Magnetosphere Dynamics during the Geomagnetic Storm 22-24 November 1997

Koleva R., Bochev A.

Solar-Terrestrial Influences Institute, Bulgarian Academy of sciences, Sofia, Bulgaria, rkoleva@stil.bas.bg

Geomagnetic storms represent a significant dissipation of energy by the magnetosphere. The energy is derived from the solar wind flow and the subsequent powerful conversion of that energy takes several different forms. We investigate the behaviour of the magnetosphere during the most intense geomagnetic storm in the minimum of the 22nd solar cycle – 22 – 24 November 1997, using data from both satellites of INTERBALL pair.

Introduction

Geomagnetic storms are the prime complex process of space weather. In the course of a storm a considerable amount of energy is extracted by the magnetosphere from the external solar wind and consequently dissipated in different regions of the magnetosphere-ionosphere system and earth atmosphere. Ring current injection and decay, ionospheric Joule heating, particle precipitation into the atmosphere, and several related physical processes are exhibited clearly in large storm events. The primary causes of geomagnetic storms are strong dawn-to-dusk electric fields associated with the passage of southward-directed interplanetary magnetic field (IMF) past the Earth for sufficiently long intervals of time (cf. [1]). But recent results have highlighted the importance of solar wind (SW) dynamic pressure (cf. [2]). Several studies outline the differences in storm activity caused by the different drivers - interplanetary counterparts of coronal mass ejections (ICMEs) and their subclass of magnetic clouds, fast solar wind streams, corotating interaction regions [2,3,4]. Case and statistical studies address the difference in storm activity during different solar cycle conditions [5, 6]. Recent investigations are directed to track out the events beginning from their probable source domain deep into the magnetosphere and ionosphere

The aim of this work is to study the magnetosphere behaviour during the largest geomagnetic storm in 22nd solar cycle minimum on 22-24 November 1997.

Data

We will use data from both satellites of INTERBAL pair. The field-aligned currents (FAC)s which transmit the stress on the magnetosphere towards the ionosphere and atmosphere will be studied on base of the three component flux-gate magnetometer IMAP-3 aboard the INTERBALL-Au (IB-2) [7]. The magnetotail behaviour will be analysed by data from the high apogee INTERBAL-Tail (B-1) satellite: the magnetic field measured by the MIF instrument [8], ion spectra and distribution measured by CORRAL spectrometer [9] and electron spectra and distributions measured by ELECTRON spectrometer. Dst index is retrieved from www.ngdc.noaa.gov/stp/GEOMAG/dst.html. Data for the IMF, SW and AL index are taken from CDAWeb, used are the 1 min data projected to 1 AU. To locate the position of IB-1 satellite with respect to the magnetospheric and ionospheric regions the Tsyganenko'04s [10] model is used for distances less than 15 R_E and Tsyganenko'96 [11] model for larger distances.

Storm overview

Fig. 1 displays ion, electron and magnetic field data, measured aboard IB-1, IMF and SW characteristics and AL and Dst indexes for the whole period of the storm. The content of the panels is as follows: panels (1) - (4) - IMF B_x, B_y, B_z and SW dynamic pressure respectively, lagged to IB-1 position; (5) – AL index; (6) – Dst index. Further follow data measured aboard IB-1: panels (7)-(9) – three components of the magnetic field in GSM coordinates, panels (10)-(12) – dynamic spectrograms of the electron fluxes measured by three of ELECTRON detectors, looking in directions $-X_{GSE}$, perpendicularly to X_{GSE}, and X_{GSE}; (13)-(15) – ion dynamic spectrograms, measured by the corresponding three of CORRAL detectors.

