. The top panels of Figures 4a and 4b give the computed profiles for the variation of the H component for two selected local time: midnight (full line) and dusk (dotted line). The panels give from top to bottom the auroral index, time variation of the ion density, flow speed and the z-component of the interplanetary magnetic field, B_z. The vertical dotted lines mark again the selected times P, A and B, for the peak, the onset and a secondary peak of the storm.

DISCUSSION AND CONCLUSIONS

It is expected (Clauer and McPherron, 1980) that in the UT-LT maps of geomagnetic perturbation, the presence of substorms will appear as nested contours of enhanced fields near local midnight, while partial ring current will appear as nested contours of depressed field near dusk. In the particular events considered in this paper it is possible to conclude the following.

i) Event I (May 14-15, 1997). The large negative perturbations shown around dusk give a strong indication of the formation of a partial ring current, during the main phase of the storm development. There is also an enhancement of the field, in the local morning sector (from midnight thru noon), at the storm onset.

ii) Event II (September 24-25, 1998). There is also a deple-

tion in the magnetic field around dusk, at the peak of the storm. Besides this, an enhancement of the field around midnight is apparent at the storm onset.

iii) Event III (October 18-19, 1998). This storm has a more complex evolution. Therefore, it presents a longer UT extension of the field depletion around dusk. It also presents a field enhancement by local midnight at the storm onset.

From the obtained UT-LT maps, it can be concluded that the three studied events present a strong indication of the formation of partial ring current during the main phase of the storm. Furthermore, they also show geomagnetic field enhancement around local midnight, possibly associated with the presence of substorms, during the storm onset.

