Field-Aligned Current Response to ICME on 11 April 1997 as Seen by Interball-Au Satellite at Mid-Altitude Cusp Magnetosphere

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We present magnetograms suggestive for unusual field-aligned currents (FACs) appearance in mid-altitude cusp of the magnetosphere at height 20,000 km during ejecta on 11 April 1997. In fact FACs are different as compared with Potemra model nevertheless that current direction may coincide with the classical system. We demonstrate: (1) an appearance of two or more current sheets with opposite polarities in the dusk flank of the cusp; (2) appearance of FAC system in a comparatively large magnetic field depletion or diamagnetic cavity. The examination of energetic particles gives evidence to suppose a simultaneous formation of cusp energetic particle (CEP) event in the region of field-aligned currents and diamagnetic cavity; (3) an unusually intense FAC system is documented in the cusp during low geomagnetic activity (Kp=2), when the magnetic field disturbance was in the order of 150 nT. This result together with POLAR study [16] is more confident conclusion that the driving process for this event including the reversed convection (sunward) through the polar cap was the reconnection between interplanetary field lines and the lobe field lines.

Introduction

Polar cusp is a key region of the Earth's magnetosphere. In the cusp the *solar wind* (SW) plasma can penetrate directly in the upper atmosphere. The main process of entering the cusp is reconnection or merging of interplanetary magnetic field lines with the geomagnetic field lines. Once the solar plasma has entered the cusp it exhibits different characteristics in energy, density and temperature which affect almost all processes in the region and vicinity. In the cusp charged particles from solar wind origin can be accelerated to high energies. This process is known as *cusp energetic particles* event (CEP). At low altitudes the energetic particles precipitate in the atmosphere and a dayside aurora may occur as a precursor of geomagnetic storm. A number of events and processes in the cusp magnetosphere have their analogues in the solar surface too. That is why cusp properties and problems continue to be a subject of modern *in situ* studies. For example, the Double Star space mission (2004) has been specially designed to operate with CLUSTER space mission in the plasma sheet and in the polar cusp.

Recently there is a tendency to find a link between the solar wind and the solar activity forms which is a rather ambitious task. To prove experimentally a direct relationship between a given solar activity event as ejecta (coronal mass ejection) and the solar wind (SW) structure observed ~ 3 days later at 1 AU is a difficult but an actual task in the modern solar-terrestrial physics ([1, 2, 3, 4] and the literature therein). A rather intriguing example is the April 10-11, 1997 in which case evidence was found that the increased geomagnetic activity was caused by a multiple ejecta that left the solar surface on April 7, 1997 [5]. The main feature to classify the event as ejecta was the availability of large concentration of helium ions in the ejected material; helium density was about ten times higher than the hydrogen in contrast to the composition of the Sun (90% H and 10% He). Indeed it was an unusual event as two different ejecta appeared in one and the same region on the solar surface. The first (fast) ejecta was not directly detected at the Earth; however the magnetic field (directed southward) which enveloped this ejecta encountered the Earth's magnetosphere and an enhanced geomagnetic activity occurred, started on April 10, 1997. Assuming constant velocity, the time of arrival of the event at Earth was predicted to be between 5 UT on April 9 and 3 UT on April 10, whereas the event (the shock) arrived at 13:50 UT on 10 April [5].

Moreover we are not able to forecast the sign of the *interplanetary magnetic field* (IMF) which is a parameter of primary importance for the geomagnetic activity.

The second (slow) ejecta frozen in northward magnetic field was detected at the Earth on April 11, 1997. The geomagnetic activity was low. However many uncertainties concerning the precise connection of SW and IMF parameters to the observed ejecta have not been cleared yet.

The present work is an attempt to show field-aligned signatures in the mid-altitude high latitude dayside magnetosphere related to the ejecta structures. IMF and SW data received aboard of WIND spacecraft [6, 7] are shown in Fig. 1.

