Indian Journal of Radio & Space Physics
Vol. 38, October 2009, pp. 245-253

Variations of geomagnetic Dst, auroral indices and cosmic ray intensity during 28-31 Oct 2003 Halloween events

R P Kane

Instituto Nacional de Pesquisas Espacias – INPE, Caixa Postal 515, 12201-970 - São José dos Campos, SP, Brazil
E-mail: kane@dge.inpe.br

Received 11 May 2009; revised 3 September 2009; accepted 7 September 2009

During 28-31 Oct 2003, there was intense interplanetary storm activity (Halloween events). A major storm started at about 0400-0600 hrs UT on 29 Oct 2003, reflected in extreme values of interplanetary parameters and geomagnetic index Dst. While few hours preceding 0400 hrs UT, it was essentially quiet but the auroral indices AL, AU, AE were not quiet and showed moderate increases. Thus, at least for this gigantic super fast storm (velocity of the solar wind disturbance exceeding 2000 kms^{-1}), auroral indices seemed to be precursors with an antecedence of a few hours. This needs to be checked for very strong storms in future, probably after 2010, when cycle 24 sunspot activity will be in full swing.

Keywords: Geomagnetic index variations, Interplanetary storm, Halloween event, Auroral indices, Geomagnetic storm, Cosmic ray intensity

PACS Nos: 91.25.Rt; 96.50.*sh*; 94.30.Lr

1 Introduction

Parker[1] formulated his theory of solar wind and further, Parker[2] and Gold[3] examined its implications for the stretching (extension) of solar magnetic field into the interplanetary space during quiet as well as enhanced solar activities. Soon after, satellite observations confirmed many of those implications and interplanetary structures, with abnormally high values of plasma parameters were found to occur frequently notably after the eruption of solar flares. It was observed that geomagnetic storms occurred when the Earth was engulfed by interplanetary abnormal structures (blobs, clouds, shock fronts), provided these structures had a substantial component of a southward pointing magnetic field component B_z (negative B_z). An explanation for the role of this negative B_z was given by Dungey[4]. If the interplanetary magnetic fields are directed opposite to the Earth's field, there is magnetic erosion on the dayside magnetosphere by magnetic reconnection and magnetic field accumulates in the nightside magnetotail region. The magnetic reconnection in the tail leads to plasma injection towards the Earth in the nightside. KeV electrons precipitate in the high latitudes and cause aurora, while high energy particles of tens of KeV to MeV drift around the Earth (protons to the west, electrons to the east) forming a "ring current" centered near the equator, which causes a reduction in geomagnetic field (storm time disturbance field Dst). This is, of course, a simplified picture.

Geomagnetic activity is represented by several indices. The hourly Dst index[5] is obtained from the superposition of data from magnetometer stations near the equator but not so close that the E-region equatorial electrojet dominates the magnetic perturbations seen on the ground. The stations are roughly 120^o apart in longitude, so that in the superposed data at the same UT, local-time effects get eliminated and only an isotropic component remains. At such latitudes, the H (northward) component of the magnetic perturbation is dominated by the intensity of the magnetospheric ring current. Dst index is a direct measure of the hourly average of this perturbation. Large negative perturbations are indicative of an increase in the intensity of the ring current and typically appear on time scales of a few hours. The recovery may take much longer, of the order of several tens of hours.

The PC-index[6] is a fifteen-minute index for magnetic activity in the (P)olar (C)ap. It aims to monitor the polar cap magnetic field signatures, as transpolar currents respond to changing solar wind conditions including the southward component of the interplanetary magnetic field (IMF), the azimuthal component of the IMF (B_y), the solar wind dynamic pressure and the solar wind velocity V. The PC index correlates best with IMF B_z and B_y and V. However, variations in high solar wind dynamic pressure also produce large changes in the PC index, which varies with the strength of convection, the magnitude and duration of solar wind dynamic pressure and the intensity of auroral currents driven by the magnetic activity. All these effects were present at various times during the Halloween super storms of 29-30 Oct 2003.

AE index is an auroral electrojet index obtained from a number (usually greater than 10) of stations distributed in local time in the latitude region that is typical of the northern hemisphere auroral zone[7]. For each of the stations, the north-south magnetic perturbation H is recorded as a function of universal time. A superposition of the data from all the stations enables a lower bound or maximum negative excursion of the H component to be determined, this is called the AL index. Similarly, an upper bound or maximum positive excursion in H is determined, this is called the AU index. The difference between these two indices, (AU-AL), is called the AE index. Negative H perturbations occur when stations are under a westward-flowing current. Thus, the indices AU and AL give some measure of the individual strengths of the auroral eastward and westward electrojets, while AE provides a measure of the overall horizontal current strength. Magnetic substorms produce excursions in the AE index from a nominal daily baseline, which are called magnetospheric substorms and may have durations of tens of minutes to several hours.

