EL — a possible indicator to monitor the magnetic field stretching at global scale during substorm expansive phase: case study

M. Meurant, C. Blockx, E. Spanswick, E.F. Donovan, B. Hubert, J.-C. Gérard, T.S. Trondsen, and M. Connors

Abstract: The Ion Isotropy Boundary (IB) is known to correlate well with the magnetic field inclination at geosynchronous orbit around 00 MLT and therefore provides a way to monitor the magnetotail stretching. Several ways to identify IB have been developed in the literature. Based on *in situ* spacecraft data, Sergeev and Gvozdevsky [12] have defined the IB position using NOAA data and Newell et al. [10] defined a comparable boundary (the b2i boundary) based on Defense Meteorological Satellite Program (DMSP) data. From the ground, Donovan et al. [3] used Meridian Scanning Photometers (MSP) to determine the "optical b2i" and Jayachandran et al. [6] demonstrated the coincidence of the b2i and the equatorward boundary of the SuperDARN evening sector E-region scatter. To complement these methods, an IB determination on a wide range of Magnetic Local Time (MLT) with a high temporal resolution is useful. To do this, Trondsen et al. [13] use IMAGE-FUV-SI12 imager to monitor IB by simultaneous comparison with MSP data during a 7 day period. Recently, Blockx et al., [1] have shown the potential of SI12 data for monitoring the magnetotail stretching during quiet periods. In this study, we focus our attention on the ability of SI12 to provide information on tail stretching during active periods and more specifically during the substorm expansive phase. Because of the dynamic character of expansive phases and mechanisms acting between the plasma sources and ionosphere during this phase, deduceing IB position from auroral optical data is likely impossible. In order to avoid confusion between the physical meaning of IB and its role as a stretching indicator, we validate a stretching determination method using the EL indicator (determined by the Donovan's algorithm applied on SI12 data) instead of IB. For this validation, we use more than 250 isolated substorms observed by IMAGE-SI12 between 2000 and 2002. Simultaneous comparison with GOES-8 and DMSP data allows us to estimate how strong is the relation between the EL position deduced from SI12 and the magnetic field stretching. Time evolutions of the EL position are also presented for different local times during individual events.

Key words: IMAGE, SI12, Substroms, Global Scale, Isotropic Boundary, Equatorial Limit.

1. Introduction

The ion Isotropy Boundary (IB) is known to correlate well with the magnetic field inclination at geosynchronous orbit around the 00 MLT sector, and therefore provide a way to monitor the magnetotail stretching. The IB is a field-aligned surface which separate the region of the magnetosphere where protons bounce between mirror points (adiabatic behavior) and the region where the pitch angle scattering is effective enough to keep the down-going loss cone full (non-adiabatic behavior) [12]. The latitude of this boundary depends on the energy of the particles, with the lower latitudes associated with the highest energies. Consequently to the definition of IB, the main fraction of ion precipitations occurs poleward of the IB and essentially no precipitation exists equatorward of the IB (corresponding to the adiabatic motion of ions).

Received 15 May 2006.

M. Meurant, E. Spanswick, E.F. Donovan, and T.S. Trondsen. Institute for Space Research, University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4, Canada.
C. Blockx, B. Hubert, and J.-C. Gérard. Laboratoire de physique atmosphrique et plantaire, Universit de Lige, 17 Alle du six Aot, 4000 Lige, Belgium.
M. Connors. Athabasca University, 11560 80 Avenue, Edmonton, T6G OR9, Canada.

Several ways to identify the IB have been developed in the literature. Based on data obtained by the NOAA spacecraft, Sergeev and Gvozdevsky [12] defined it as the location where the ratio of precipitating to trapped flux dropped below 1 when the spacecraft moves equatorward. Using DMSP measurements, Newell et al. [10] defined the b2i boundary as the position of the maximum total ion energy flux recorded by the satellite when it crosses the auroral oval. Newell et al. [11] showed a close association between the IB of 30 keV protons detected with NOAA satellites and the b2i boundary. Based on MSP measurements, Donovan et al. [3] developed an algorithm to infer the b2i from latitudinal H_β (486.1 nm) profiles and demonstrated a strong correlation between the b2i boundary and this 'optical b2i'. The ability of the SI12 imager onboard the IMAGE spacecraft to monitor magnetospheric stretching was suggested by Trondsen et al. [13]. Using Donovan's algorithm applied on 916 boundary determinations obtained simultaneously by MSP and the SI12 imager, they find a correlation coefficient of 0.65 suggesting a reasonably well correlated data set. This result opens the possibility of monitoring the b2i across all local times at the cadence of the IMAGE data, i.e. one image every two minutes. The ability of SI12 to monitor the magnetospheric stretching was recently confirmed by Blockx et al. [1] during quiet periods. Instead to propose an IB determination from the SI12 data, Blockx et al. use the MAX-SI12 and MLAT-MAX-SI12 (the maximum intensity of SI12 at each local time and its magnetic latitude respectively) as an indicator of the stretching rate. They present the relation between the IB determined by NOAA and DMSP and the latitude of the maximum proton precipitation observed by SI12. The links between SI12 data (MAX-SI12 and MLAT-MAX-SI12) and the magnetic field distortion was established by comparison GOES-8 data.

