Nonlinear Processes in Geophysics (1996) 3: 221–227

Nonlinear Processes in Geophysics

Conjectured chaotic nature of the ionosphere-magnetosphere coupling in a reconfigurating magnetosphere

E. B. Wodnicka

Space Research Centre, Polish Academy of Sciences, Bartycka 18A,00716 Warsaw, Poland

Received 4 July 1995 -Revised 5 February 1996 - Accepted 15 May 1996 - Communicated by E. Marsch

Abstract. During substorms the magnetic field configuration changes in time; stretching of the magnetosphere during growth phase is followed by its collapse after the onset of the expansion phase. In this study the ionospheric origin oxygen ion dynamics in a time-dependent magnetosphere is analyzed. An induction electric field of several mV/m due to the reconfigurating magnetic field determines the details of the ion extraction from the auroral topside ionosphere. Two regimes of motion are discernible; a regime in regions far from the equatorial plane where the magnetic moment is conserved and a regime near the equatorial plane, in which the motion produces magnetic moment jumps and oscillations. The time spent by the ion in the regions is determined by the initial characteristics of the ion and by the field transition features. Lyapunov characteristic exponents are calculated to estimate the sensitivity of the system to initial conditions. Their values are higher for orbits with chaotic segments compared with the orbits in the static magnetic field and depend on the amplitude of the induced electric field. It follows from the study that the region of chaos usually localized far beyond 10 R_E in the plasma sheet is expected to approach closer to the Earth (r = 6 - 7 R_E) during substorm associated reconfigurations of the magnetosphere, due to the auroral ionospheric ions.

1 Introduction

The coupling between the high-latitude ionosphere and the near-equatorial regions of the magnetosphere is realized by charged particles moving along the magnetic field lines linking the two regions.

The ionosphere as a source of the magnetospheric plasma was the subject of numerous studies (e. g. Yau et al.,1984,1985,Chappell et al.,1987). In particular it was revealed that the intensity of this source correlates strongly with geomagnetic activity. Substorm time auroral flux density reaches value of 10^{25} cm^{-2}s^{-1}sr^{-1} for oxygen ions. Measurements of the substorm time fluxes of the upflowing ions on board the DE1 and DE2 spacecraft in conjunction in the premidnight sector were interpreted by Reiff et al.(1988) and by Lu et al.(1992). At the altitude of about 2 R_E at 2100 MLT on the 70° MLAT magnetic field line field aligned O^+ ions with energy in the range 0.2 - 3 keV were observed.

Equatorial plasma composition correlates with the auroral activity (Daglis et al.,1993). During active time on the nightside the abundance of O^+ and its contribution to the total energy density increase much more than that of protons,especially at energies of tens of keV. The O^+ population is field-aligned and its energy density correlates well with the AE index during substorm expansion phase (Daglis et al.,1994).

Large scale reconfigurations of the magnetosphere take place during substorms; taillike magnetosphere stretched during the growth phase collapses after the substorm onset to a dipolelike configuration (Lopez et al.,1988;Jacquey and Sauvaud,1994). The amplitude of the induced electric field associated with the time-dependent magnetic field can reach values of 30 mV/m in the equatorial plane (Aggson et al.,1983).

Plasma sheet ion motion in the time-dependent magnetic field with the induced electric field taken into account was investigated by Mauk (1986) in adiabatic approximation and by Delcourt et al. (1990) by solving the full equation of motion. In the latter study it was shown that the motion is not adiabatic and the energization of ions reaches values of tens of keV. A charged particle moving in a magnetic and electric fields is a dynamical system. It can be adiabatic (i. e. there exist integrals of motion), integrable (regular i. e. the integrals of motion are in involution), chaotic (i. e. nonintegrable and with sensitive dependence on initial conditions). Some authors identify chaos with nonintegrability. In the case of static magnetic field reversal models the parameter

$\kappa = \frac{B_z}{B_x}\sqrt{\frac{d}{\rho_z}}$ (Büchner and Zelenyi, 1989) determines the level of chaos(nonintegrability) of the system. It is a function of the strength ($\frac{B_x}{B_z}$) and thickness (d) of the reversal and of the gyroradius (ρ_z) of the particle. When κ approaches unity there do not exist integrals of motion; the motion becomes chaotic (nonintegrable). Chapman and Watkins (1993) and Chapman (1993,1994) parameterized the charged particle equation of motion in a simple time-dependent field reversal with time-independent induced electric field. They showed that the regime of motion regular or chaotic the particle realizes depends on a new parameter p (α t in the original paper) which is a function of time and of the reversal and particle space and time scales. It was shown that there were no trajectories which are regular for all t when $\kappa = 1$; the motion becomes chaotic when $p = p_o t \rightarrow 1$, ($p_o = \frac{\tau_{cz} B_x \rho_z}{T_f B_z d}$, τ_{cz} stands for cyclotron period, T_f - for magnetic field time scale).