The auroral indices have been under constant scrutiny and Rostoker[8] and Kamide & Rostoker[9] have expressed great apprehensions about their physical meaning, particularly of the AE index. Nevertheless, AU and AL do represent at least roughly two major features, namely, westward and eastward electrojets in the auroral region, while AE is a sort of a rough measure of the total energy input in the auroral region. In the present paper, Dst, AU, AL and AE have been examined in a rough qualitative way during 28-31 Oct 2003 (Halloween events) and compare with interplanetary and cosmic ray (CR) neutron monitor data (FD, Forbush decreases).

2 Data

Interplanetary data (proton number density N, temperature T(N), solar wind speed V, total magnetic field B and its components B_x, B_y, B_z (GSE coordinates), CR data were obtained from NOAA websites (SPIDR, etc.). Data for Dst and the auroral indices were obtained from WDC; for Geomagnetism, Kyoto website (http://swdcwww.kugi.kyoto-u.ac.jp/wdc/Sec3.html). The earlier interplanetary data obtained from satellites going round the Earth were found to be of a rather poor quality. In some major storms, the instruments often failed or became saturated, giving only lower limits for the data values. On 25 August 1997, Advance Composition Explorer (ACE) was successfully launched from Cape Canaveral Air Station by a Delta II rocket. The ACE observatory, a spinning spacecraft (5 rpm), orbits around the Sun-Earth L1 libration point at 240 Re (Earth radii) sunward of the Earth (approximately 1/100 of the distance from the Earth to Sun). The data from this satellite were expected to be of a better quality and were mostly so, but during the severe storm of 28-29 October 2003 (Halloween event), some instruments seem to have failed partially[10]. Data are mainly from the Solar Wind Electron, Proton and Alpha Monitor (SWEPAM) and the Magnetic Field Experiment (MAG). Some data are from the GEOTAIL satellite, which was launched on 24 July 1992 by a Delta II launch vehicle from Cape Canaveral, Florida, USA, primarily to study the structure and dynamics of the tail region of the magnetosphere with a comprehensive set of scientific instruments. GEOTAIL's present orbit is 9 Re × 30 Re with inclination of -7° to the ecliptic plane. Data for this study are used only for the interval when GEOTAIL was in interplanetary space outside the magnetosphere[11].

3 Plots of the hourly values for 28-31 October 2003

Figure 1 shows the plots of hourly values of solar wind parameters during 28-31 October 2003. The full vertical lines mark the 0000 hrs UT of the dates. The storm commenced at about 0400 hrs UT on 29 October 2003 (marked by the small vertical lines) when interplanetary proton number density N (full lines, SWEPAM data; crosses, GEOTAIL data), proton temperature T(N), solar wind speed V and total magnetic field B started rising. Positive values are painted black and negative values are shown hatched. The B_x component had negative values at about 4 hours later (0800 hrs UT on 29 October 2003). The B_y component had small negative values even before 0400 hrs UT, but large negative values started only with large negative B_x (0800 hrs UT on 29 October 2003). The B_z component had small negative values