The storm was driven by a magnetic cloud (MC) [6] and took place in two steps – the first one driven by the sheath region and the second by the cloud itself. The sheath reaches the Earth at ~ 9:50 UT on 22 November. A pulse in SW dynamic pressure hits the magnetopause. IB-1 was in the tail at ~ - 10.6 R_E, heading towards perigee. It registers the increased two times magnetic flux about 1.5 – 2 min later. The 100% increase of the magnetic flux is a signature of lobe flux loading. From about 8:00 IB-1 was travelling in the plasma sheet, but with beginning of flux loading it sharply exited into the southern lobe, therefore a plasma sheet thinning took place. Respectively, a substorm began developing. As Dst is given as an 1 hour index, sudden commencement in Dst data is related to the interval 10 – 11 UT and then the growth phase of the storm began. Both due to the passing away of the sheath region and the corresponding decrease in SW dynamic pressure, and to the approaching the Earth, IB-1 again enters the plasma sheet at ~13 UT. An evident plasma sheet thinning connected with the growth of a new substorm is observed at ~14:10 UT. IB-1 measurement in the interval 17:30 – 20:00 UT are discussed in detail in [13]. The most interesting feature were up-going beams of energetic (E>100 eV), relatively cold, O^+ and He^+ ions, ejected from the ionosphere and undergoing acceleration at the poleward boundary of velocity dispersed ion structures.

During this period IB-2 passed through the dayside cusp/cleft region and the northern polar cap at altitudes between 10 000 and 15 000 km every 6 hours. Authors in [14] report about strong enhancement in escaping O^+ fluxes, typically by two orders of magnitude, but the increase of the O^+ energy flux was less pronounced.

The main phase of the storm driven by MC – 23 November, 00 - 12 UT, will be discussed in the next section.

During the recovery phase IB-1 was in the northern tail lobe. This period is discussed in details in [15]. The counterstreaming electrons with highly ansotropic and complicated distributions were identified as polar rain electrons, having entered into the magnetosphere through the