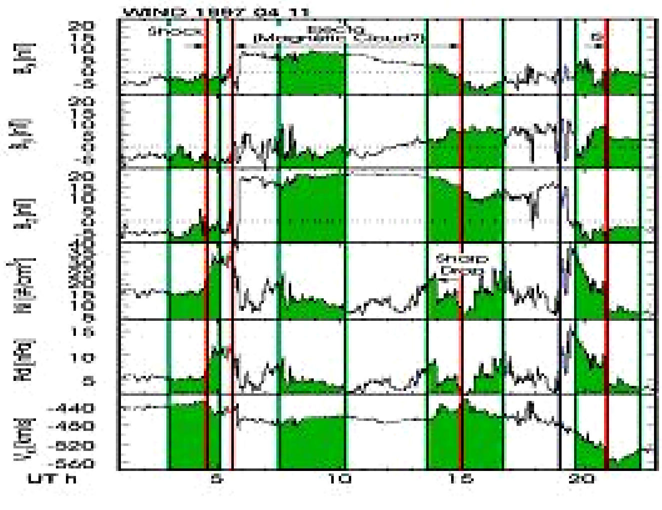

Fig.1. Interplanetary magnetic field components and solar wind density, dynamics pressure and velocity. Red lines point the ejecta structures: the shock, the ejecta itself, and inverse interplanetary shock (IS). Intervals in green indicate time of analysis of INTERBALL –Au.

In our work we will use the same identification of the IMF and solar wind (SW) structures as given in the first study of this event [5]. In particular for 11 April they are: The ejecta itself on 11 April from 05:50 to ≈ 15:00 UT; A sharp drop of SW dynamics pressure during ejecta at 13:50 UT the same day (this name is given by us) and; The trailing edge, marked by a reverse interplanetary shock (IS) on 11 April at 20:52 UT.

For cusp investigation by particles we analyze data from the PROMICS -3 spectrometer aboard the INTERBALL-Au [8, 9]. To study the magnetic field disturbances we present data from the magnetic field experiment IMAP –3, designed and manufactured in STIL-BAS, Bulgaria, aboard the same spacecraft [10]. For determination of the position of the cusp relative to the ring current we use data from the DOK-2 experiment [11]. We try to verify the position of the auroral oval-polar cap boundary by using DMSP satellite images [12, 13]. A part of our results have been published already [14].

Observations and analysis

The INTERBALL-Au footprints (squares) in corrected geomagnetic coordinates in the apogee part of the orbits are shown in the upper part of Fig. 2, panel 1, step 10 min [15]. Numbers indicate the UT time at the beginning and at the end of each pass. The satellite moves from dawn to dusk. The INTERBALL-Au orbital period is about 6 hours so four orbits cover the whole period of ejecta (including pre and post periods) interaction with the magnetosphere on 11 April, 1997. The forth orbit projection which is in the middle between the second and the third orbit is omitted. The duration of each orbital interval is about three hours. It is seen that the apogee occurs near noon. In Fig. 2, panel 2-5, IMAP-3 magnetograms *dByz* (residuals measured - main magnetic field trend) are shown for 11 April. For simplicity we examine only the spin plane component

$$Byz = \sqrt{By^2 + Bz^2}$$

where *By* and *Bz* are measured magnetic field components along *y* and *z* axes respectively. Blue line indicates the noon meridian. In fact *Byz* lies in the *yz* plane of GSE coordinate system. The *dByz* is a proxy of FACs. It is estimated that *dByz* is proportional to the magnetic field disturbance due to FACs, the coefficient of proportionality being in the range 0.1 to 0.7 for INTERBALL-Au passes shown in Fig. 2, panel 1. Note that for a comparison with SW parameters in Fig. 1 we have to shift WIND record 55 min for the SW propagation time from WIND to the Earth. An exception is the forth orbit when the time delay is smaller (47 min) due to the high SW velocity Vsw = 550 km. For example the first orbit FAC disturbances (Fig. 2, panel 2, 03:50-06:00 UT) corresponds to 02:55-05:05 UT interval in Fig. 1. In the present study we concentrate on 11 April 1997 third and forth orbits as a quite interesting period.