The aim of this study is to investigate the motion of oxygen ions flowing up from the auroral ionosphere into the dipolarizing magnetosphere. The induced electric field is taken into account. Two regimes of motion are distinguished: one, in which magnetic moment is conserved, and a motion with jumps and oscillations of the magnetic moment. The details of the motion are implied by the particle initial energy and pitch angle and by the electric field dependence on time and on space coordinates. The motion is discussed referring to the time-dependent reversals. Lyapunov exponents are calculated for trajectories with electric field of increasing amplitude and are compared with exponents for orbits in the static field. It is suggested that the region of chaos, usually localized at radial distances beyond 10 R_E in the plasma sheet may move closer to the Earth due to the ionospheric ions during substorm associated reconfigurations. The paper is organized as follows. In the next section the field model is presented and the initial conditions for the motion equation are formulated. In section 3 ions trajectories are discussed. Section 4 contains the description of energy and pitch angle changes and is followed by section 5 where the magnetic moment evolution is discussed. Lyapunov exponents are the subject of section 6. The summary is presented in section 7. In the appendix the details of the magnetic and electric field model are described.

2 Time - dependent magnetic field.

Any simple, smooth transition between two states of the magnetosphere may be simulated using the formula:

$$\mathbf{B}(\mathbf{r},t) = \mathbf{B}(\mathbf{r},t_o) + f(t)\Delta_t\mathbf{B} \qquad (1)$$

$$\Delta_t\mathbf{B} = \mathbf{B}(\mathbf{r},t_f) - \mathbf{B}(\mathbf{r},t_o) \qquad (2)$$

where t_o, t_f are the begin and the end time of the event of duration $t_d = t_f - t_o$. The initial and final state of the magnetosphere are represented by $\mathbf{B}(\mathbf{r},t_o)$ and $\mathbf{B}(\mathbf{r},t_f)$ respectively and are assumed to be given. The vector potential is of the same form:

$$\mathbf{A}(\mathbf{r},t) = \mathbf{A}(\mathbf{r},t_o) + f(t)\Delta_t\mathbf{A} \qquad (3)$$

The induced electric field is:

$$\mathbf{E}^{ind} = -\frac{\partial\mathbf{A}}{\partial t} = -\frac{df}{dt}\Delta_t\mathbf{A} \qquad (4)$$

The function f(t) features the time characteristics of the transition and the amplitude of the electric field at a given point in space.

In this study the Mead-Fairfield model magnetosphere (Mead and Fairfield,1975) is adopted to simulate the global transition from a stretched taillike configuration (at t_o $K_p > 3$) to the relaxed ,dipolelike state (at t_f $K_p = 0$). The transition duration time $t_d = 10$ min. and f(t) has the form:

$$f(t) = 0.5 + 1/\pi \arctan(\alpha\frac{t}{t_d}) \qquad (5)$$

The transition rate and the amplitude of the induced electric field at a point in space is controlled by the event duration time t_d and by the parameter α which allows to separate the time scale of the field change from the time scale of plasma processes associated with it. For the details of the field model construction see appendix.

In Fig. 1. f(t) and df/dt are plotted for four values of α: 5, 10, 15, 30.

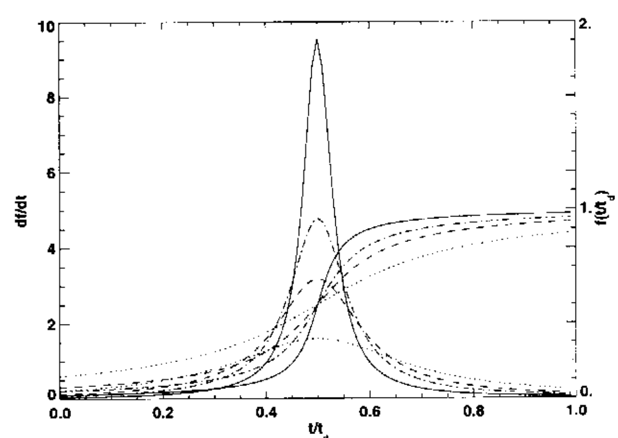


Fig.1. The function $f(t) = 0.5 + 1/\pi \arctan(\alpha t/t_d)$ and its derivative versus time normalized to t_d for $\alpha = 5$ (dotted), 10 (dashed), 15 (dash-dot), 30 (solid).

