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BEHAVIOR OF IONS NEAR THE SUBSTORM ONSET FROM THEMIS OBSERVATIONS

T.V. Kozelova, B.V. Kozelov *(Polar Geophysical Institute, Apatity, Murmansk region, 184209 Russia)*

Abstract. The substorm associated slow and fast changes of ions near the Earthward edge of plasma sheet is examined using data from THEMIS-C during the late growth and early expansion phases on January 6, 2008. Near the equatorial plane at r~6-6.5 R_E, the spacecraft observed both a signatures of the *b*2*i* and the 29 keV ion isotropy boundaries. The convection boundary of 10-keV electrons was embedded in this ion region. A few minutes before the substorm onset, simultaneously with an intensification of auroral arc in same longitudinal sector, the oscillations of the E and B fields and particles with period ~50-60 s start near this convection boundary. During substorm onset, the injection of higher-energy (81-157 keV) ions occurs simultaneously with the sharp pressure drop of ions with the energies less than 29 keV. The observed variations near substorm onset are consistent the standing Alfven waves coupled to slow magnetosonic mode. Our analysis supports the idea about the ballooning instability in transition region between the inner magnetosphere and active plasma sheet as associated with the initiation of substorm onset.

1. Introduction

The Near-Earth Neutral Line (NENL) [*Hones*, 1979] and the near-Earth Current Disruption (CD) [*Lui*, 1991] models are two basic models of substorm onset and expansion. They are distinguished by the temporal sequence in the formation of the substorm current wedge (SCW) and NENL [*Ohtani*, 2004]. The debate about the first substorm process is continued up to now, because the detailed analyses of the field and particle fluctuations in the near-Earth tail may provide clues to understanding of basic substorm onset processes. A well-known signature of the substorm expansion phase, the '*dipolarization*' is accompanied by the injections of the particles and high level of magnetic fluctuations. Sometimes, ~1 min prior to the sharp substorm dipolarization, the *Bz* magnetic component and the magnetic field elevation angle at r<9 R_E suddenly decrease. This short interval before the dipolarization was named the *explosive growth phase* (EGP) [*Ohtani et al*., 1992]. *Cheng and Lui* [1998] proposed that the kinetic ballooning instability with a period of 50-75 s can cause EGP.

Kozelova and Kozelov [2012] reported a detailed analysis of explosive local magnetic field line stretching just before dipolarization observed by THEMIS-C satellite during the breakup followed by local substorm of 6 Jan 2008. Basing on the simple line-current model, *Kozelova and Kozelov* [2012] proposed that observed magnetic field and particle variations can be a manifestation of the magnetospheric generator of the 3-D meridional current system with the driving electric field in the meridional direction during nonlinear growth of ballooning instability when non-MHD processes are also turning on.

Here we continue the consideration of the substorm event on January 6, 2008, which was began by *Kozelova and Kozelov* [2012]. We further analyze the state of the magnetospheric plasma in the outer region of the trapped energetic ions and demonstrate the structure of the low-frequency waves observed by THEMIS-C at ~6.3 R_E prior to the local substorm onset.

2.1 Ground-based observations

As was shown in [*Kozelova and Kozelov*, 2012], the evening of 6 January 2008 was characterized by ground magnetic activity of 500-800 nT. At ~18:31:50 UT, the brightening began at the arc that was equatorward of all arcs previously existed during growth phase in the field of view of Loparskaya all-sky camera (64.9°N; 113.6°E in CGM coordinates). Azimuthally spaced auroral foldes move from the east to the west. This was the first stage of a (pseudo-)breakup, as it was discussed by [*Voronkov et al*., 2003]. At the moment 18:33:50 UT, the most equatorial auroral arc was brightened again and the auroral breakup began at the moment ~18:34:19 UT. Then the vortex formation and its spatial expansion constitute together the second stage of a breakup [*Voronkov et al*., 2003]. For the interval 18:30-18:44 UT, the THEMIS-C footprint (traced by TSY-98C model) was located nearly auroral breakup region (see Fig.1 from *Kozelova and Kozelov*, 2012).