11 APRIL Ejecta Dynamics Pressure Sharp Drop (15:00 – 17:30 UT)

During this pass the INTERBALL-Au was more close to the magnetic pole, MLAT= 82 deg, in contrast to other orbits (Fig. 2, panel 1). Both IMF *By* and IMF *Bz* were strong positive and the magnetosphere remained fully under IMF *Bz* influence for a long time of about 12 hours (IMF *By* = 8 nT and IMF *Bz* = 12 nT), (Fig.1). The geomagnetic activity was low (Kp=2). There was a

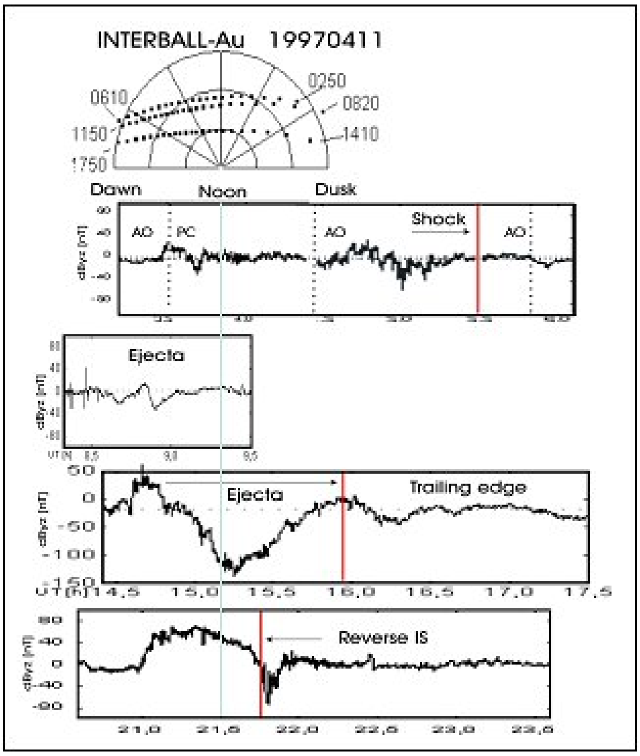

Fig. 2. Panel 1: The INTERBALL footprints in corrected geomagnetic coordinates. Panel 2-5: Summary plot of INTERBALL Byz magnetic field component (IMAP-3 magnetometer) in particular; Panel 2: magnetic field disturbances during high geomagnetic activity (Kp=7); Panel 3: the same during ejecta in orbit at comparatively low latitudes; Panel 4 and 5 are explained in the text. The blue line corresponds to 12 MLT.

smooth increase of solar wind *Pdyn* followed by a sharp drop at 14:55 UT (used as a name for the whole pass).

Very large space and time variations of the encountered magnetic field were documented in the cusp (Fig. 2, panel 4; Fig. 3, panel 1). During this interval the FAC system was most strong (*dByz*=150 nT).

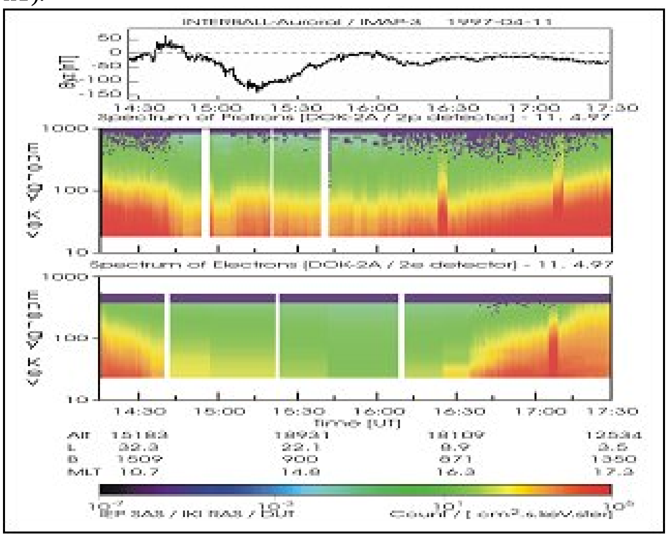

Fig.3. INTERBALL observations. Panel 1: The Byz magnetogram (IMAP-3 magnetometer); Panel 2: Energetic particle fluxes (DOK-2 spectrometer).