These different ways (*in situ* - NOAA and DMSP - ground based - MSP - and remote sensing - SI12 - measurements) to determine the IB have their own positive and negative aspects. *In situ* spacecraft provide a high spatial resolution of the IB identification at each transit across the oval, i.e. usually with a period of roughly one hour. This time scale is relevant to study certain processes such as magnetic storms but too large for monitoring the tail stretching during minutes around substorm onset, even if the oval is crossed around the onset meridian, which may not necessarily happen. The high spatial resolution allows however an understanding of injection mechanisms thanks to spectrometric measurements. The MSP allows a continuous monitoring using multiple magnetic local times but is subsect to the variation of the atmospheric optical thickness. Finally, monitoring by a remote sensing camera, as the SI12 imager, provides a global covering of the entire auroral region with an appropriate time resolution and with a spatial resolution of 100 km. All these types of measurements are complementary to combine global view and high spatial and time resolution.

During active periods like substorm expansive phase, different mechanisms at the origin of particle precipitation into the ionosphere play a more important role than during quiet periods. These different mechanisms may be fresh particles with isotropic pitch angle distribution, electric fields diffusing particles into the loss cone or a magnetic reconfiguration [8]. Because of the more important role of these possible mechanisms of precipitation during substorms, we cannot claim that the limit deduced from optical data also separates the region where protons have an adiabatic motion from the region where protons present a non-adiabatic motion due to the pitch angle scattering caused by the field line stretching. In order to avoid confusion about the physical meaning of the limit, we will consider the Equatorial Limit (EL) instead of the IB. In this study, we determine if the time evolution of the EL during the substorm expansive phase may be an indicator of magnetotail stretching and we present the evolution of EL during three substorms to illustrate the possibilities of EL as a stretching indicator.

2. Data

2.1. IMAGE

The FUV instrument [7] onboard the IMAGE satellite [2] provides three simultaneous snapshot with approximately the same field of view of the auroral region with a 2 min time resolution. The SI12 camera is sensitive to the Doppler-shifted Lyman-α auroral emission and provides images of the entire polar cap. The two other snapshots image the pattern of electron induced emissions in the 140 - 180 nm band (WIC) and in a 5-nm region centered on the OI line at 135.6 nm (SI13). Substorm events used for this study are selected on the basis of the list given by Frey et al.[4]. We only consider "isolated events" and defined them as an event separate from the previous and the next one by at least two hours. The procedure of data selection is extensively developed in Meurant et al. [9]. Restrictions applied to the initial list decrease the number of events from 2437 to 262 events.

The equatorial limit (EL) is deduced from SI12 data using Donovan's algorithm. The process starts with the subtraction of the small background present in SI12 data [5]. In a second step, Donovan's algorithm is applied and consists of a gaussian fit of the longitudinal profile and a determination of the limit at 1.4 σ equatorward of the gaussian fit's maximum. More details concerning the method are provided in [9].

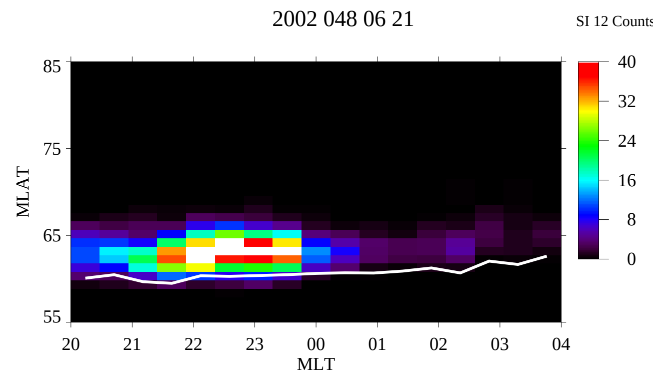

Fig. 1. SI12 data displayed in keogram (2002 048 at 0621UT, i.e. 4 minutes after onset). The solid line represents the EL position determined by the Donovan's algorithm. The grey scale represents the intensity recorded by the SI12 instrument for the MLT-MLAT location.