2.2 THEMIS satellite observations

Near substorm onset under consideration the THEMIS-C satellite was located at (X,Y,Z) = (-6.3, 2.17, -1.8) R_E in GSM coordinates. The THEMIS-C satellite observations are shown in Fig. 1-3.

Fig.1 presents the electron (from 6 eV to 30 keV) spectrum, ion density (from 5 eV to 25 keV), six components of the total ion pressure tensor and total electron pressure. Hereinafter the auroral breakup marked as a moment '1'. Remember here from paper *Kozelova and Kozelov* [2012], that the considered auroral breakup was accompanied by a sudden drop of *Bz* component ('*explosive stretching*') with rate *dBz/dt* = 0.8 nT/s and duration approximately 15 s. After this stretching the THEMIS-C observed a slow dipolarization with small-scale dipolarization bursts of *dBz*>0 in moments '2' and '3'. Here we analyze the dynamic changes and the role of ions both in substorm physics and in a precondition for substorm onset in the premidnight sector of the magnetosphere. The details of the ion behaivior one can see also in Fig. 2, where the ion flux variations for energies 0.1 - 419 keV observed by ESA and SST detectors of THC are shown.

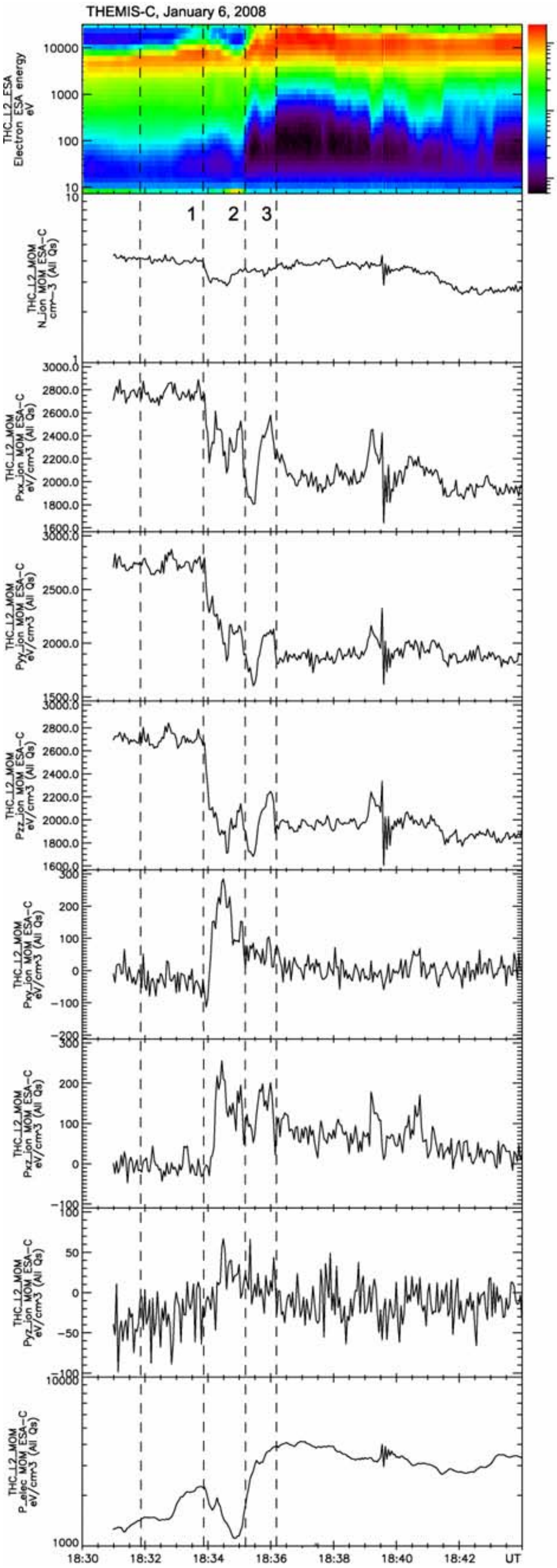

Fig.1. THEMIS-C data between 18:30 and 18:44 UT on Jan 6, 2008. From top to bottom: ESA electron energy flux (< 30 keV), density of ions (<30 keV), six components of pressure tensor of these ions, electron (< 30 keV) pressure.