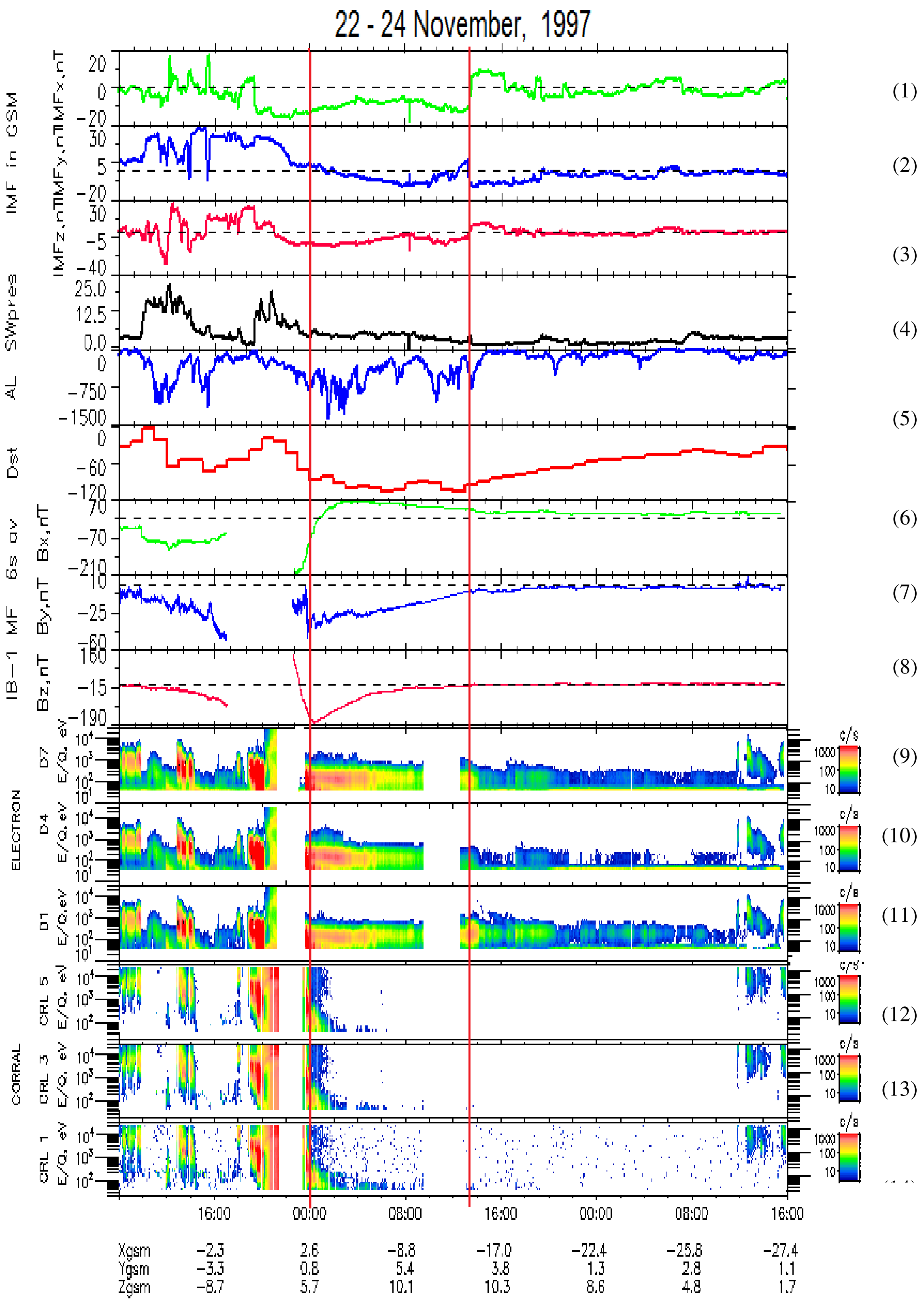
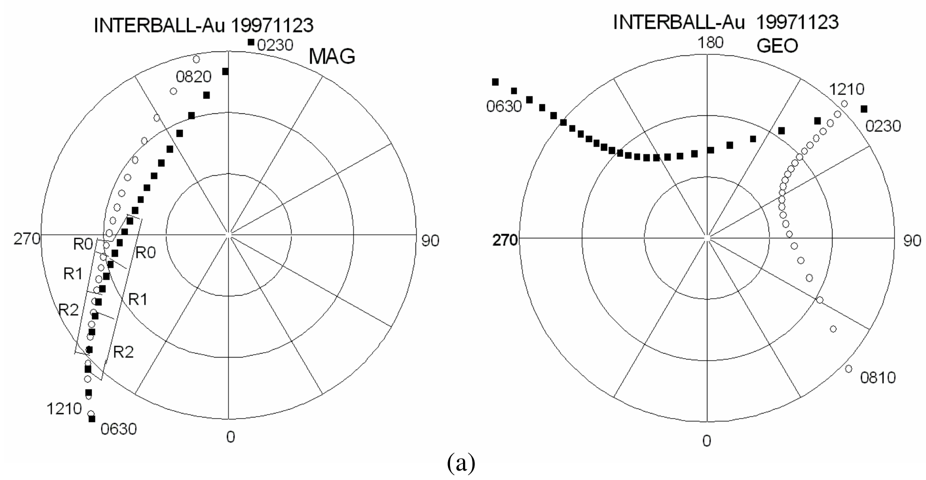
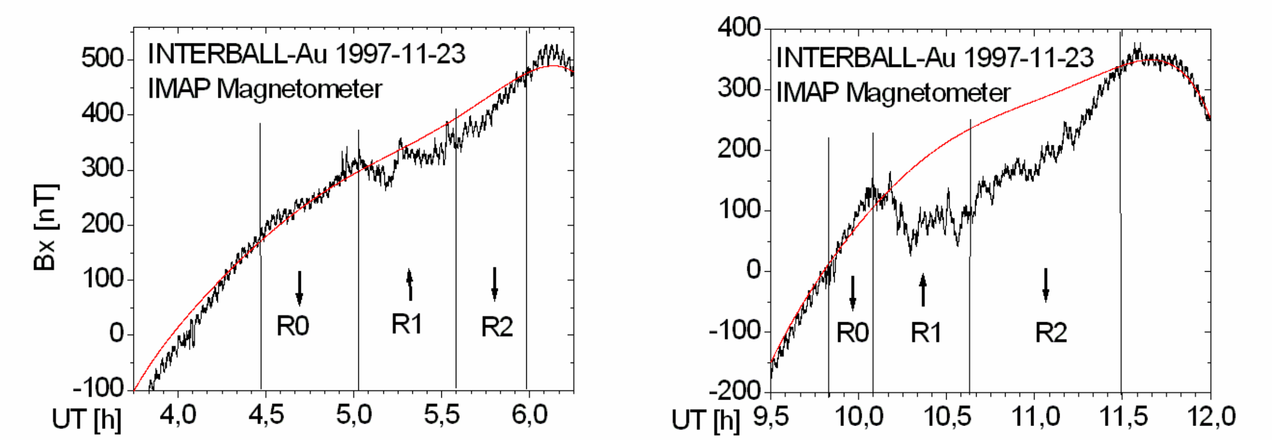