2.2. GOES-8

The GOES-8 satellite is a geosynchronous spacecraft. It carries a magnetometer providing continuous measurements of the Earth's magnetic field. These magnetic data are used to monitor the magnetic field stretching via the elevation angle. This elevation angle is deduced from B_e (the magnetic field parallel to the satellite-Earth center line and points earthward) and B_p (the magnetic field parallel to the satellite spin axis, perpendicular to the satellite's orbital plane) with the relation $E_l = \arctan(B_p/B_e)$

2.3. DMSP

Spectrograms recorded by the SSJ/4 detectors on board the DMSP spacecraft make it possible to identify several boundaries like the b2i boundary, which is a good proxy of the IB [11]. As developed in [9], in order to evaluate the difference between the EL position determined with SI12 data and b2i positions determined by DMSP crossing, we have selected 304 DMSP crossings in the 20 - 04 MLT sector in the -90 min to +90 min period around onset. Each of these crossings provides the MLAT and MLT of each b2i determination. Because of the DMSP orbit configuration, all these 304 crossing are confined to the 20 - 21.6 MLT sector.

3. Validation

In order to evaluate how strong is the relation between the position of EL and the magnetospheric stretching, we present here two comparisons. For the first comparison, we use simultaneous measurements obtained from GOES-8 and SI12. Figure 2a represents the pattern of the 1313 simultaneous measurements. In order to make it easier to read, Figure 2b reproduces the cloud of Figure 2a by squares representing the mean value of each two degree bins and bars indicating a one sigma deviation. The linear regression using the entire sample is represented by the thick solid line and could be compared to results provided by [12] (thin solid line) and the method developed in [1] applied to our sample (dashed line). A shift of one degree between [12] and [1] was already discussed in [1]. However, we observe a larger shift (2 °) due to a larger width of the oval than during quiet periods investigated in [1]. These results are also very close to those obtained by Sergeev and Gvozdevsky [12], both for absolute values and the slope.

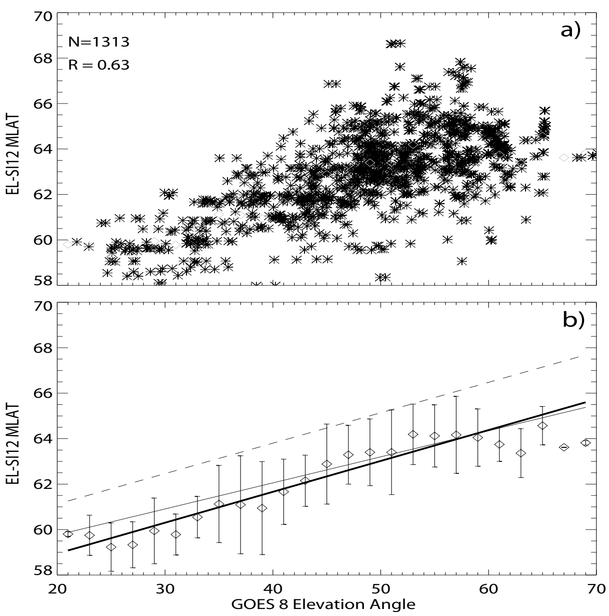

Fig. 2. a) Scatter plot of 1313 elevation angles deduced from GOES-8 measurements in the 21-03 MLT sector vs the magnetic latitude of EL deduced from SI12 data at the same MLT. These measurements are recorded by GOES-8 during the 20 minutes following the onset. Squares represent the mean value of the MLAT of EL for bins of an arbitrary width of two degree of the elevation angle. b) The average values obtained with two degree bins are reproduced for the comparison with error bars representing a 1σ deviation. The solid line represents the linear regression of the entire sample presented in a). For comparison, the solid-dashed line represents the regression obtained in [12] and the dashed line was obtained by the method developed in [1] and applied to our data set.