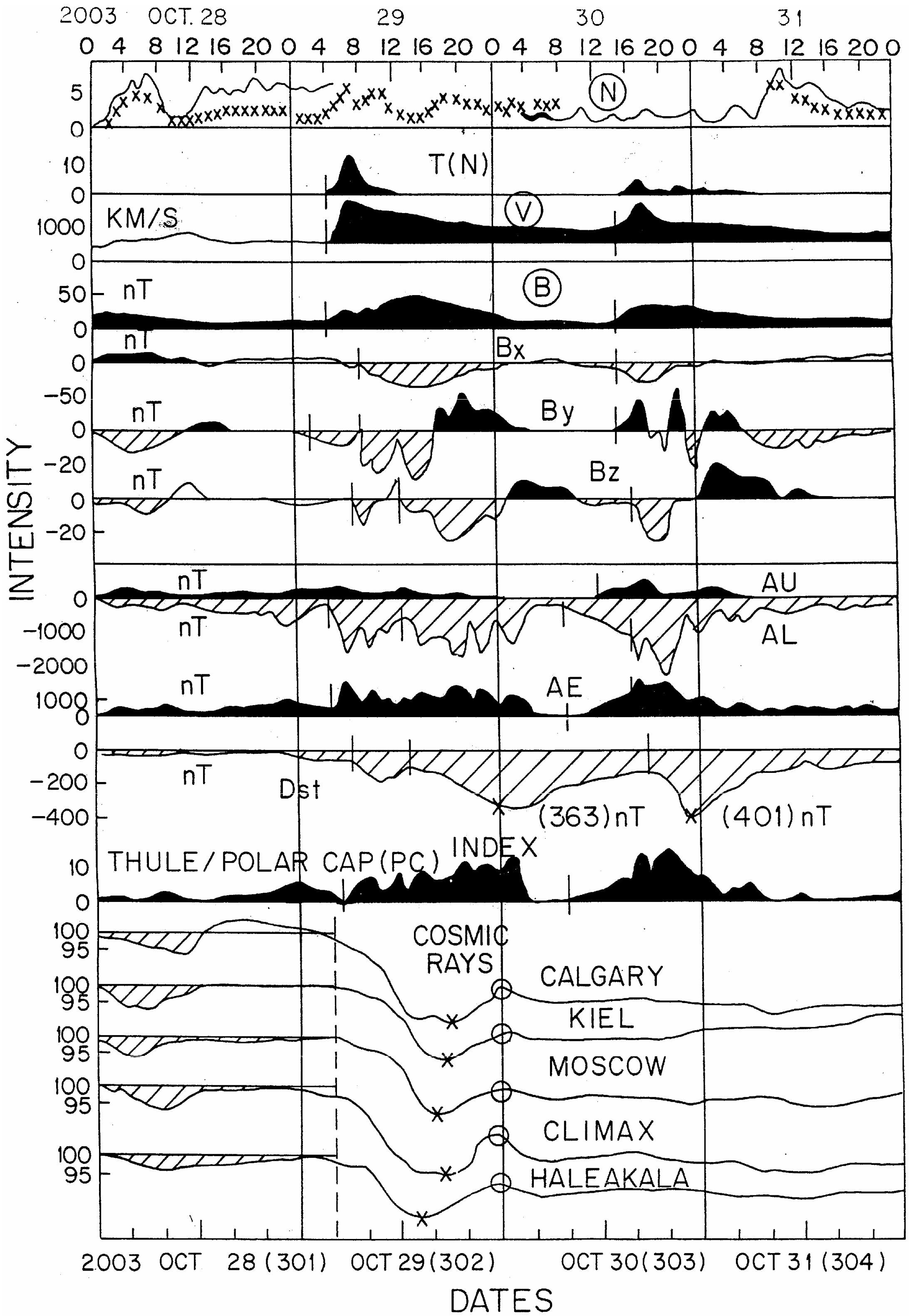

Fig. 1 — Plots of hourly values, during 28-31Oct 2003, of interplanetary proton number density (N), temperature T(N), solar wind speed V, total magnetic field B and its components B_x, B_y, B_z (GSE coordinates), auroral AU, AL, AE, ring current Dst, Thule Polar Cap index PC and cosmic ray (CR) neutron monitors. Full vertical lines mark 0000 hrs UT of each date. Small vertical lines mark beginnings of events. Positive values are painted black and negative values are shown hatched

starting at about 0700 hrs UT on 29 October 2003, but large negative values started only several hours later at about 1300 hrs UT. Thus, the three components B_x, B_y and B_z did not evolve alike. The absolute values of the auroral indices AU, AL, AE started increasing in a major way at about 0400 hrs UT on 29 October 2003 (same as total interplanetary field B), but values were moderately high (AL, AE ~1000 nT) even before 0400 hrs UT on 29 October 2003. The scale in Fig. 1 is very compressed and only values exceeding 1000 nT are seen properly, but an examination of the actual values showed that in the earlier part (0000-1200 hrs UT) on 28 October 2003, B_x and negative B_z values were near about 5 nT. According to Gonzalez *et al.*[12] and Gonzalez & Echer[13], these are quiet day values. The Dst values during this interval were also very low (0-50 nT) as expected. However, with the enhanced auroral indices observed at this time, the contribution of auroral currents to the Dst index cannot be completely ruled out. In the latter part (1200-2400 hrs UT) on 28 October 2003, interplanetary magnetic field data are missing, but the absolute values of Dst were very low (almost zero), so the B_z values should have been very low. Thus, during most of 28 October 2003, the B_z values should have been near about 5 nT, which is commensurate with absolute Dst values 0-50 nT. Therefore, absolute values of auroral indices near 1000 nT before 0400 hrs UT on 29 October 2003 appear abnormally high raising the possibility that they may be precursors of the severe storm that followed. (It may be pointed out that the last week of October 2003 was full of solar activity. So some of it, having leaked in on 28 October 2003 cannot be completely ruled out.) The auroral indices increased considerably several hours later, at ~ 2200 hrs UT on 28 October 2003, then decreased for a few hours, and started a major increase at ~ 0400 hrs UT on 29 October 2003. The Dst index had a small negative excursion coinciding with the small negative values of B_z, and a large negative swing starting at ~1400 hrs UT (same as B_z). On 30 October 2003, there was another storm starting at ~1400 hrs UT, as V, B, B_x and B_y increased but B_z turned negative ~2 hrs later (~1600 hrs UT) and Dst had a negative swing another 2 hrs later (~1800 hrs UT). Thus, all B_z negative excursions initiated Dst negative swings, but the end of negative B_z swings did not result in Dst recovery, for the well known reason that Dst recovery (ring current decay) is unrelated to interplanetary parameters and is guided by the dissipation of ring current particles by a charge exchange process with plasma at lower terrestrial altitudes. However, the relationship of auroral indices (notably AL) with negative B_z is uncertain. When B_z is negative on 29 October 2003, AL is certainly negative but AL is at times negative even before negative B_z starts. The PC (Polar Cap) index at Thule seems to vary similar to AL and AE and was moderately high even before 0400 hrs UT on 29 October 2003.