Fig.1. The geomagnetic storm 22-24 November 1997. Data for the IMF, SW, AL, Dst;IB-1 data - magnetic field and electron and ion fluxes. See text for details.



(a)



(b)

Fig. 2. (a) Geographical (GEO) and geomagnetic (MAG) corrected coordinates of INTERBALL-Au footprints on 23 November, 1997. The UT (initial and final) of each orbital segment is indicated by numbers [hhmm]. Field-aligned current regions are designated by rectangles. (b) Intense FAC disturbances on the Bx_{GSE} component. The base line (in red) is an approximation of the same component during a quite period two days before.

distant tail magnetopause. Nearer the Earth, though the earthward and tailward fluxes were almost equal, there were energy ranges from ~ 100 eV to 200 eV where the tailward flux exceeded the earthward, which suggests the presence of an additional source earthward of the observations.

Main phase of the MC-driven storm

Here we will discuss in details the period 00:00 – 12:00 UT on 23 November, the main phase of the storm, when the Dst index reached values down to -180 nT. It was characterised by multiple successive substorms, AL reaching -1400 nT. In Fig. 1 this is the interval enclosed between the two vertical red lines.

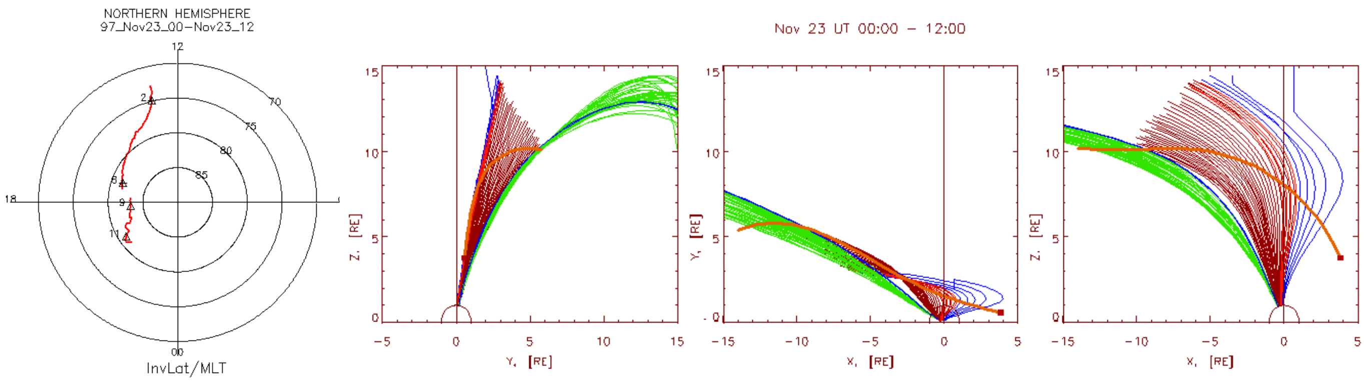
Prominent features for this period are the strong FACs, measured by IMAP-3 magnetometer aboard of INTERBALL-Au. Figure 2a, displays IB-2 footprints for two intervals: 02:20 - 06:30 UT – black squares, and 08:10 - 12:10 UT – empty circles. For such a segment the transverse (East-West) disturbances, informative for FACs, could be approximately presented by the Bx (roughly Bx GSE) component. The IMAP-3 magnetogram for the first interval - 02:20 - 06:30 UT – is presented in Figure 2b, left panel. It indicates an intense large-scale structured negative perturbation with respect to the base-line (in red) as defined by the measured field before the storm. Its negative sign (the X-axis is positive towards the Sun) means that the disturbance is westward. Traditionally we associate such disturbances, detected when the satellite moves from polar cap towards low latitudes, with crossing a pair of FAC sheets of upward and downward currents. The poleward part of this current system, which corresponds to magnetic field decreasing, is known as region 1 (R1) and the equatorward part corresponding to magnetic field increasing is region 2 (R2). Poleward from R1 an interval of increasing field can be associated with a weak downward FAC known as region 0 (R0). Region 1 is structured in a considerable degree. It includes at least two pairs of upward and downward FAC currents. The whole perturbation zone covers a large latitudinal band from 58o to 74o MLAT.