In the second comparison, we use b2i boundaries determined by the DMSP spacecraft. This boundary is considered as a good proxy of IB and therefore as a good indicator of the tail stretching. Figure 3 represents the comparison of EL and b2i positions obtained at the same location and the same time. Typically, the b2i boundary is located $\sim$1° poleward of the EL position and about 72% of the points are within a +/- 1.5° interval.

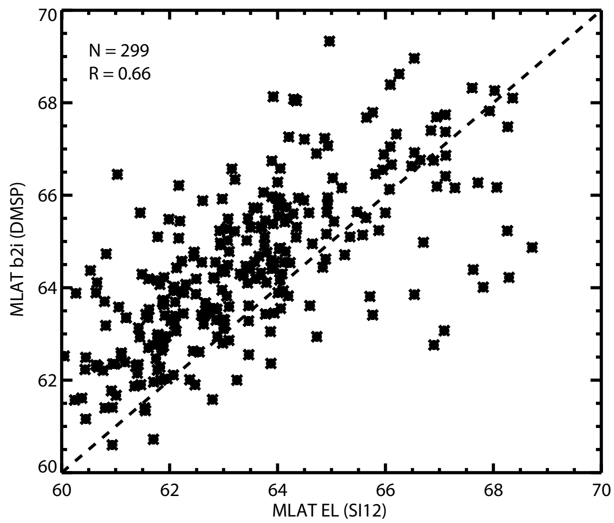

Fig. 3. Scatter plot of b2i obtained by DMSP and EL deduced from SI12 data at the DMSP MLT.

These comparisons indicate that the EL position is dependent on the tail stretching and consistent with previous studies [12] [1]. Based on this indicator, Meurant et al. [9] describe the statistical pattern of the time evolution of the EL position during the expansive phase. For this study, we will consider the case study aspect by the description of three individual cases.

4. Case Study

4.1. First case

The first substorm studied in this paper occured on September 29, 2001, and the onset was observed at 0854UT. The position of the EL deduced from SI12 data are plotted in Figure 4a and elevation angles at the same time and at the same MLT deduced from GOES-8 data are plotted in Figure 4b. The onset was observed at 01.05 MLT, i.e. roughly 3 MLT duskward of the GOES-8 position at onset time. The dipolarisation consecutive to onset is observed by GOES-8 $\sim$ 5 minutes after the onset identification by IMAGE/FUV. By comparison, the EL position starts a poleward motion $\sim$ 8 minutes after the onset identification. This time delay of three minutes can be interpreted as the reaction time between the modification of the magnetic field topology and the consequences on the ionospheric precipitations.

4.2. Second Case

This second substorm occurred on April 02, 2002 at 05:06 UT (Figure 5). The GOES-8 spacecraft was located $\sim$ 2 hours dawnward of the onset position. The dipolarisation is observed by GOES-8 $\sim$6 minutes after the onset identification and presents a sharp increase of the elevation angle. The corresponding poleward motion of the EL position is observed $\sim$ 2 minutes after the magnetic field reconfiguration. The evolution of the EL position doesn't present the sharp variation of the GOES-8 data.

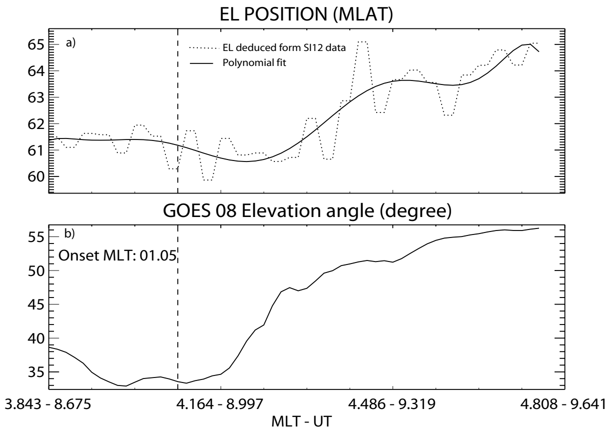

Fig. 4. a) EL position deduced from SI12 data at different MLT or UT during the event of Sept. 29, 2001. Dotted line is for real positions of EL and the solid line for a polynomial fit based on the dotted line. The vertical dashed line represent the time of the onset (08:54 UT) observation at the MLT indicated in panel b). b) MLT / time evolution of the elevation angle deduced from GOES-8 measurements.