The lower part of Fig. 1 shows plots for cosmic ray (CR) neutron monitor counts at the mid latitude locations Calgary, Kiel, Moscow, Climax at different longitudes and Haleakala at a low latitude. All show a small decrease in the early part of 28 October 2003, a mild storm probably related to the low values of about 20 nT of the interplanetary magnetic field B. However, in the latter part of 28 October 2003, there was no indication of a CR storm, not even a small one. Later, large CR storm-time decreases (known as Forbush decreases, FD) starting at ~0400 hrs UT on 29 October 2003 coinciding with the increases in interplanetary V, B and B_y but not with B_z. Thus, cosmic ray decreases began at the start of the interplanetary abnormal structure engulfing the Earth, but with no relationship to the B_z component as such, which is known to be intimately related to the Dst changes. CR intensities continued low for the next three days, though interplanetary parameters varied a lot indicating that CR intensities are affected by disturbed interplanetary regions much wider than the near-Earth regions seen by satellites. The small increase in CR intesities near 0000 hrs UT on 30 October 2003, marked by circles, is most probably a solar energetic particle event (SEP) (ref. 14).

4 Plots with high time resolution for shorter time-scales

From Fig. 1, the major storm interval for 29 October 2003 during 0400-2100 hrs UT was selected for plots with high time resolution (4 min in some cases, 15 min in others, according to availability of data). Figure 2 shows the plots for six-hour time intervals at a time, in three successive panels for (a) 0400-0900 hrs UT, (b)1000-1500 hrs UT and (c) 1600-2100 hrs UT on 29 October 2003. In each panel, successive plots are for interplanetary B, B_x, B_y, B_z, polar cap index (PC), auroral AU, AL and AE. Long vertical lines mark 00 min of each hr UT. The following may be noted:

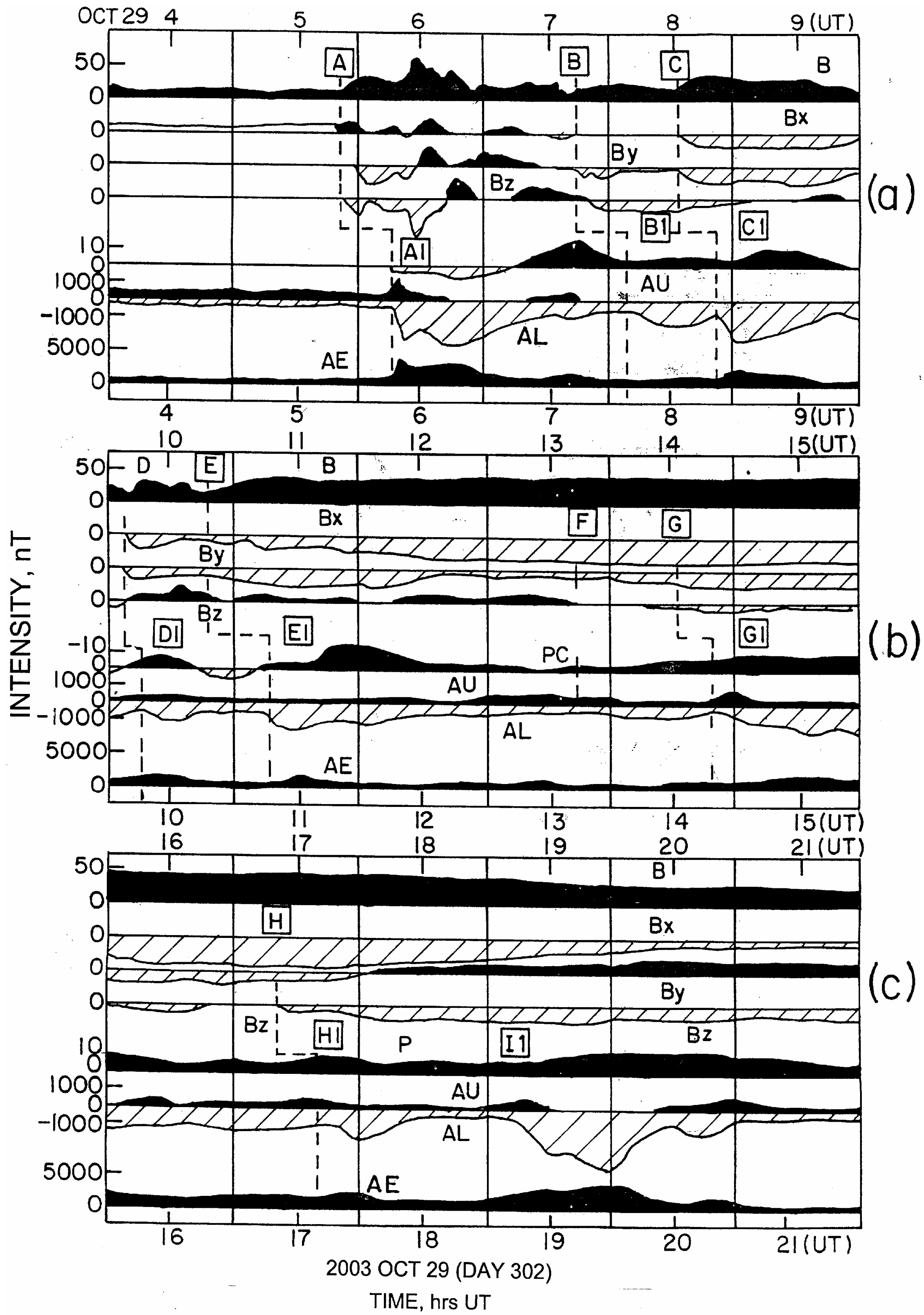

Fig. 2 — Plots for short time-scales (tens of minutes) for 29 Oct 2003: for 0400-0900 hrs UT (top panel), 1000-1500 hrs UT (middle panel), 1600-2100 hrs UT (bottom panel). Full vertical lines mark 0000 hrs UT. Positive values are painted black and negative values are shown hatched. A-I and A1-I1 indicate specific events

(1) In the first (top) panel [Fig. 2(a)], interplanetary parameters show the start of the disturbance at ~0550 hrs UT on 29 October 2003 (small vertical lines, event marked as [A]). Disturbed PC and AU, AL, AE indices started ~25 min later at ~0615 hrs UT on 29 October 2003 (event marked as [A1]). The ACE satellite is upstream of the Earth at approximately 1/100 of the distance from the Earth to the Sun. Light takes about 500 s to reach Earth from the Sun and would take 5 s to cover the ACE-Earth distance. In the present case, the interplanetary solar wind disturbance has a speed of ~2000 kms-1, ~1/150 of the speed of light and hence, would cover the ACE-Earth distance in ~750 s, or 12-13 min. Considering the temporal resolution of the present plots (~± 5 min) and the uncertainty of the solar wind speed (1500-2200 kms-1), the delay of ~25 min seems reasonable (the data are not corrected for 1 AU).

(2) The PC index went slightly negative for ~1/2 hrs and then became positive and increased and oscillated for the next 3 hrs. The IMF Bz component had a negative swing for ~50 min, a positive swing of ~65 min, a negative swing of ~65 min and then a quiet interval of ~70 min (during the total of ~4 hrs, 0600-0900 hrs UT on 29 October 2003). These could be the DP2 sub-storm patterns15. If so, these are not reproduced as such in the AL index (AU values are very small as compared to the AL values, thus indicating that the westward auroral electrojet was more prominent than the eastward auroral electrojet). The AL index was large negative when Bz was negative, but AL continued to be large negative even when Bz stopped remaining negative and even turned positive. Thus, electrojet particles do not decay immediately after their injection through the negative Bz value. In the Dst ring current, the particles decay is very long, several tens of hours, mainly because the decay is in a very low density region and depends upon collisions (charge exchange) with particles in this region. In the case of the ionosphere, solar flare effects (SFE) causing enhancements in the ion density are known to occur on time-scales of minutes and last for several tens of minutes.

(3) A second storm was initiated at ~0745 hrs UT on 29 October 2003 (small vertical lines, event marked as [B]). Disturbed PC and AU, AL, AE indices started ~25 min later at ~0810 hrs UT (event marked as [B1]). This event seems to have intensified later at ~0830 hrs UT (event marked [C]) with B increasing mainly because Bx and By attained large negative values. Notably, Bz, which was already negative started approaching zero. Since PC, AL, AE had large increases a few tens of minutes later (event marked as [C1]), it suggests a good relationship with Bx, By and geomagnetic indices in the absence of negative Bz.

In the second (middle) panel [Fig. 2(b)], there seems to be a new but short-lived event at ~1010 hrs UT on 29 October 2003 (event marked as [D]), which produced increases of PC, AL, AE a few minutes later (event marked as [D1]). However, a major event started at ~1045 hrs UT on 29 October 2003 (event marked as [E]) with B increasing mainly because B_x and B_y attained large negative values, while B_z was almost zero. The PC, AL and AE had large increases ~30 min later (event marked as [E1]), again indicating a good relationship with B_x, B_y in the absence of negative B_z. During the next few hours (1100-1500 hrs UT on 29 October 2003), B and B_x were uniformly high, but B_y (negative) had reduced to almost zero by ~1310 hrs UT and started increasing again (event marked as [F]). The PC increased simultaneously but AL did not have any significant change. On the other hand, later at ~1445 hrs UT on 29 October 2003, AL and AE indices had large increases (event marked as [G1]), which may be related to a change in B_x (event marked as [G]). Thus, B_x and/or B_y seem to have an influence on the auroral indices in the absence of negative B_z.