In the interval 08:10 - 12:10 UT the spacecraft crosses the dusk sector from cusp to evening hours at 71 MLAT near to its apogee. Similar to the first case we examine the Bx component. The IMAP-3 magnetogram in Figure 2b, right panel, indicates an unusually intense large-scale and highly structured negative perturbation. Similar to previous case it might be accepted that the magnetometer resolves a pair of FACs namely R1 and R2. Poleward from R1 an interval of increasing field is quite clearly seen. It could be associated with a downward FAC R0. FAC region 1 is structured in a very considerable degree. Similar to pervious orbit it could be considered composed by several small pairs of FACs. Some small-scale structures look like isolated FACs. The whole FAC interval occupies also a large latitudinal interval from 58° to 71° MLAT.

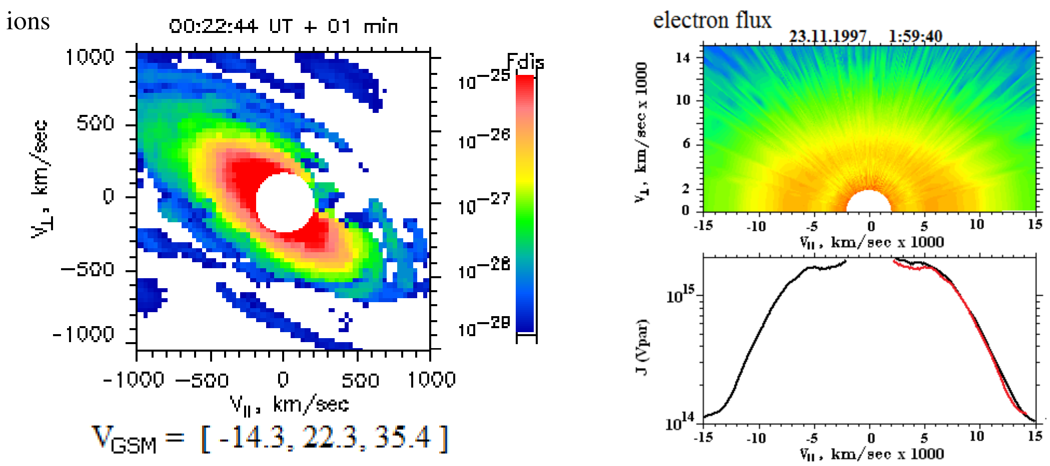
During this time interval IB-1 moves from its perigee tailwards. It has left the inner magnetosphere and moves northward near the noon meridian plane. Figure 3a, right panel, shows satellite trajectory – thick red line, projected on GSM coordinate planes, and the model field lines intersected by the s/c. The projection of the trajectory on the ionosphere in InvLat/MLT coordinates is shown on the left panel of Fig.3a. To calculate the field lines and project the orbit we used two models. The storm-time Tsyganenko'04s model [11] was used for the part of the orbit in the interval 00:00 – 8:25 UT. As this model is valid over distances up to 15 R_E, for the rest part of the model we used Tsyganenko'96 model [12]. This explains the discontinuity of the trajectory in the InvLat/MLT coordinates – an artefact of the modelling. The picture is only qualitative.

Both models and onboard magnetic field and plasma measurements indicate that IB-1 crosses the northern lobes, starting just at the 'beginning' of the tail – the high latitude region backwards the cusp. Up to ~02:00 UT CORRAL observes highly magnetised ions, with gradually decreasing energy, from magnetosheath-like to less than 100 eV. The ion flow weakens and after ~ 02:00 UT is already below instrument's threshold. The ion distribution function, an example presented in Fig. 3b, left, is typical of ions undergoing an ExB drift. The picture indicates that we observe the equator-most part of the plasma mantle.