In Fig. 3, Panel 2 and -3 show standard spectrograms from the DOK-2 experiment for energetic ions and electrons respectively (Lutsenko et al., 1995). It is seen that the increase of *dByz* in the beginning of the magnetogram from 04:30 to 04:40 UT (supposed to be region 2) is collocated in the ring current; the equatorward boundary of the cusp at about 76 MLAT is well defined by particles; this is a common feature usually observed during different IMF condition. Then *dByz* displays a large depression from 04:40 to 16:30 UT centered at noon meridian (supposed to be region 1 and region 0); simultaneously DOK-2 encountered electrons with small energy suggestive for the cusp/polar cap (Fig. 4, panel 3). Unexpectedly in this region the spectrometer documented a continuous structured distribution of energetic protons E = 10 s keV. The cusp-ring current boundary in the dusk flank is not clear. In the cusp dusk flank the magnetometer detected two smaller magnetic structures which could be related to convective cells.

During the period of interest the POLAR spacecraft was moving from below the cusp latitudes to above the cusp (poleward of the cusp) at altitude about 7 Earth's radii. The polar orbit plane was roughly at 13:30 MLT [16]. From their Plate 1 it is evident that the cusp sector during 13-14 UT is characterized by increased proton densities mainly in the low energy range $E \leq 3.3$ KeV/e which is significantly smaller than INTERBALL results. Further along its trajectory and simultaneously with the INTERBALL, POLAR documented features suggestive for reconnection near the magnetopause poleward of the cusp; the ionospheric convection pattern shows a reversed convection (i.e. sunward) over the polar cap due to high latitude reconnection [16]. So we could conclude that the observed FAC distribution via INTERBALL may be a result of enhanced reconnection due to high solar wind velocity and strong positive IMF *Bz*. Note that in the dusk flank both POLAR ([16], Plate 1) and INTERBALL did not observe large-scale intense FAC structures. However we can not explain the appearance of intense energetic protons E=10s KeV throughout the cusp in the INTERBALL records and the lack of such particles at POLAR altitudes (?).

11 APRIL Ejecta Trailing Edge (20:30-23:00 UT)

During this transit IMF *By* = 4 nT, and IMF *Bz* = -3 nT; the ejecta reverse shock reached the Earth at 21:50 UT (Fig. 1). It is characterized by a sharp drop of concentration Ni (from 15 cm-3 to 7 cm-3); under such conditions a reconnection in the dusk flank of the cusp at high latitudes and in the LLBL could be expected [14].

In Fig. 4 the PROMICS standard spectrograms indicate crossings of the following structures: the ring current (20:30-21:00 UT); the boundary cusp-dawn flank (21:05-21:10 UT); the cusp proper (21:10-21:20 UT); the boundary cusp-dusk flank (21:40-21:55 UT) and the ring current (from 21:10 UT on). It is seen that the separation between both flanks of the cusp is rather small (at noon the pass was in the polar cap but near to the poleward boundary of auroral oval.

In the beginning of the magnetogram a sharp increase of *Byz* corresponds probably to FAC region 2 located in the poleward part of the ring current (21:00-21:05 UT). FAC region 1 can not be identified because the magnetogram is dominated by a positive trend. The latter probably is an effect of skimming a cusp current sheet at noon; this effect may be exaggerated by the base line definition. The most intense pair of large-scale FACs detected by the