Finally, some considerations should be done about the symmetric index computed in this work as compared to the values reported by Iyemori *et al*. (1997, 1998). For event I (May 14-16, 1997), they have used mid-latitude stations: Frederiksburg, Tucson, Honolulu, Memambetsu, Martin de Vivies and Hermanus, averaging a north geomagnetic latitude of 36.4°, which is about 9° higher than the value used here. For event III, they used Boulder instead of Tucson, which gives an average geomagnetic latitude 11° higher than in this work. These differences can explain the small discrepancies between the computed and the WDC symmetric indices, observed in the bottom panels of Figures 2a and 2b. On the other hand, the largest discrepancies are those observed with respect to the Dst index. Indeed, the reason for this is the fact that this index is taken in one-hour intervals. Since the process of averaging the magnetic field disturbance among stations at different local times filters out the local time variation, neither the Dst nor the symmetric indices it would be good indicators for the development of a partial ring current.
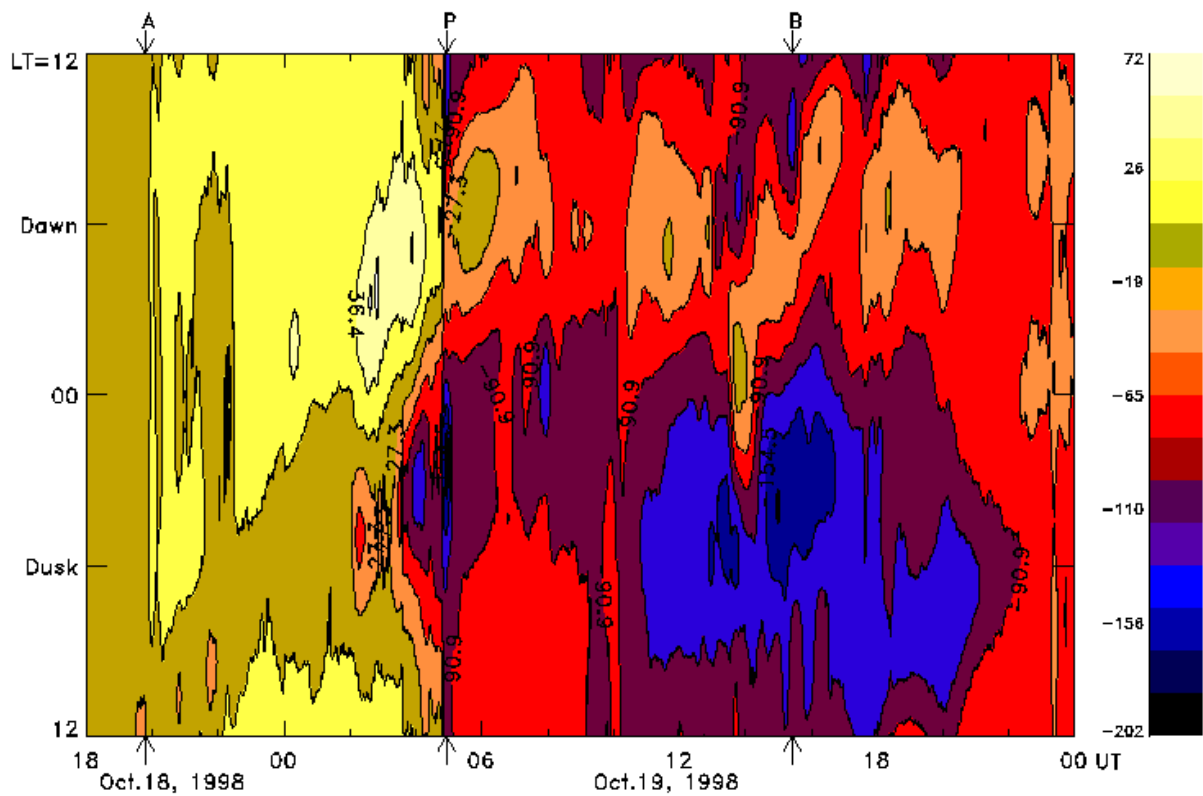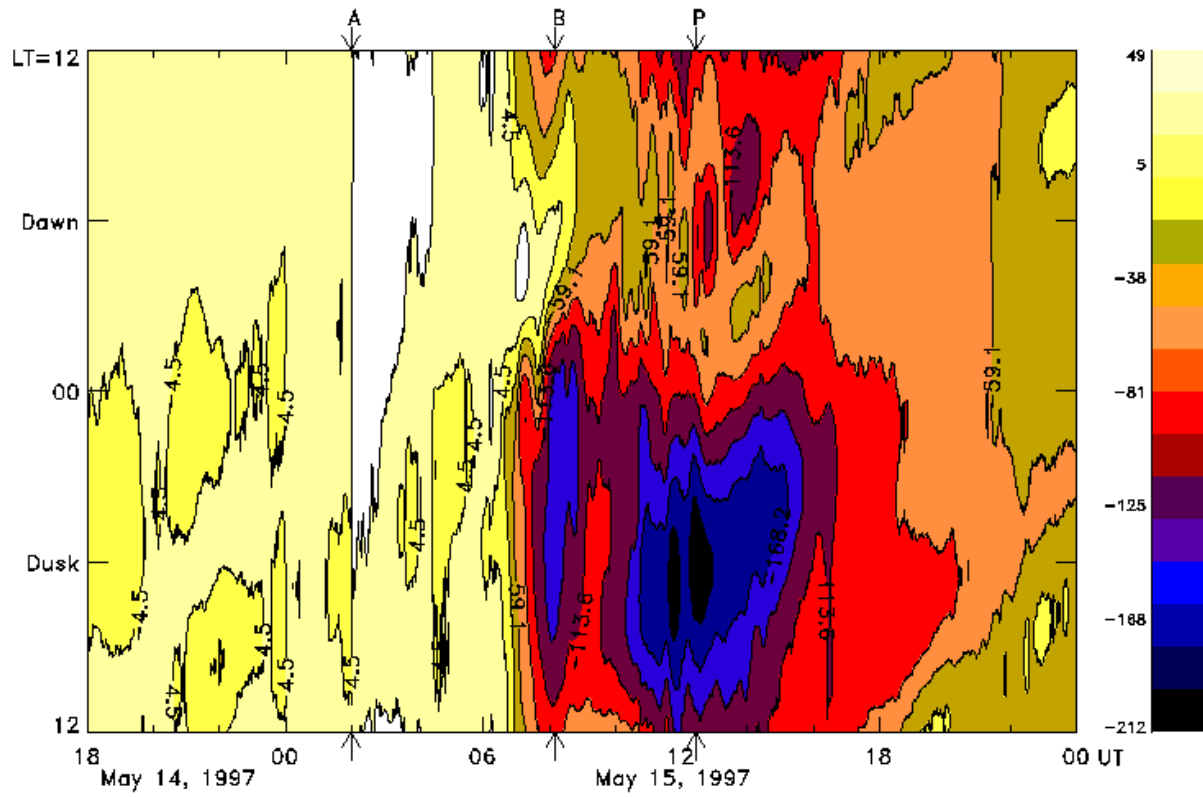
Fig. 3a,b. UT-LT map of the disturbances of the horizontal geomagnetic component, for events I and III respectively. The bars on the right give the color codes. The LT variation of the disturbance (vertical axis) is obtained from smoothed curves like those shown in Figures 2a,b, for each UT minute. The selected UT values referred in Figures 2a and 2b as P, A and B are shown by arrows, in the respective maps.