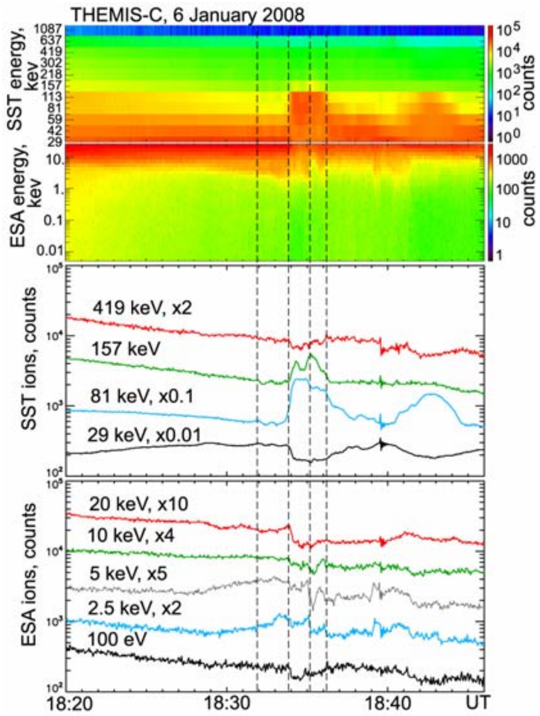

Fig. 2. THEMIS-C data between 18:20 and 18:46 UT on Jan 6, 2008. ESA and SST ion fluxes.

2.2.1 *Ion isotropic boundary.* During the growth phase before 18:28 UT, the ion flux changes depend on the particle energies (Fig.2). The flux of the higher-energy (> 29 keV) ions is decreasing. These particles (*a population '1'*) are 'old' trapped particles on the closed drift paths [*Walker et al.*, 1976; *Sauvaud and Winckler*, 1980] at the region with quasi-dipolar magnetic field lines.

The flux of low-energy (< 29 keV) ions is increasing or nearly constant. These particles (*population '2'*) are convecting toward the THC from the tail and associated with the increase of the cross-tail current during the substorm growth phase. Nearly constant and maximum flux of 29 keV ions (Fig.2) and the isotropic pressure of the low-energy (< 29 keV) ions (Fig.1) may testify about both the *b*2*i* boundary [*Newell et al.*, 1996a, b] and the ion isotropy boundary (IB) [*Sergeev et al.*, 1983].

Note that the geophysical significance of these boundaries is that they represent a good approximation to the earthward edge of the tail current sheet [*Sergeev et al.*, 1983; *Sergeev and Malkov*, 1988; *Newell et al.*, 1998]. In the nightside sector they are usually observed at the distance range from 5 to 10 R_E. Due to different physical processes, these boundaries are formed on the different time scales and sometimes may be quite sharp. In our event, before substorm onset, the *b*2*i* boundary and the 29 keV- ion IB were observed at radial distance 6.3 R_E .

We suppose that these ions from *population '2'* maintain the cross-tail current structure in the (quasi-) dipolar region of the magnetosphere and play an important role in the substorm onset. This region in the magnetosphere can be a source for unstable pressure gradient (or ballooning) modes [*Roux et al*., 1991; *Holter et al*., 1995]. As was shown in [*Kozelova and Kozelov*, 2012], in the end of this substorm growth phase, the convection boundary of 10-keV electrons was embedded in this region near the ~ 29 keV ion isotropy boundary.