At the same time the electron population exhibits two components, well separated in energy. These two components are very well expressed on the flux distribution, depicted in Fig. 3b right. The component with lower energy, ~100 eV and gradually decreasing with time, has a large pitch angular distribution and disappears together with the ion flows. Obviously, together with the ions, these electrons comprise the mantle population – magnetosheath plasma, which has entered either through the cusp or as a result of dayside reconnection (IMF is steadily southward). The calculated distance to the magnetopause, defined by Shue model [16] is ~3 R_E, defining a very thick mantle. The higher-energy part of the electron flux however is highly anisotropic, forming two counterstreaming along and opposite the magnetic filed fluxes. The fluxes are almost equal, yet the earthward flux is slightly more intense than the tailward. This is demonstrated in the 1-dimentional distribution of the flux – to facilitate comparison, the red curve is just the mirrored curve for negative Vpar. The energy of the fluxes – steadily 100 – 300 eV and their distribution, gives us ground to identify these electrons as the polar rain electrons.



(a)



(b)

Fig.3. (a) Projection ob IB-1 orbit for 23 November 00 – 12 UT: left – on the ionosphere, right – on the three GSM coordinate planes together with the field lines crossed. S/c moves from the square on. (b) Representative ion distribution (left) and electron flux distribution (right). See text for details

Discussion and conclusions

To give quantitative characteristics of FAC systems we assume "infinite" current sheets of uniform intensity across their width. In the first set of space–time disturbances, the upward region 1 current (04:05 – 05:30 UT) and downward region 2 current (05:30 – 06:10 UT) intensities are i1 = - 0.111 A/m (ΔBx = - 140 nT) and i2 = 0.095 A/m (ΔBx =120 nT) respectively; the downward region 0 current is small i0 = 0.016 A/m(ΔBx =20 nT). In the second set of disturbances the intensities of region 1 current (10:05 – 10:35 UT) and region 2 current are i1 = - 0.159 A/m (ΔBx = - 200 nT) and i2 = 0.127 A/m (ΔBx = 160 nT) respectively. This case differs with its significant downward region 0 current i0 = 0.048 A/m (ΔBx = 60 nT). By summation of positive (negative) values along the orbit we obtain that the large-scale FAC current systems are nearly balanced. Small-scale FAC pairs imbedded in region 1 and -2 appear as very intense (for example see the second magnetogram 10:30-10:32 UT).

At least two intermediate (mean duration about 20 min) structures could be distinguished in each magnetogram. For example in the second magnetogram the respective intervals are 10:05 – 10:30 UT and 10:30 – 10:50 UT. It is interesting to note that in the first magnetogram the respective interval begins with a 15 min structure (05:00 – 05:15 UT) where the upward current (05:00 – 05:10 UT) is less intense than the downward current (05:10-05:15). This "inversion" contrasts the usually observed pattern. The similarities between both orbits indicate that intermediate structures are comparatively stable events. The structures could be related to the appearance of strong convective vortices overlapping the general convection pattern in the magnetosphere. We will pay more attention to this question in future investigations.

The present study is a first step in the analysis of the 22-24 November 1997 storm. Data from other satellites DMSP, GOES - should be involved. We plan to calculate the balance between the input and dissipated energy. The energy dissipated in the ionosphere can be estimated from the FACs. Energy is dissipated also in the inner magnetosphere, in the ring current. As there are not sufficient measurements, we plan to use models. As a verification of the models we will compare the measured onboard INTERBALL pair magnetic field with the model one.

Acknowledgments

The authors are thankful to M. Nozdrachev, V. Styazhkin and V. Petrov who made the data processing of IB-1 magnetic field data, to V. Prohorenko for IB-1 and IB-2 orbital parameters; to A. Fedorov for providinf CORRAL data and J.-A. Sauvaud for electron data. We acknowledge J.H. King and N. Papitashvilli at AdnetSystems, NASA GSFC and CDAWeb for providing OMNI IMF, SW and AL data.