As $f(t,\alpha)$ approximates the steplike function, the induced electric field is of impulsive type when α tends to infinity. Assuming $\alpha = 10$, the maximum amplitude of the electric field attained in the model is about 3 mV/m. In Fig. 2. the two states of the Mead-Fairfield magnetosphere $\mathbf{B}(\mathbf{r},t_o)$, $\mathbf{B}(\mathbf{r},t_f)$ represented by four auroral field lines (65^o - 68^o MLAT) in the noon-midnight plane are shown.

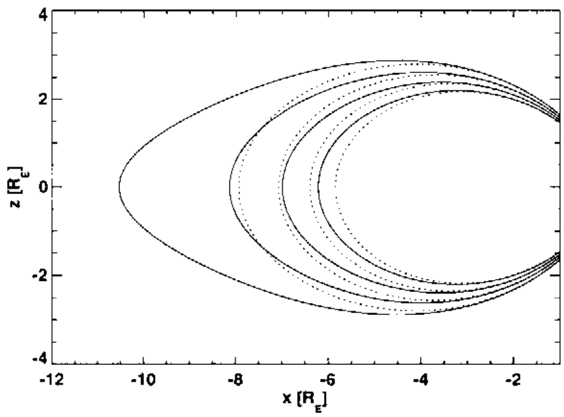


Fig.2. The Mead-Fairfield magnetosphere represented by 65^o - 68^o MLAT lines in the disturbed (solid) and quiet (dotted) states.

In the disturbed state B_x component varies with x from 26.2 nT to 10.6 nT (x = [-8,-11] R_E, z=1 R_E, y=0) . In the quiet state B_x decreases from 24.3 nT at x=-8 R_E to 8.7 nT at x = -11 R_E. B_z component changes from 33 nT to 7 nT. The transition disturbed → quiet may be regarded analogous to the transition in the magnetic field reversal models when the current sheet thickens and may be interpreted as an x-dependent increase of the reversal thickness by a factor of 26.2/24.3=1.186 and 10.6/8.7=1.22 at x=-8 R_E and x = -11 R_E, respectively. As $\frac{B_x}{B_z} \approx 1$, the reversal is weak.

3 Oxygen ion motion.

The full equation of motion

$$\mathbf{r}'' = q/m(\mathbf{E}^{ind}(\mathbf{r},t) + \mathbf{r}' \times \mathbf{B}(\mathbf{r},t)) \qquad (6)$$

is solved numerically for oxygen ions of energy ranging from 0.3 keV to 3.2 keV in correspondence with the results reported by Reiff et al.(1988). The ions are launched from the northern ionosphere from auroral latitude (68^o MLAT) at 2100 MLT at 2 R_E altitude. The initial pitch angle is from the interval 90^o - 180^o. The equation is integrated during a 10 min collapse event; the magnetosphere is reconfigurating from the taillike to the dipolelike state. The motion of four ions identified by initial values of energy and pitch angle will be illustrated in details: (1) 3.2 keV, 90°, (2) 0.3 keV, 90°,(3) 3.2 keV, 180°, (4) 0.3 keV, 180°.

4 Ions trajectories.

The near-equatorial region (NER) is defined as a layer 1.5 R_E thick, z = (- 0.75, 0.75) R_E above and below the equatorial plane (EP). In Fig. 3 ion trajectories are plotted.