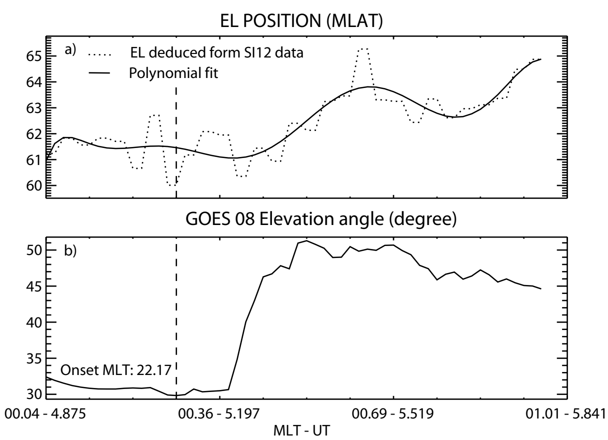

Fig. 5. Same caption as Figure 4 for the Apr. 02, 2002 event. Onset is observed at 05:06 UT.

4.3. Third case

The third substorm occurred on June 13, 2002 at 03:03 UT (Figure 6). The GOES-8 spacecraft was located less than 1 MLT dawnward to the onset position (0.82 MLT). A slight stretching is observed in GOES-8 data before the dipolarisation. The dipolarisation is observed 6 minutes after the onset identification and presents a very sharp increase of the elevation angle. By comparison, the evolution of the EL position at the GOES-8 MLT is more smooth than the GOES-8 observations but presents the same trends.

5. Discussion and conclusion

The determination of the magnetic field reconfiguration during substorm expansive phase is very challenging because of the large scale of the volume of interest and short periods of time of these mechanisms. Since the direct observation of such

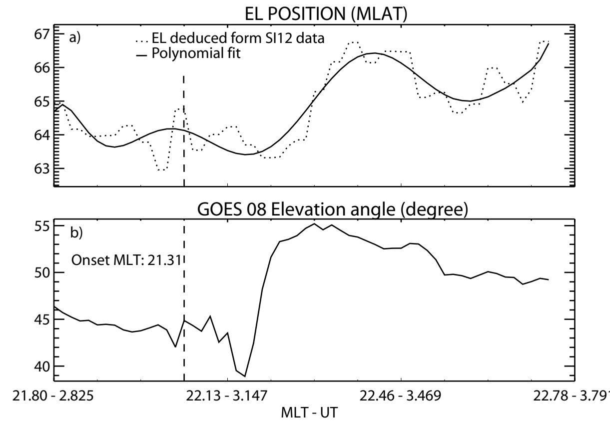

Fig. 6. Same caption as Figure 4 for the June 13, 2002 event. Onset is observed at 03:03 UT.

a topology and its observation is impossible, the most convenient ways are modelling and deduction from available data. Data obtained in the auroral region are very interesting to investigate for this purpose since auroral precipitations are the reflect of magnetospheric processes. In this study, we address the question of the monitoring of the magnetospheric stretching by using optical data recorded by IMAGE/FUV/SI12 in which we apply Donovan's algorithm. These data are relevant for this purpose since they cover large regions and they are obtained at the rate of one image each two minutes. Donovan's algorithm was initially developed to infer a proxy of the Isotropic Boundary. However, we have no evidence allowing to say that the boundary provided by this algorithm during active periods is the footprint of the surface separating the magnetospheric region where proton presents an adiabatic motion to the region where their motion is non-adiabatic. For this region and because the IB is typically located close to the oval's equatorward boundary, we consider the Equatorial Limit (EL) in this study.

By comparison with GOES-8 data for 1313 simultaneous measurements during the 20 minutes following onset, the EL position presents a dependence close to those observed in [12] for the isotropic boundary. This relation between the EL position and the magnetic field stretching is confirmed by the comparison with b2i boundaries determined by the DMSP spacecraft. It appears that the EL is located one degree equatorward of the equivalent b2i boundary.

In the second part of this study, we apply Donovan's algorithm to data obtained during three substorms events and compare the results to elevation angles deduced from GOES-8 data. These comparisons show that the trend of GOES-8 observations are reproduced by the time evolution of the EL position. These similarities give us confidence on the ability to monitor magnetotail stretching thanks to Donovan's algorithm applied to optical global scale data such as SI12 data. Pointing problems affecting SI12 data make the polynomial fit necessary. This step affects the time resolution of information provided by the EL position. Beyond this technical problem, EL appears to be an interesting indicator of the magnetospheric stretching, which opens the door to global surveying of the tail stretching during active periods.