In the third (bottom) panel [Fig. 2(c)], during 1600-1700 hrs UT on 29 October 2003, B, B_x, B_y had large values and AL, AE also had moderately high values, but B_z had a major negative change at ~1720 hrs UT on 29 October 2003 (event marked as [H]) associated with changes in PC, AL, AE ~20 minutes later ((event marked as [H1]). However, later at ~1905 hrs UT, a very large change occurred in AL and AE (event marked as [I1]), which occurred when B, B_x, B_y, B_z were already high but without any striking alterations. Thus, the source of this abnormal increase in auroral indices in the beginning of 1900 hrs UT on 29 October 2003 remains obscure.

In Fig. 1, the early part of 30 October 2003 was relatively quiet and a major storm commenced only at

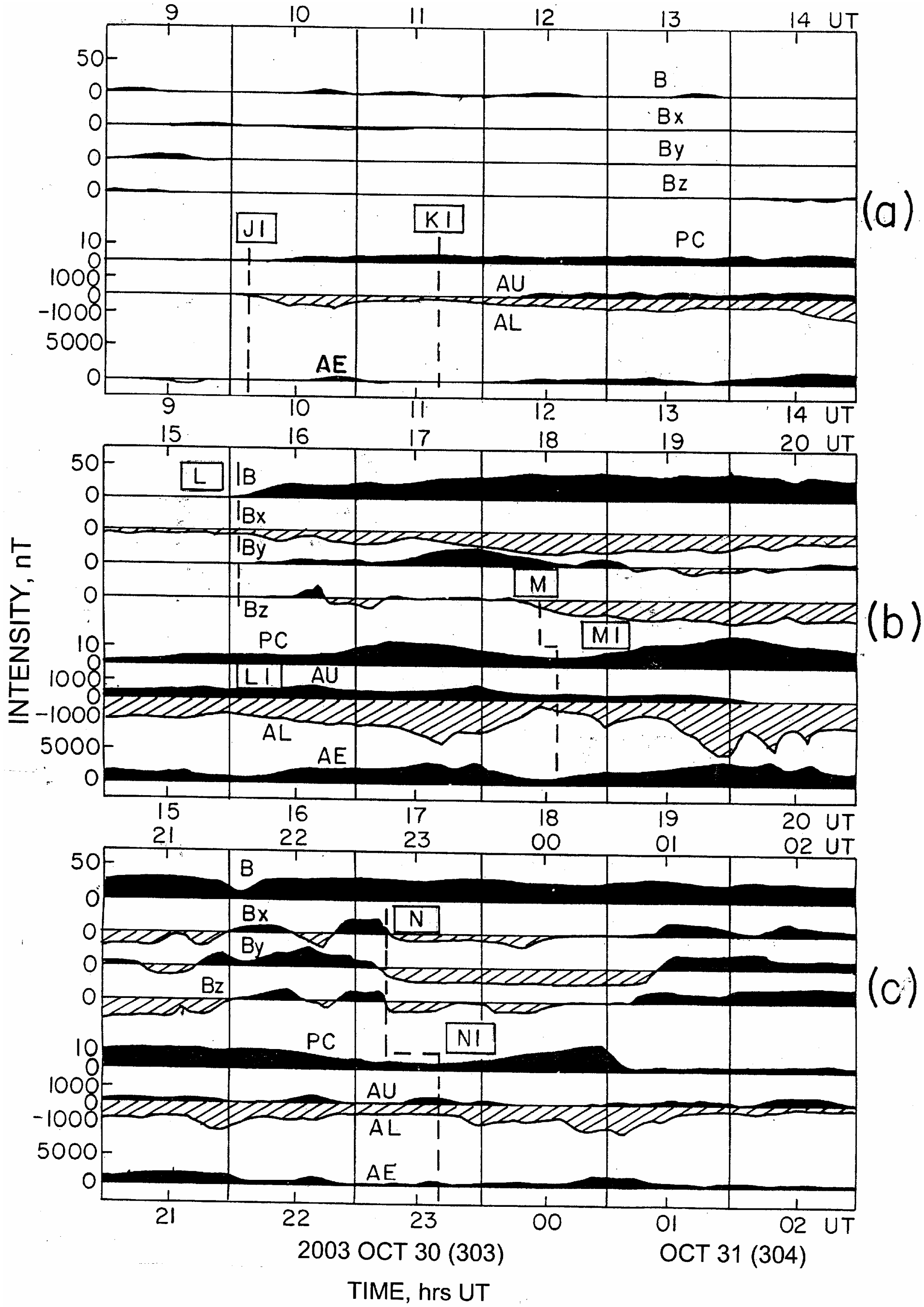

Fig. 3 — Plots for short time-scales (tens of minutes) for 30-31 Oct 2003, for 0900-1400 hrs UT (top panel), 1500-2000 hrs UT (middle panel), 2100-0200 hrs UT (bottom panel). Full vertical lines mark 0000 hrs UT. Positive values are painted black and negative values are shown hatched. A-I and A1-I1 etc. indicate specific events