2.2.2 ***Substorm ion injection.*** During substorm onset one can see: (i) both the (<29 keV) ion density and pressure are sharply dropping (Fig.1). After this drop the ion pressure was not isotropic. The non-zero non-diagonal components of ion pressure tensor indicate existence of dissipation and violation of the frozen-in condition. Beside, (ii) the short-living injection of fresh higher-energy ions (81 -157 keV) (*population '3'*) occurs (Fig.2). Note that in this time, the THC observed the negative *Ey* component [*Kozelova and Kozelov*, 2012]. The decrease of the electron flux at the open drift paths (Fig.1) indicates that there was no source of electrons tailward the satellite in this time. Simultaneous sharp drop of the low-energy (< 29 keV) ion flux indicates that the old source of this ions (the dominant current carriers) is insufficient to provide the current required for the more tail-like magnetic field configuration. We suggest that the injection of higher-energy ions (81 -157 keV) observed in this time occurs as a result of serpentine cross-tail motion of the ions establishing the plasma sheet current system [*Speiser*, 1965].

Note finally, that (iii) the anticorrelation of the high energy ions and electron fluxes appears. This is usually observed during passage of the WTS across the spacecraft meridian and can be associated with the interchange instability [*Roux*, 1985; *Roux et al*., 1991; *Kozelova et al*., 1986; *Kozelova et al*., 2006]. The substorm onset is a source of these fresh westward drifting energetic ions (protons). These particles with a sharp gradient of the particle flux in the direction of the gradient-**B** drift may excite the drift-wave resonance of magnetic field lines [*Cladis*, 1971] and support (increase) the particle flux oscillations on the transitional boundary from the inner magnetosphere to active plasma sheet.

Thus, in the end of considered substorm growth phase, the THC was located at the region near the ~29 keV ion IB, which become steeper and converge both with the convection boundary for ~10-keV electrons and the boundary of transition between different configurations of the magnetic field. This convergence leads to exposure one more boundary, namely, a boundary between adiabatic and non-adiabatic ion motion, which is very important for non-linear developing of plasma instability as was discussed by [*Kozelova and Kozelov,* 2012]. Just in this region the weak variations with period ~50-60 s are beginning simultaneously with the occurrence of the most equatorial auroral arc ~2 minutes before substorm onset [*Kozelova and Kozelov,* 2012].

2.2.3 Oscillations with ~50-s period. In this section, we demonstrate the structure of the low-frequency waves observed by THEMIS-C prior to the local substorm onset on 6 January 2008.

We use an approach, when the total magnetic field is sum of slow changes and more fast variations of magnetic field. The sliding 54s-smoothed values of the magnetic field, <***B***>, demonstrate slow changes of the field, while the deviations of measured magnetic field from these smoothed values present more fast fluctuations of the magnetic field (*dBx*, *dBy*, *dBz*).The same approach was used for the electric field. The Fig. 3 shows these more fast fluctuations *B* and *E* fields observed by THEMIS-C in the interval near the substorm onset under consideration. Note that the *dBy* component was more variable than other components and wherefore the bottom panel presents 18s-smoothed values of this *dBy* component. On the Fig. 3, the letters *k*, *l*, *m*, *n*, *p* and *q* note the moments of the small peaks (enhancements) of ion pressure near the substorm onset.

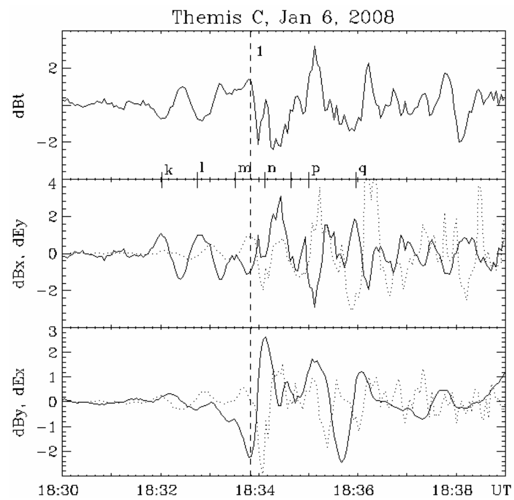

Fig. 3. Low-frequency waves observed by THEMIS-C near the local substorm onset on Jan 6, 2008. From top to bottom: the fluctuations of the magnetic field *dBt* and its components. *dBx* and *dBy* are noted by solid lines. Dotted curves in panels 2 and 3 present *dEy* and *dEx* components of the electric field.