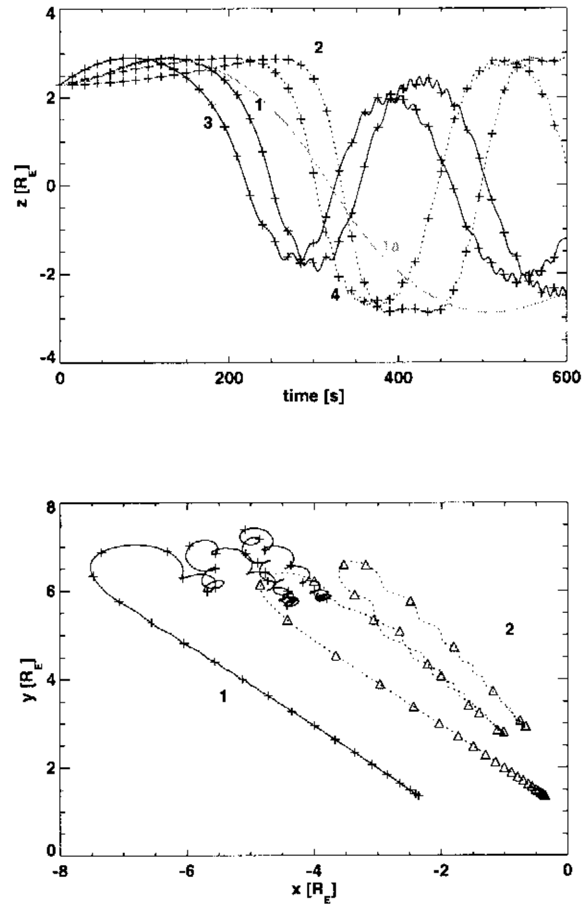


Fig.3. Trajectories of the ions, (top) in (z,t) coordinates, (bottom) as projected in (x,y) plane. Odd numbers are for the 3.2 keV ion, even numbers - for the 0.3 keV ion (1,2 - 90^o, 3,4 - 180^o initial pitch angle). The light curve (1a) is the trajectory of the 3.2 keV,90^o ion in the static filed. The symbols indicate the time in 15-s steps. The curves 1 and 2 in (b) were displaced by vectors [-1,0] and [1,0], respectively.

Ion (3) reaches the EP in 221 s, while ion (1) ion 29 s later. Its meandering in the projection of the motion in the (x,y) plane and fluctuations in z-component are seen.At that time the change of the electric field perpendicular component is large enough to disturb the regularity of gyration. Ions drift about 1 R_E radially earthward and about 1 h westward, mainly due to the polarization drift. Low energy ions cross the EP only twice during the event.Their drift is smaller: 1/2 h in local time. The trajectory of the 3.2 keV,90^o ion in the static field is overplotted for comparison. It crosses the equatorial plane once in the 7th minute of the motion and drifts only 15 min. in local time due to the curvature and gradient of the magnetic field.

5 Energy and pitch angle changes.

The low energy ions (4 and 2) are energized most reaching a maximum energy of 44 - 50 keV, the field aligned ion at half-collapse (302 s),the perpendicular ion 31 s later (see Fig. 4).

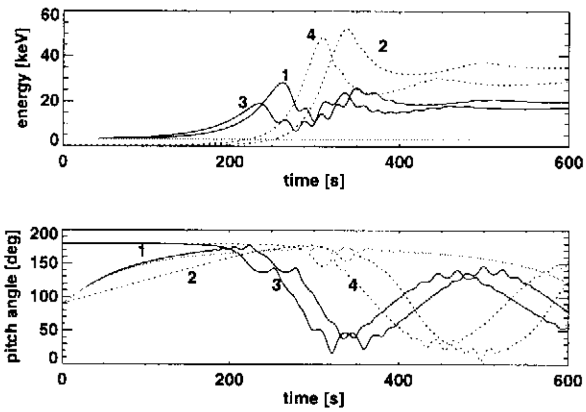


Fig.4. Ions energy and pitch angle versus time. The light curves refer to the static field

At that time the ions are below the EP, at z = - 0.7 R_E and z = - 0.55 R_E. Their pitch angles at that moment are 153° and 157°. They cross the EP again as nearly field-aligned ions as well; pa_{eq} = 10°-30°. Their final energy is at the level of 30 keV. The energetic ions maximum energy (18 and 28 keV for pa_i=180° and 90° ions) is reached at the level of z = - 0.75 R_E with pitch angle value 137° (at 235 and 263 s). Their final energy is at the level: 17 and 19 keV. Summarizing: ionospheric ions are energized substantially during the event reaching the energy level of tens of keV. The maximum energy is reached below the EP where the ion pitch angles are between 137° and 157° .

To elucidate ion pitch angle changes the induced electric field components along the ion trajectory are plotted in Fig. 5. The component perpendicular to the magnetic field attains the level of 3.5 mV/m. Its fluctuations discernible for the energetic ions illustrate the fact that the ion in its meandering follows a sequence of points with sharply different field intensity. The field-aligned component, upward (negative) in the northern hemisphere and downward below the EP drives the parallel motion.

The low energy ions reside about 5 min. in the north hemisphere. They encounter high values of $E_{||}$ before crossing the EP. The perpendicular ion becomes field-aligned at the moment of half-collapse. The increasing value of $E_{||}$ in the south hemisphere again drives the ion to align with the field.