~1500 hrs UT. In order to highlight the salient features observed in the interplanetary parameters and simultaneous changes in the auroral indices during the period 0900-2400 hrs UT on 30 October 2003 and 0000-0200 hrs UT on 31 October 2003, Fig. 3 shows the plots for six-hour intervals at a time, on expanded time-scales, in three successive panels (top, middle, bottom) for 30 October 2003 during 0900-1400, 1500-2000, 2100-2300 hrs UT and 31 October 2003 during 0000-0200 hrs UT. As in Fig. 2, in each panel, successive plots are for interplanetary B, B_x, B_y, B_z, polar cap index PC, auroral AU, AL, and auroral AE. Long vertical lines mark 00 minutes of each UT hr. The following may be noted:

(1) During 30 October 2003, 0900-1500 hrs UT, interplanetary B, B_x, B_y, B_z had very small values. But as seen in the first (top) panel [Fig. 3(a)], PC values started increasing at ~1010 hrs UT (event marked as [J1]). The AL, AE also had small deviations. Later, at ~1140 hrs UT, AL, AE started a moderate increase (event marked as [K1]), for which there were no equivalent changes in B, B_x, B_y, B_z. Thus, changes of ~1000 nT in AL could occur in the absence of interplanetary IMF triggers.

(2) In the second (middle) panel [Fig. 3(b)], disturbed values of IMF B and B_x started at ~1605 hrs UT on 30 October 2003 (event marked as [L]), and for B_y and B_z in a small way, ~20 min later. The PC, AL, AE, which were already high continued to increase further (event marked as [L1]), though B_z changes were very small. Later, at ~1830 hrs UT of 30 October 2003, B_z turned negative (event marked as [M]), and PC, AL, AE started large changes a few minutes later (event marked as [M1]).

(3) In the third (bottom) panel [Fig. 3(c)], B was high throughout, but B_x, B_y and B_z turned negative at ~2315 hrs UT on 30 October 2003 (event marked as [N]), and PC, AL, AE started changes about 20 min later (event marked as [N1]).

5 Conclusions and discussion

The interval 28-31 October 2003 was examined for storm-time changes. A major storm onset occurred near 0500-0600 hrs UT on 29 October 2003 with large increases in interplanetary parameters, decreases in geomagnetic Dst and cosmic ray neutron monitor counts, as well as increases in auroral indices. However, in the hours before these large changes, whereas interplanetary parameters including negative B_z were at quiet levels, the auroral indices were not low and showed fairly high values (~1000 nT). Thus, at least in this storm, auroral indices proved to be precursors with an antecedence of a few hours. As a warning for storms, such a precedence is important, longer the better, to be able to take precautionary measures. The 29 October 2003 storm was due to a very fast interplanetary disturbance (velocity more than 2000 kms^{-1}) and such precedence could be the characteristic of only severe storms. It is being examined presently whether such precedence occurred for other storms in cycle 23.

Considerable information is now available from the GEOTAIL satellite (website http://www.isas.jaxa.jp/e/enterp/missions/geotail/achiev/typical.shtml) about the entry of solar wind particles in the geomagnetic tail. As stated there, GEOTAIL observations have demonstrated that the structure and dynamics of the magnetotail are basically determined by magnetic reconnection under both southward and northward IMF conditions except possibly when IMF is almost due northward. When IMF is southward, the distant neutral line is formed at ~140 Re down the tail. An important finding is that the neutral sheet in the distant tail is twisted under the influence of the B_y component of IMF and more severely so when the IMF is northward. It suggests that reconnection can still take place in the distant tail under the northward IMF condition (with a significant B_y component), but it generates an apparently different signature; field lines that are convected tailward beyond the neutral line have a northward B_z. The results presented in the present paper indicate possible B_y effects in the magnetotail even in the absence of negative B_z values. It also explains why aurora is seen all the time even in quiet conditions.