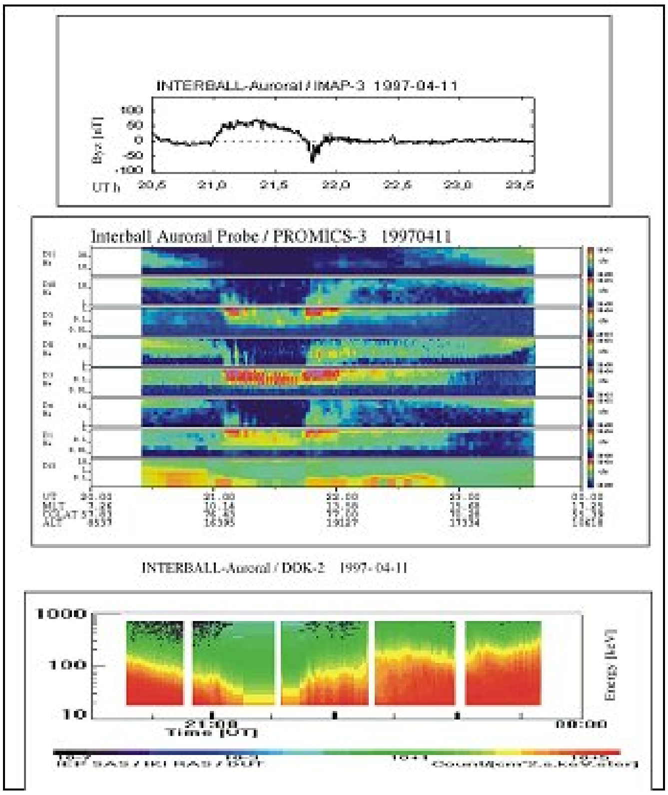

Fig.4.The same as in Fig. 3 for the forth interval (14:10-17:50 UT) plus energetic particle fluxes (PROMICS-3 spectrometer), (see [14], Fig. 5).

magnetometer was in the interval 21:45-21:55 UT i.e. in the boundary cusp at the dusk side. This case demonstrates a collocation of a pair of large-scale FACs in the cusp dusk flank, predominantly in the BC and partially in the CP.

Bottom panel shows ion standard spectrograms from DOK-2 experiment aboard the spacecraft [11]. Note the availability of another population of plasma – energetic ion fluxes with characteristic energy 10s keV in the FAC regions. These fluxes seem more energetic in the cusp dusk flank (BC) where the most intense FACs were concentrated. This indicates that there is a relation between both populations (low energetic and high energetic).

In the next Fig. 5 we have enlarge the dusk portion of the Panel magnetogram to see better the interval of magnetic field disturbances in the dusk flank of the cusp (21:40-22:00 UT). The large pair of FACs appears in the interval 78-77 MLAT predominantly in the BC, between 12:55 and 13:58 MLT. Panel 1 represents the module of the field (B) and Panel 2 is the *Byz* component. We distinguished two events: (1) The first event is that the module *B* has a minimum in the region of *Byz* minimum suggestive for a diamagnetic cavity (?) or a result of SW dynamic sharp pressure drop (Fig. 1); (2) The second event is that the middle of the *B* minimum is characterized by a sharp 40 nT "pulse" of *Byz* (21:46-21:50 UT). For more confident interpretation we examined the *Bx* component which also shows a sharp 40 nT increase of its absolute value (*Bx* is negative) correlating with the *Byz* pulse. This gives us ground to suppose that the magnetometer has encountered a strong FAC in the "diamagnetic" cavity interval.

The width of the current region is about 700 km, i.e. three to four times less that the “diamagnetic” cavity [14].