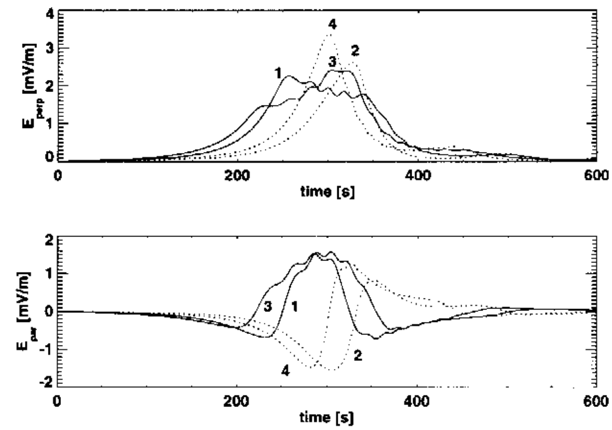


Fig.5. Induced electric field components,(top) perpendicular and (bottom) parallel to the magnetic field as seen by the moving ions.

6 Magnetic moment jumps and oscillations.

The magnetic moment and the cyclotron period as functions of time are plotted in Fig. 6.

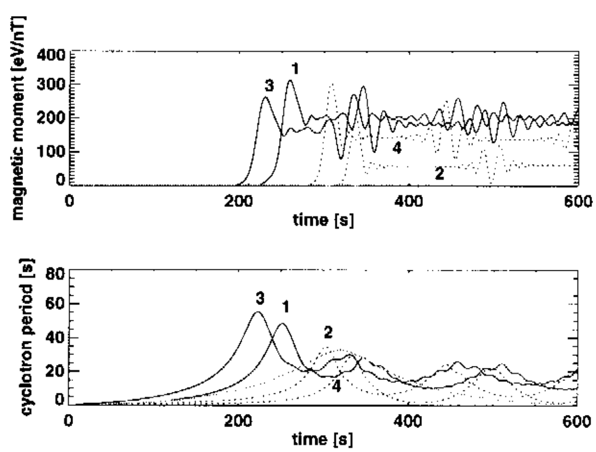


Fig. 6. Ions magnetic moment and cyclotron period versus time. The light curves refer to the ion motion in the static field.

In the static magnetic field (light curve) the 3.2 keV, 90° ion reaches radial distance of 9 R_E where the magnetic field intensity is 31 nT and the ion gyration period is 33 s at the moment of the single crossing of the EP. The magnetic moment changes from 1.65 eV/nT to 5.12 eV/nT due to the spatial changes of the magnetic field along the ion trajectory during one cyclotron period. In the time-dependent case after 3 min. of motion of the 3.2 keV, 90° ion the change of the electric field during the (long) cyclotron period is large enough to result in a jump of the magnetic moment. The jump is followed by oscillations in the NER, which disappear outside the region. The motion of the other ions is of the same nature.

The magnetic field model is reversallike, the ions motion features are similar to the motion of ions traced by Chapman and Watkins (1994) in a time-dependent reversal. The equivalence of the two dynamical systems is conjectured.

The parameter $\kappa = \frac{B_z}{B_x}\sqrt{\frac{d}{\rho_z}}$ can be estimated. In the fourth minute of the event the magnetosphere is in the $K_p = 2$ state, $\frac{B_z}{B_x}$ ranges from 1.37 at x = - 8 R_E to 0.96 at x=-10 R_E. Ion (1) is in the NER , its energy is 10 keV and it gyrates with 17 s period. The cyclotron radius $\rho_z = 1.32$ R_E. $\kappa = 1$ if the reversal thickness d = 0.7 - 1.4 R_E . So the magnetic field model adopted in the study may be regarded as a weak and thick reversal thickening in time; the dynamical system is expected to be chaotic i. e. nonintegrable and sensitively dependent on initial conditions.

7 Lyapunov characteristic exponents.

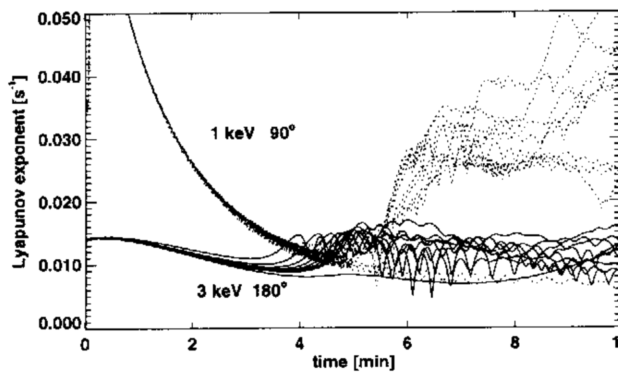
Lyapunov characteristic exponents (LCE) measure the rate of exponential divergence of phase space trajectories of a dynamical system identified by a set of differential equations $\mathbf{x}' = g(\mathbf{x}(t), t)$. The trajectories are infinitesimaly nearby at $t = t_o$. The main points concerning the evaluation of LCE are resumed for completness (see e. g. Lichtenberg and Liebermann, 1983, Eckmann and Ruelle, 1985). For $\mathbf{x} = [x, y, z, x', y', z']$ and $\Delta\mathbf{x} = [\Delta x, \Delta y, \Delta z, \Delta x', \Delta y', \Delta z'] = \mathbf{x} - \mathbf{x}^*$, the exponential divergence means $\mid \Delta x_i \mid = \mid \Delta x_{oi} \mid e^{\lambda(t)t}$. For ergodic systems LCE are defined as asymptotic quantities:

$$\lambda_i = \lim_{t\to\infty} \lambda_i(t) = \lim_{t\to\infty} \frac{1}{t} \ln \frac{\mid \Delta x_i \mid}{\mid x_{oi} \mid} \qquad (7)$$

Introducing $\mathbf{x} = \mathbf{x}^* + \Delta\mathbf{x}$ into the system $\mathbf{x}' = g(\mathbf{x}(t), t)$ one gets, after linearization, a set of linear equations for $\Delta\mathbf{x}$: $d\Delta\mathbf{x}/dt = D_x g\, \Delta\mathbf{x}, D_x g$ is the matrix of partial derivatives of g at x. The system is solved simultaneously with equations for the "reference" trajectory $\mathbf{x}^*$.. To circumvent the divergence of the magnitudes Δx_i and possible folding of the vector $\Delta\mathbf{x}$ to the direction of most rapid growth, the vector frame $\{\Delta x_i\}_{i=1,...,6}$ is reorthonormalized using the Gram-Schmidt procedure (Benettin et al., 1980, Wolf et al., 1985).

Ergodic approach is irrelevant to transient events and there is no mathematical theory for transient accumulative/dissipative chaotic systems. An averaging procedure is required to calculate the phase space averages of LCE. As the problem of the time evolution of the phase space distribution function for transients is open and not addressed in the study, the LCE are computed as functions of time and their final values are considered. There is no reason for rejection the idea that the Lyapunov exponents measure the rate of divergence of trajectories with nearby initial conditions during a transient process. The event simulated in the study is a transient. The sensitive dependence on initial conditions is attributed to chaotic dynamical systems and is quantified by the Lyapunov exponents. LCE were computed as functions of time using the method of Wolf et al.,1985.

The maximal Lyapunov exponent is much more dependent on the amplitude of the electric field than on the initial characteristics of the ions.



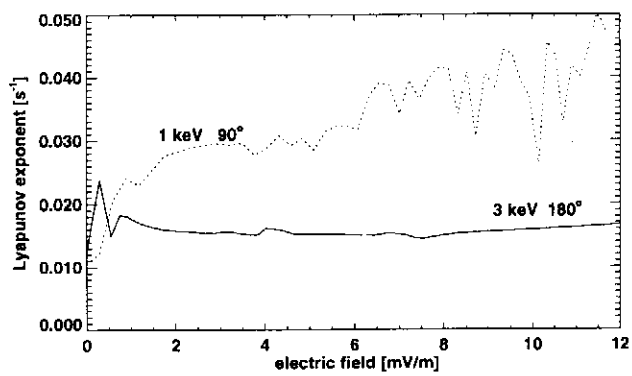


Fig.7. Maximum Lyapunov characteristic exponent LCE for orbits of 1 keV,90° and 3 keV,180° ions. (top) LCE for nine values of the parameter α from the interval 0 - 48, (bottom) LCE versus the maximum amplitude of the electric field encountered by the ion.

It is plotted in Fig. 7 for 1 keV, 90° and for 3 keV, 180° ions . α values from the interval 0 -48 were adopted to simulate electric field of increasing amplitude. If $\alpha =$ 48 then the electric field the 1 keV ion encounters is 13 mV/min which is not an unrealistic value - see observations reported by Aggson et al.(1983). The ion crosses the EP four times and its drift is 3 h westward. The jumps of the magnetic moment are stronger than in the $\alpha = 10$ case. In Fig. 7 (bottom panel) the maximum Lyapunov exponents are plotted versus the maximum electric field value ions encounter to illustrate the difference between the two ions. The sensitivity of the motion to the initial conditions is more pronounced for the

1 keV ion than for the 3 kev ion and it has a tendency to increase with the amplitude of the electric field. Martin (1986) calculated Lyapunov characteristic exponent for a dynamical system composed of a charged particle moving in a two-dimensional magnetic field with an electric field. For that system the LCE values are in the range 0.1 - 0.01 s^{-1} and the author concluded that the chaotic nature of the motion is more important for a thick reversal d $> 2R_E$ than for a thin one.