Whether the antecedence of auroral indices is useful or is being used by researchers is a moot question. Damages due to geomagnetic storms are mostly in higher latitudes where electrical installations are affected (for example, transformers burn up) and hence, accurate information about the commencement, duration and maximum intensity of the storm is very useful. In general, storms with Kp exceeding 8 (Dst exceeding ~250 nT) are extreme events which pose significant threats to power grids. But what matters at any location is not just the Dst level but the DS component also, which depends on local time. Neither Dst nor DS are available with any antecedence. So, electrical engineers in high latitudes must monitor the local H field for warning of space weather disruptions rather than use global auroral indices. Beland[16] mentioned that "for Hydro-Quebec (HQ) in the province of Quebec in Canada, there are now two measurement systems (one primary and one backup) monitoring ground-induced current (GIC) effects on the grid in real time. To be informed in advance of a probable GIC occurrence, HQ now relies on a specialized organization providing geomagnetic activity alert and forecast. Following an alert or the detection of GIC effects on the network exceeding a minimal threshold, special operation rules take effect in order to ensure maximum stability and safety margin. Also, series capacitors were introduced on several 735 kV lines, which increase network stability and also block GIC circulation". Other installations might be using other methods. In some cases, operations are stopped (if possible) during the storm interval. Obviously, statistical correlation and regression analyses do not have much role to play in this scenario.

Recently, some researchers[17] have reported relationships between geomagnetic indices and the nature of interplanetary features (sheaths, shocks, etc.). However, all these occur when storm has already started, so no prediction potential is seen.

Acknowledgements

The author gratefully acknowledges the partial support provided by FNDCT, Brazil, under contract FINEP-537/CT for this work.

References

1 Parker E N, Supra thermal particle generation in the solar corona, *Astrophys J (USA),* 128 (1958) 677.
2 Parker E N, Extension of the solar corona into interplanetary space, *J Geophys Res (USA)*, 64 (1959) 1675.
3 Gold T, Plasma and magnetic fields in the solar system, *J Geophys Res (USA)*, 64 (1959) 1665.
4 Dungey J W, Interplanetary magnetic field and the auroral zones, *Phys Rev Lett (USA),* 6 (1961) 47.
5 Sugiura M, Hourly values of equatorial Dst for IGY, in *Annals of the International Geophysical Year (USA)* (Pergamon Press, Oxford), 35 (1964) 945.
6 Troshichev O A, Andrezen V G, Vennerstroem S & Friis-Christensen E, Magnetic activity in the Polar Cap - a new index, *Planet Space Sci (UK),* 36 (1988) 1095.
7 Davis T N & Sugiura M, Auroral electrojet activity index AE and its universal time variations, *J Geophys Res (USA)*, 71 (1966) 785.
8 Rostoker G., Why we have not yet solved the substorm problem, in *Sixth International Conference on Substorms*, ed by Winglee R M (University of Washington, Seattle), 2002, pp 1-8.
9 Kamide Y & Rostoker G, What is the physical meaning of the AE index? *EOS Trans Am Geophys Union (USA)*, 85 (19) (2004) pp 188, 192.
10 Skoug R M, Gosling J, Steinberg J, McComas D J, Smith C W, Ness N F, Hu Q & Burlaga L F, Extremely high speed solar wind: October 29-30, 2003, *J Geophys Res (USA),* 109 (2004) *A09102,* doi:10.1029/2004JA010494.
11 Terasawa T, Oka M, Nakata K, Saito Y, Mukai T, Hayakawa H, Matsuoka A, Tsuruda K, Ishisaka K, Kasaba Y, Kojima H, Matsumoto H, Keika K, Nose M & McEntire R W, *GEOTAIL observation of interplanetary shocks during the solar storm season in October-November 2003*, Paper SH51A-13 presented at the 2004 Joint Meeting (CGU, AGU, SEG, EEGS), 17-21 May 2004, Montreal, Canada, 2004.
12 Gonzalez WD, Joselyn J A, Kamide Y, Kroehl H W, Rostoker G, Tsurutani B T & Vasyliunas V, What is a geomagnetic storm?, *J Geophys Res (USA)*, 99 (1994) 5771.
13 Gonzalez W D & Echer E, A study on the peak Dst and peak negative B_z relationship during intense geomagnetic storms, *Geophys Res Lett (USA),* 32 (2005) L18103, doi:10.1029/2005GL023486
14 Belov AV, Eroshenko E A, Oleneva V A, Yanke V G, Mavromichalaki H, Plainaki Ch & Mariatos G, *Cosmic ray variations during two greatest bursts of solar activity in the 23-rd solar cycle*, Abstract submitted to the Symposium on Solar extreme events of 2003. Fundamental Science and Applied Aspects, Moscow State University, Moscow, 12-14 July 2004.
15 Nishida A, DP2 and polar substorm, *Planet Space Sci (UK),* 19 (1971) 205.
16 Beland J, *Hydro-Quebec and geomagnetic storms: Measurement techniques, effects on transmission network and preventive actions since 1989*, paper presented at 35th Scientific Assembly, COSPAR, Paris, 19–25 July 2004.
17 Echer E, Gonzalez W D, Tsurutani B T & Gonzalez A L C, Interplanetary conditions causing intense geomagnetic storms (Dst ≤ -100 nT) during solar cycle 23 (1996-2006), *J. Geophys Res (USA*), 113 (2008) A05221, doi: 10.1029/2007JA012744.