From Fig. 3 one can see, that before substorm onset: (i) the magnetic field variations with period ~50 s are dominated in the *X* direction, *dBx*>*dBz*>*dBy* (*dBz* not shown); (ii) The perpendicular fluctuations of the magnetic field and the electric field *dBx* and *dEy* are ~90 degrees out of phase as for standing Alfven waves; (iii) the ion pressure *dPi* oscillations and the magnetic *dBt* oscillations are ~180 degrees out of phase as for the *slow magnetosonic mode*. We can deduce that the observed magnetic field variations before substorm onset are consistent the standing Alfven waves coupled to slow magnetosonic mode. This conclusion corresponds with results [*Holter et al.*, 1995; *Kozelova et al.*, 2004; *Saito et al.*, 2008a,b]. These oscillations may be excited by the ballooning instability.

Thus, our analysis supports the idea about the ballooning instability near the inner edge of the plasma sheet as a mechanism associated with the initiation of substorm onset.

3. Discussion

In terms of the magnetotail dynamics, substorm initiation models are often grouped into two opposing types: the inside-out and outside-in models. Fig.4 represents these models schematically as it was shown in [Ohtani, 2004]. In the inside-out model (Fig. 4a), CD takes place in the near-Earth region and launches a rarefaction wave tailward. This rarefaction wave makes a local magnetic configuration more stretched in the midtail and sets up a favorable condition for a NENL form. The other model, the outside-in model (Fig. 4b), puts the NENL in the midtail region as the first process. In this model the fast earthward flow is considered as a possible trigger for the CD disturbance in the near-Earth plasma sheet. In short, the NENL model predicts the earthward fast mode wave in the near-Earth region before the CD.

Our analysis show: (i) the absence of a fast earthward plasma flow; (ii) tailward expansion of the CD (simulated equivalent eastward current *djE)* with the velocity ~320 km/s [*Kozelova and Kozelov*, 2012]; (iii) the presence of the *slow magnetosonic mode and* the absence of the *fast magnetosonic* mode wave before the substorm onset, and (iiii) the sharp ion pressure drop during substorm onset. These observed characteristics of disturbance are consistent with the near-Earth initiation CD model [*Lui*, 1991] and the inside-out model for the present substorm.

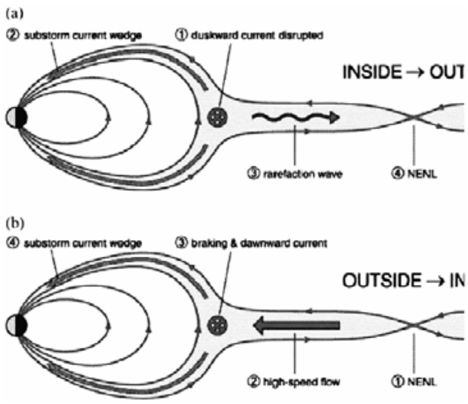

Fig. 4. Schematic diagram for two substorm initiation model (as was shown by Ohtani, 2004). (a) The inside-out model, when a rarefaction wave is a trigger of the NENL. (b) The out-inside model with the earthward fast mode wave. Numbers 1-4 present the time sequence of disturbances

4 Conclusion

We present observations, which are consistent with the ballooning mode signatures in Jan 6, 2008 event at (*X*,*Y*,*Z*) = (-6.3, 2.17, -1.8) R_E in the near-Earth magnetotail. The penetration of the hot electron plasma sheet to the region of trapped energetic ion is a *'pre-condition*' for the substorm onset in the pre-midnight sector of magnetosphere. In the end of the substorm growth phase, three boundaries become steeper and converge: the convection boundary for 10-keV electrons, the ~29 keV ion isotropy boundary and the boundary of transition between different configurations of the magnetic field. This convergence leads to exposure one more boundary, namely, a boundary between adiabatic and non-adiabatic ion motion, which is very important for non-linear developing of plasma instability. The observed variations near substorm onset are consistent the standing Alfven waves coupled to slow magnetosonic mode.