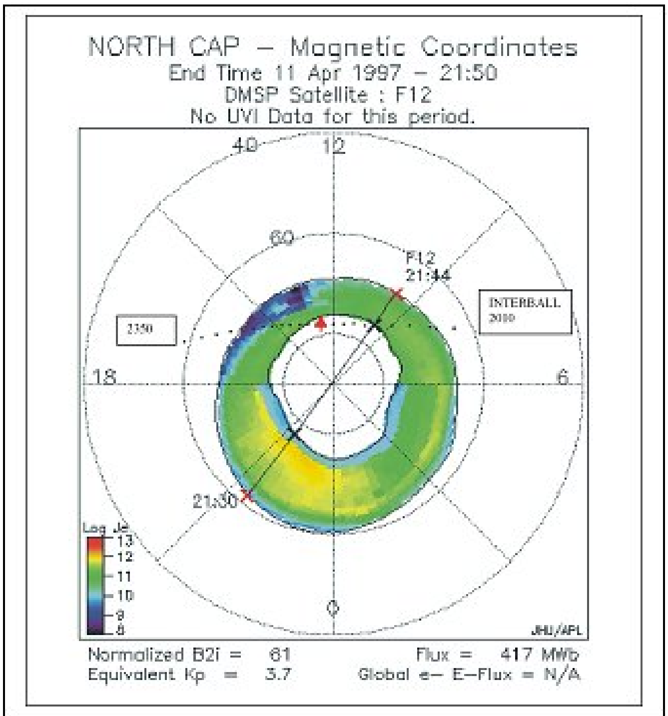

Fig.6.The INTERBALL transit (squares) during the forth orbit overlapped on the auroral oval view determined by DMSP spacecraft. Red arc points the position of a large-scale pair of field-aligned currents in the cusp dusk flank at 21:50 UT (poleward of auroral oval), ([14], Fig. 6).

The next Fig. 6 demonstrates a configuration of AO typical for substorm with a superposition of INTERBALL transit. By chance the INTERBALL crossed the cusp dusk flank at 21:50 nearly simultaneously with the DMSP data time (21:45). It is evident that a large-scale pair of FACs occurred in the dusk side of the polar cap near to its equatorial boundary (BC and CP). This figure demonstrates appearance of two FAC sheets in the cusp which is in contrast with Potemra model [17].

Summary and conclusions

In this paper we presented cases with in situ observations from INTERBALL-Au in the polar cusp and simultaneous images of high latitude ionosphere from DMSP and POLAR. The solar wind data from WIND were considered in terms of multiple ejecta. We have determined field-aligned current (FAC) features corresponding to ejecta structures.

1. The comparison with images provided a further support that FAC systems may occur on open field lines. We have demonstrated an appearance of two sheets of oppositely directed currents in the cusp magnetosphere. The new view on FAC contrasts Potemra model.

2. The examination of energetic particles gives evidence to suppose a simultaneous formation of another event – cusp energetic particles in the region of diamagnetic cavity during ejecta trailing edge reverse shock. The availability of energetic protons (E=10s of keV) in the cusp, collocated with the FAC region might be classified as CEP.

As far as we know cases like the present one giving a relationship of diamagnetic cavity and FACs were not reported till now in the framework of INTERBALL mission [14]. The obtained results might be useful in solving the fundamental problem - the origin of accelerated particles in the upstream of the magnetosphere.

3. An unusually intense FAC system is documented in the cusp during ejecta (Kp = 2) on 11 April, 1997 when the magnetic field disturbance was in the order of 150 nT. Our results together with POLAR study ([16]) help to do a more confident conclusion that the driving process for this event including the reversed convection (sunward) through the polar cap was the reconnection between interplanetary field lines and the lobe field lines. We could conclude that the 15 UT orbit on 10.04.97 which had similar FAC appearance may be related to reconnection of a similar type (?).

4. The amplitude of FAC disturbance could be considered as a new index – “FAC index” a quantity which expresses the amount of energy transferred to the atmosphere in particular when the traditional Kp index is small. Note that it is supposed that during this period (p.3) very intense electric field was transferred to low altitudes where it affected a number of ionospheric and aeronomic processes. We were among the first who showed experimental evidence via INTERCOSMOS Bulgaria (13:00) satellite that FACs were accompanied by strong electric fields [18].

5. During the ejecta the ionosphere got additional quantity of helium ions. We believe that the helium ejecta did change in some extent the chemistry of the Earth’s ionosphere.

It is expected that other experiment aboard INTERBALL-Au like ION or SKA might detect helium ions needed for a detailed study to prove the origin of structures and to find links with high altitude cusp studies which may be a subject of other study.

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