REFERENCES

[1] Gonzales, W.D., Joselyn, J. A., Kamide, Y., et al., What is geomagnetic storm? *J. Geophys. Res*, vol. 99, 1994, pp 5771-5792.

[2] Pulkkinen, T.I., Palmroth, M., Tanskanen, E.I. et al., Solar wind—magnetosphere coupling: A review of recent results, J. *Atmos. Solar-Terr. Phys.,* vol. 69, 2007, pp 256–264

[3] Denton, M. H., Borovsky, J. E., Skoug, R. M., et al., Geomagnetic storms driven by ICME- and CIR-dominated solar wind, J. *Geophys. Res.,* vol. 111, A07S07, 2006, doi:10.1029/2005JA011436.

[4] Pulkkinen, T.I., Partamies, N., Huttunen, K. E. J., et al., Differences in geomagnetic storms driven by magnetic clouds and ICME sheath regions, *Geophys. Res. Lett.*, vol. 34, L02105, 2007, doi:10.1029/2006GL027775.

[5] Daglis, I.A., Tsurutani, B.T., Gonzalez, W.D., et al., Key features of intense geospace storms—A comparative study of a solar maximum and a solar minimum storm, Planet. Space Sci., vol. 55, 2007, pp 32–52

[6] Wu, C.-C., Lepping, R.P., Solar cycle effect on geomagnetic storms caused by interplanetary magnetic clouds. *Ann. Geophys.*, vol. 24, 2006, 3383-3389.

[7] Arshinkov, I.S., Zhuzgov, L.N., Bochev , A.Z. et al. Magnetic field experiment IMAP in the INTERBALL project , in *INTERBALL: Mission and Payload*, ed. A. A. Galeev, RKI-IKI– CNES, 222-228, 1995.

[8] S. Klimov, S. Romanov, E. Amata, E., 1995, ASPI experiment: Measurements of fields and waves onboard the INTERBALL-TAIL mission. In: *INTERBALL Mission and Paylod*. RKA, IKI and CNES, pp. 120–152 , May 1995.[9]Yu. I. Yermolaev, A. Fedorov, O. Vaisberg, et al., Ion distribution dynamics near the Earth's bow shock: first measurements with the 2D ion energy spectrometer CORALL on the INTERBALL/tail-probe satellite, *Ann. Geophys.,* vol. 15, 1997, 533.[10] Sauvaud J.-A., Koperski P., Beutier, T., et al., The INTERBALL-Tail ELECTRON experiment: initial results on the low-latitude boundary layer of the dawn magnetosphere. *Ann. Geophys*., vol. 15, 5, 1997, pp 587-595.

[11] Tsyganenko, N. A. and Sitnov, M. I, Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms, *J. Geophys. Res.*, v. 110 , A3, 2005, A03208, doi: 10.1029/2004JA010798.

[12] N. A. Tsyganenko, Effects of the solar wind conditions on the global magnetospheric configuration as deduced from data-based field models. In: *Proc. of 3rd International Conference on Substorms (ICS-3)*, ESA SP-389, 181-185, 1996.[13] Popielawska, B., Sandahl, I., Sachiko Joke, et al., Oxygen ion beams at the boundary of velocity dispersed ion structures in the high-latitude magnetosphere under northward interplanetary magnetic field with a large by-component: interball-tail observations, *Adv. Space Res.* vol. 31, 5, 2003, pp. 1363-1370.

[14] Malingre, M., Bouhram, M., Dubouloz, N., Sauvaud, J.A., INTERBALL-AURORAL observations of intense ion outflows during the November 22, 1997 CME event. *Geophysical Research Abstracts*, European Geophysical Society, vol. 5, 2003, 10196.

[15] Koleva, R., Sauvaud, J.-A., Plasmas in the near Earth magnetotail lobes: properties and sources, *J. Atmos. Solar-Terr. Phys.*, vol. 70, 2008, pp. 2118-2131.

[16] Shue, J.-H., Song, P., Russell, C.T., et al., Magnetopause location under extreme solar wind conditions. *J. Geophys. Res.*, 103, 1998, 17691-17700.