Our analysis supports the idea about the ballooning instability as a mechanism associated with the initiation of substorm onset.

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References

Cheng, C. Z., and A. T. Y. Lui (1998), *Geophys. Res. Lett., 25(21)*, 4091-4095, doi:10.1029/1998GL900093.

Cladis, J. B. (1971), *J. Geophys. Res.,* 76, 2345-2356.

Hones, E. W. (1979), *Space Sci. Rev., 23*, 393-410.

Holter, O., C. Altman, A. Roux et al., (1995), *J. Geophys. Res.,* 100, A10, 19109-19119.

Kozelova, T. V., B. V. Kozelov (2012), THEMIS observations of substorm intensification near inner edge of the plasma sheet, *Proceedings of XXXV Apatity seminar "Physics of auroral phenomena"*, Apatity, p. 21-25.

Kozelova, T. V., B. V. Kozelov, and L. L. Lazutin (2004), *Adv. Space Res., 33*, 774-779.

Kozelova, T. V., L. L. Lazutin, B. V. Kozelov et al., (2006), *Ann. Geophys., 24*, 1957-1968.

Kozelova, T. V., M. I. Pudovkin, L. L.Lazutin et al., (1986), *Geomagnetism and Aeronomy*, 26, 4, 621-627.

Lui, A. T. Y. (1991), *J. Geophys. Res*., *96*, 1849-1856, doi:10.1029/90JA02430.

Newell, P. T., Feldstein, Ya. I., Galperin, Yu. I. and Meng, C.-I. (1996a), *J. Geophys. Res*., 101, 10737-10748.

Newell, P. T., Feldstein, Ya. I., Galperin, Yu. I. and Meng, C.-I. (1996b), *J. Geophys. Res.,* 101, 17419-17421.

Newell P. T., V. A. Sergeev, G. R. Bikkuzina, S. Wing (1998), *J. Geophys. Res*., 103, A3, 4739-4745.

Ohtani, S., K. Takahashi, L. J. Zanetti, T. A. Potemra, R. W. McEntire, and T. Iijima (1992b), , *J. Geophys. Res., 97*, 19311-19324, doi:10.1029/92JA01832.

Ohtani, S., *Space Science Reviews* **113:** 77–96, 2004.

Roux, A. (1985), *Proc. ESA Workshop on Future Missions in Solar, Heliospheric nd Space Plasma Physics*, Garnisch-Partenkirchen, Germany, ESA SP–235, 151-159.

Roux, A., S. Perraut, P. Robert, A. Morane, A. Pedersen, A. Korth, G. Kremser, B. Aparicio, D. Rodger, and R. Pellinen (1991), *J. Geophys. Res*., 96, 17697-17714, doi:10.1029/91JA01106.

Saito, M. H., Y. Miyashita, M. Fujimoto, I. Shinohara, Y. Saito, and T. Mukai (2008b), J. Geophys. Res., 113, A06201,doi:10.1029/2007JA012778.

Sauvaud J.-A. and J. R. Winckler (1980), *J. Geophys. Res*., *85*(A5), 2043-2056.

Sergeev, V. A., M. V. Malkov, and K. Mursula (1993), *J. Geophys. Res.,* 98, 7609-7620.

Sergeev, V. A., E. M. Sazhina, N. A. Tsyganenko et al. (1983), *Planet. Space Sci.,* 31, 1147-1155.

Speiser, T. W. (1965), *J. Geophys. Res*., 70, 17, 4219-4226.

Voronkov, I., E. F. Donovan, and J. C. Samson (2003), *J. Geophys. Res., 108* (A2), 1073, doi:10.1029/2002JA009314.

Walker R. J., K. N. Erickson, R. L. Swanson, and J. R. Winckler (1976), *J. Geophys. Res., 81*(31), 5541-5550