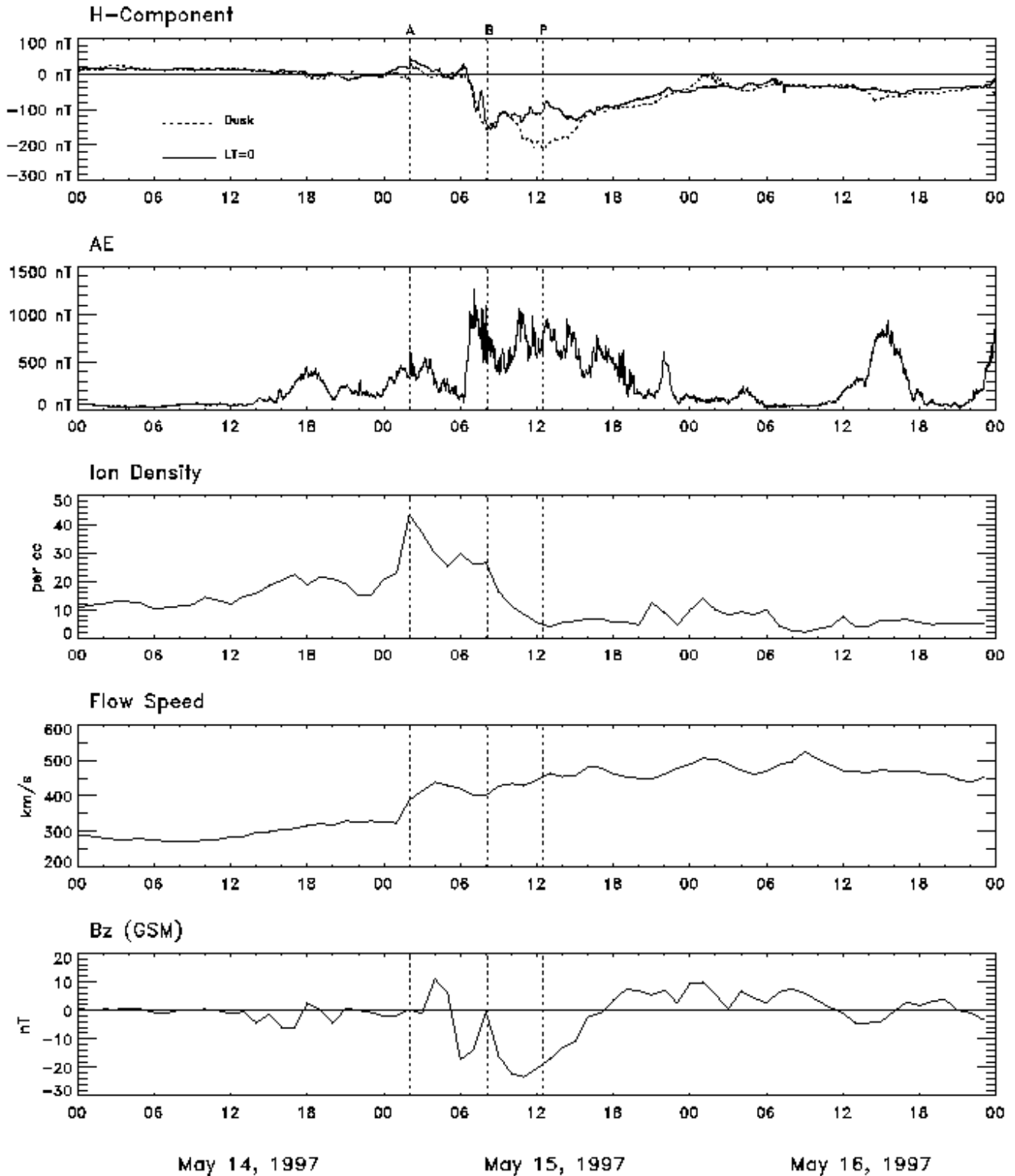
Fig. 4a. UT profiles of some of the variables corresponding to event I. From top to bottom are plotted the computed disturbance observed at two fixed local times, dusk (point line) and midnight (solid line), the auroral index, AE, ion density, flow speed and the south component of the interplanetary magnetic field (http://swdcdb.kugi.kyoto-u.ac.jp/, and http://nssdc.gsfc.nasa.gov/omniweb/). The vertical dotted lines correspond to the selected UT values P, A and B of Figure 2a.
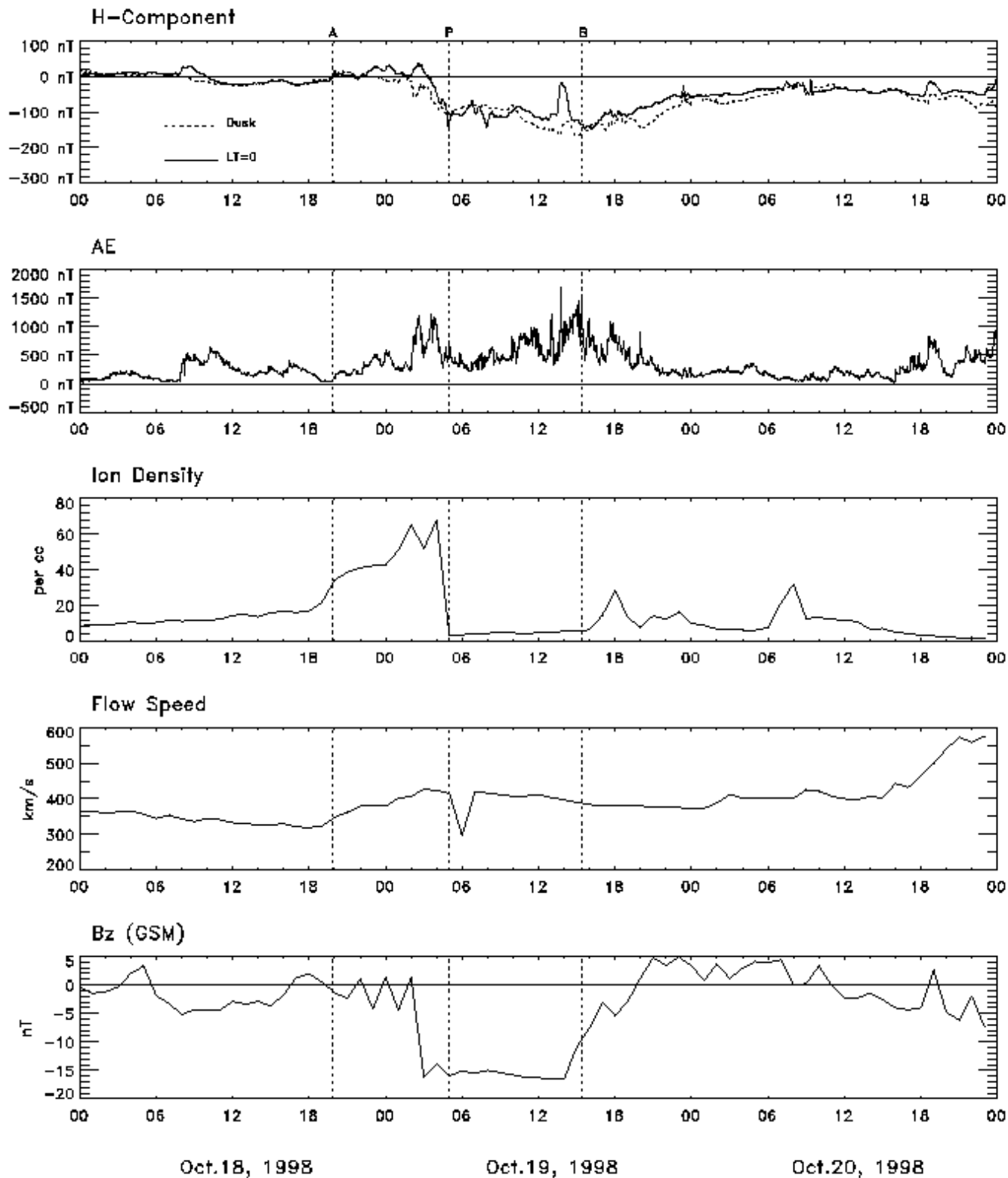
Fig. 4b. Similar to Figure 4a, for event III.

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