8 Discussion and conclusions.

The dynamical system investigated in the study is composed of an oxygen ion moving in a three-dimensional time-dependent magnetic field with the induced electric field. The magnetic field may be regarded as a weak and thick reversal thickening in time. The 10 min. long reconfiguration of the magnetic field is nonlinear with respect to time and the induced electric field is of impulsive character. Ions of different initial energy and pitch angles were traced. The changes of energy, pitch angle, magnetic moment and of cyclotron period during the motion were presented. The level of chaos of the system was assessed by computing the Lyapunov characteristic exponents.

It follows from the reported results that: 1. the field-aligned oxygen ions of the energy at the level of several tens of keV are expected in the NER at radial distances 6 - 8 R_E, 2. during the motion of ions in the NER the magnetic moment is not conserved, 3. the jump of the magnetic moment at the EP crossing initiates oscillations with the period nearly equal to the gyration period, 4. the amplitude of the oscillations is in proportion to the value of the perpendicular component of the induced electric field, 5. the trajectories with nearby initial conditions of the 1 keV, 90^o component diverge exponentially in time during the reconfiguration event.

Estimate of the κ parameter which controlls the transition to chaos of parameterizable dynamical system and the positive values of LCE suggest that the ions after the regular, magnetic moment conserving motion far from the NER, realize chaotic segments of trajectories near EP.

The ions supply should be simultaneous with the event beginning to get the effects; if the supply of ionospheric ions is in delay to the beginning of the reconfiguration, the event will be missed by the ions,they will move in the static field. If the event is fast or if ions are too energetic they may again miss the field evolution and the maximal values of $\mathbf{E}^{ind}$ in the NER. So an appropriate combination of ion initial characteristics and the event profile is required to produce chaos in the NER.

The nonadiabaticity effects would be strongest for ions reaching NER just at the half-collapse. This is in convergence with the considerations of Chapman (1993), supposing the two systems are equivalent. In that study it was shown that the particle motion is regular if the gyration and bouncing frequencies are not commensurable and becomes chaotic when the two frequencies become equal. The time dependent adiabaticity parameter constructed by Chapman (1993) $p(t) = p_o t$ approaches unity when the reversal is thick and thickens slowly. Then the motion evolves from regular, magnetic moment conserving to chaotic segments and the time needed to approach chaos is determined by ion and reversal time and space scales. For the transient studied $\kappa \approx 1$, $p_o < 1$ and $t \to T_f$ corresponds to the transition to chaotic regime in the time-dependent reversal .

So, the chaos usually localized in the middle tail may be introduced to the NER located closer to the Earth by ions of ionospheric provenance. Oxygen ions, because of cyclotron period and cyclotron radius larger than for protons, are more effective in the process of chaotization. Martin (1986) and Horton and Tajima (1990) discussed the modification of the collisionless conductivity as the result of chaos. Martin (1986) defined an effective chaotic conductivity inversely proportional to the maximal Lyapunov exponent. Horton and Tajima(1990) gave a modified conductivity formula for collisionless plasma. It follows from those studies that the change of electrical conductivity is the result of the decorrelation of particles velocities in chaotic plasma. So, the ionospheric ions with diverging nonintegrable orbits, populating NER during substorm associated reconfigurations of the magnetosphere may modify the conductivity of equatorial plasma.

Appendix A

Mead-Fairfield model of the Earth's magnetic field (Mead and Fairfiled,1975) is the sum of the dipole field and an external field: $\mathbf{B}(\mathbf{r}) = \mathbf{B}^d + \mathbf{B}^{ext}$. The external field is represented by a polynomial with coefficients depending on the level of geomagnetic activity. For zero tilt angle : $\mathbf{B}^{ext} = [a_1 z + a_2 xz, b_1 yz, c_1 + c_2 x + c_3 x^2 + c_4 y^2 + c_5 z^2]$. Vector potential of the external field was chosen to satisfy Faraday's law $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ and quasineutrality condition $\nabla \cdot \mathbf{E} = 0$:

$$\mathbf{A}(\mathbf{r}) = [b_1 yz^2/2 - c_4 y^3/3, -a_1 z^2/2 - a_2 xz^2/2 + c_1 x + c_2 x^2/2 + c_3 x^3/3, 0].$$

Aknowledgment. The authoress thanks M. Banaszkiewicz for computational assistence and appreciates stimulating criticism of an anonymous referee. The study was supported by the Polish Committee of Scientific Research, grant 6 6229 92 03

References

Aggson,T.L., Heppner,J.P., and Maynard,N.C., Observations of large magnetospheric electric fields during the onset phase of a substorm, *J.Geophys.Res.*,88,3981-3990,1983.