Acknowledgements
M.M is supported by the AIF fellowship, J.C.G. and B.H. are supported by the Belgian National Fund for Scientific Research (FNRS). The IMAGE FUV investigation was supported by NASA through SWRI subcontract 83820 at the University of California, Berkeley, contract NAS5-96020. Participation from J.C.G was funded by the PRODEX program of the European Space Agency (ESA) and the Fund for Collective and Fundamental Research (FRFC grant 2.4517.02). We acknowledge data providers to CDAWeb for the GOES data. The DMSP particle detectors were designed by Dave Hardy of AFRL, and data were obtained from JHU/ APL. We thank Dave Hardy, Fred Rich, and Patrick Newell for the use of the particle detector data.

References

1. Blockx, C., J.-C. Gérard, M. Meurant, B. Hubert, and V. Coumans, Far-Ultraviolet remote sensing of the isotropic boundary and magnetotail stretching, *J. Geophys. Res., 110*, A11215, doi:10.1029/2005JA011103., 2005.

2. Burch, J. L., Image Mission Overview, *Space Science Reviews, 91*, 1-14, 2000.

3. Donovan, E. F., B. J. Jackel, I. Voronkov, T. Sotirelis, F. Creutzberg, and N. A. Nicholson, Ground-based optical determination of the b2i boundary: A basis for an optical MT-index, *J. Geophys. Res., 108*, 1115, doi:10.1029/2001JA009198, 2003.

4. Frey, H. U., S. B. Mende, V. Angelopoulos, and E. F. Donovan, Substorm onset observations by IMAGE-FUV, *J. Geophys. Res., 109*, A10304, doi:10.1029/2004JA010607, 2004.

5. Hubert B., J.C. Grard, D.S. Evans, M. Meurant, S.B. Mende, H.U. Frey and T.J. Immel, Total electron and proton energy input during auroral substorms: remote sensing with IMAGE-FUV, *J. Geophys. Res., 107*, doi:10.1029/2001JA009229, 2002.

6. Jayachandran, P. T., E. F. Donovan, J. W. MacDougall, D. R. Moorcroft, K. Liou, P. T. Newell, and J.-P. St-Maurice, Global and local equatorward expansion of the ion auroral oval before substorm onsets, *J. Geophys. Res., 110*, A05204, doi:10.1029/2004JA010837. , 2005.

7. Mende, S. B., H. Heetderks, H.U. Frey, M Lampton, S.P. Geller, S. Habraken, E. Renotte, C. Jamar, P. Rochus, J. Spann, S.A. Fuselier, J-C Grard, G.R. Gladstone, S. Murphree, and L. Cogger, Far Ultraviolet Imaging from the IMAGE spacecraft : 1 System Design, *Space Science Reviews, 91*, 243, 2000.

8. Mende, S. B., H. U. Frey, T. J. Immel, D. G. Mitchell, P. Brandt and J.-C. Gérard, Global comparison of magnetospheric ion fluxes and auroral precipitation during a substorm, *Geophys. Res. lett., 29*, 12,1609, 10.1029/2001GL014143, 2002.

9. Meurant,M., C. Blockx, E. Spanswick, E.F. Donovan, B. Hubert, J.-C. Gérard, V. Coumans, and M. Connors, EL - a possible indicator to monitor the magnetic field stretching at global scale during substorm expansive phase: statistical study, *J. Geophys. Res., to be submitted*.

10. Newell, P. T., Y. I. Feldstein, Y. I. Galperin, C. I. Meng, Morphology of nightside precipitation, *J. Geophys. Res., 101*, 10,737, 1996.

11. Newell, P. T., V. A. Sergeev, G. R. Bikkuzina, and S. Wing, Characterizing the state of the magnetosphere : Testing the ion precipitation maxima latitude (b2i) and the ion isotropy boundary, *J. Geophys. Res., 103*, 4739, 1998.

12. Sergeev, V.A. and Gvozdevsky,B. B., MT-index - a possible new index to characterize the magnetic configuration of magnetotail, *Ann. Geophys., 13*, 1093, 1995.

13. T. S. Trondsen, E. F. Donovan, N. A. Nicholson, B. J. Jackel, L. L. Cogger, D. Lummerzheim, H. Frey, and M. Meurant, Multipoint Observations of the Ion Isotropy/b2i Boundary, *Annales Geophysicae, to be submitted*.