Benettin,G., Galgani,L., Giorgilli,A., and Strelcyn,J.M., Lyapunov characteristic exponents for smooth dynamical systems and for Hamiltonian systems: a method for computing all of them, *Meccanica*, 15, 9-20,1980.

Büchner,J., Zelenyi,L., Regular and chaotic charged particle motion in magnetotaillike field reversals 1. Basic theory of trapped motion, *J. Geophys.Res.*, 94,11821-11842,1989.

Chapman,S. C., Watkins,N.W., Parametrization of chaotic particle dynamics in a simple time-dependent field reversal, *J. Geophys. Res.*,98,165-177,1993.

Chapman, S., Chaotic single particle dynamics in a multi-timescale parameterizable field reversal, *Annales Geophys.*, 11,239-247,1993.

Chapman,S. C., Properties of single-particle dynamics in a parabolic magnetic reversal with general time dependence, *J. Geophys. Res.*,99,5977-5985,1994.

Chappell,C.R., Moore,T.E., and Wait,Jr.J.H.T., The ionosphere as a fully adequate source of plasma for the Earth's magnetosphere, *J.Geophys.Res.*,92,5896-5910,1987.

Daglis,I.A., Sarris,E.T., Wilken,B., AMPTE/CCE CHEM observations of the enrgetic ion population at geosynchronous altitudes, *Ann. Geophys.*,11,685-696,1993.

Daglis,I.A., Livi,S., Sarris,E.T., Wilken,B., Energy density of ionospheric and solar wind origin ions in the near-Eart magnetotail during substorms, *J. Geophys.Res.*, 99,5691-5703,1994.

Delcourt,D.C., Sauvaud,J.A., Pedersen,A., Dynamics of single-particle orbits during substorm expansion phase, *J.Geophys.Res.*,95,20853-20865,1990.

Eckmann,J.-P., Ruelle,D., Ergodic theory of chaos and strange attractors, *Rev. Mod. Phys.*,57, 617-656,1985.

Horton, W., and Tajima,T., Decay of correlations and the collisionless conductivity in the geomegnetic tail, *Geophys. Res. Lett.*,17,123-126,1990.

Jacquey,C., Sauvaud,J.A., Magnetosphere-ionosphere response to an enhanced energetic coupling with the solar wind, *J.Geophys.Res.*,99,11331-11339,1994.

Lichtenberg, A.J., Lieberman,M.A., *Regular and stochastic motion*, Springer Verlag,New York, Heidelberg,Berlin,1983.

Lopez,R. E., Lui,A.T.Y., Sibeck,D.G., McEntire,R.W., Zanetti,L.J., Potemra,T.A., and Krimigis,S.M., The longitudinal and radial distribution of magnetic reconfigurations in the near-Earth magnetotail as observed by AMPTE/CCE, *J. Geophys. Res.*,93,997-1001,1988.

Lu,G., Reiff,P.H., Moore,T.E., and Heelis,R.A., Upflowing ionospheric ions in the auroral region, *J.Geophys.Res.*,97,16855-16863,1992.

Martin,R. F., Chaotic particle dynamics near a two-dimensional magnetic neutral point with application to the geomagnetic tail, *J. Geophys. Res.*,91,11985-11992,1986.

Mauk,B.H., Quantitative modeling of the "convection surge" mechanism of ion acceleration, *J.Geophys.Res.*,91,13423-13431,1986.

Mead,G.D., Fairfield,D.H., A quantitative magnetospheric model derived from spacecraft magnetometer data, *J. Geophys.Res.*,80,523-534,1975.

Reiff,P.H., Collin,H.L., Craven,J.D., Burch,J.L, Winningham,J.D., Shelley,E.G., Frank,L.A., Friedman,M.A., Determination of auroral electrostatic potentials using high- and low-latitude particle distributions, *J. Geophys.Res.*, 93,7441-7465,1988.

Wolf,A., Swift,J.B., Swinney,H.L., and Vastano,J.A., Determining Lyapunov Exponents from a time series,*Physica*,16D,285-317,1985.

Yau,A.W., and Whalen,B.A., Peterson,W.K., and Shelley,E.G., Distribution of upflowing ionospheric ions in the high-altitude polar cap and auroral ionosphere, *J.Geophys.Res.*,89,5507-5522,1984.

Yau,A.W., Shelley,E.G., and Peterson,W.K., Lenchyshyn,L., Energetic auroral and polar ion outflow at DE 1 altitudes:magnitude,composition,magnetic activity dependence,and long-term variations, *J. Geophys.,Res.*,90,8417-8432,1985.