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Role of periodic loading-unloading in the magnetotail versus interplanetary magnetic field B_z flipping in the ring current buildup

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[1] Introducing kinetic corrections into the to BATSRUS code in the magnetotail region leads to fast reconnection rates observed in kinetic simulations and quasi-periodic loading-unloading cycles in the magnetotail during a long period of steady southward interplanetary magnetic field (IMF) B_z (Kuznetsova et al., 2006, 2007). We use the global MHD code BATSRUS output to drive the Fok Ring Current (FRC) model, which then exhibits quasi-periodic oscillations of geosynchronous energetic particle fluxes, similar to "sawtooth" injection profiles. We compare these results with the results of the FRC model driven by BATSRUS for periodically flipping IMF B_z component, without kinetic corrections. The comparison shows the dominant role of quasi-periodic loading-unloading in the tail over the role of flipping IMF B_z component in the formation of geosynchronous fluxes for various energies. This same result is confirmed by the analysis of particle number and energy content within geosynchronous orbit.

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1. Introduction

[2] Observations demonstrate that "sawtooth" profile, quasi-periodic, large-amplitude oscillations of energetic particle fluxes are often detected at geosynchronous orbit during prolonged intervals of steady southward IMF B_z component [e.g., see *Reeves and Henderson*, 2001; *Henderson et al.*, 2006a, 2006b].

[3] In MHD modeling numerical resistivity alone produces a steady magnetosphere for steady solar wind conditions, so in previous simulations periodical flipping of the IMF B_z component was required to reproduce geosynchronous flux oscillations [*Keller et al.*, 2005]. Without flipping of IMF B_z the fluxes were basically flat. *Keller et al.* [2005] used a combination of the University of Michigan's global magnetosphere BATSRUS model [*Powell et al.*, 1999] and the Fok Ring Current (FRC) model [*Fok et al.*, 1995; *Fok and Moore*, 1997] to study the effect of multiple substorms on the ring current. Multiple dipolarizations in the tail were modeled using periodic flipping (changing sign) of the IMF B_z. They found that ionospheric potential increases during period of southward IMF B_z and that energy growths are more dependent on the duration of large ionospheric potential than on the number of substorm dipolarizations.

[4] Recently, *Kuznetsova et al.* [2006, 2007] used the global magnetosphere MHD code BATSRUS to analyze the influence of different dissipation mechanisms triggering magnetic reconnection. They introduced kinetic corrections to the MHD code in the vicinity of the reconnection site in the magnetotail region. This led to the fast magnetotail reconnection rates observed in kinetic simulations and quasi-periodic loading-unloading (multiple reconnection) in the magnetotail for steady southward IMF B_z conditions.

[5] In our previous studies [*Taktakishvili et al.*, 2007] we used the FRC model to investigate the buildup of the ring current during the quasi-periodic loading-unloading in the magnetotail for steady southward IMF. As input to the FRC model we used the results of the simulation obtained with the method of *Kuznetsova et al.* [2007]. As a result we obtained "sawtooth" profile, quasi-periodic, large-amplitude oscillations of energetic particle fluxes at the geosynchronous orbit during prolonged intervals of southward IMF B_z. Therefore, in contrast to the result of *Keller et al.* [2005], geosynchronous flux oscillations are not necessarily caused by IMF B_z flipping/cross polar cap potential variations.

[6] It is important to understand which of the mechanisms plays the dominant role in geosynchronous fluxes enhancement and the ring current buildup: periodical loading-unloading in the tail, or flipping of the IMF B_z component/cross polar potential variation. In this paper we address this

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question by comparing the results of two different simulations: (1) the FRC model driven by output of the BATSRUS code with kinetic corrections in the tail region (the technique of *Kuznetsova et al.* [2007]); (2) the FRC model driven by output of the BATSRUS code without kinetic corrections for periodically flipping IMF B_z component. For this second case we take the same values for the solar wind input conditions (density, velocity, temperature, magnetic field magnitude) as in the first case, but periodically change the sign of B_z in the course of the simulation.

2. Description of the Models Used and Solar Wind Input Conditions

[7] The global magnetosphere MHD model BATSRUS developed at the University of Michigan [*Powell et al.*, 1999] uses solar wind input as an upstream boundary condition. It calculates, self-consistently, a magnetic field, ionospheric potential, and plasma sheet temperature and density distributions that are then used as input to the FRC model. The BATSRUS adaptive grid structure permits increasing resolution where and when it is needed, which in turn makes it possible to perform global simulations with spatial resolution comparable to ion kinetic scales. This allowed *Kuznetsova et al.* [2007] to include kinetic corrections in the MHD equations, taking into account nongyrotropy of ion motion near reconnection sites in the magnetotail region. As a result, *Kuznetsova et al.* [2007] obtained multiple, quasi-periodic reconnection in the magnetotail for steady southward IMF B_z conditions, a result never accomplished before in theoretical simulations.

[8] Unphysical numerical resistivity alone produces a steady magnetosphere for steady solar wind conditions. That is why in previous simulations by *Keller et al.* [2005], periodical flipping of the IMF B_z component was required to reproduce geosynchronous flux oscillations. The simulation by *Kuznetsova et al.* [2007] makes it possible to obtain more physical dynamics of the magnetic reconnection in the magnetotail and opens the way for modeling of the "sawtooth" events: it reproduces a dynamical tail for steady solar wind with a prolonged interval of southward IMF B_z. For more detailed description of their simulation see the paper by *Kuznetsova et al.* [2007].

[9] For our comparative analysis we used two different BATSRUS outputs: (1) The results of the simulation by *Kuznetsova et al.* [2007] for steady southward IMF B_z component with kinetic corrections in the tail region; (2) The results of the simulation for flipping IMF B_z component, without kinetic corrections.

[10] Solar wind input parameters, velocity $V_x = -400$ km/s, $V_y = V_z = 0$, density $n = 2$ cm^{-3}, temperature $T = 2 \cdot 10^5$ K and IMF magnetic field x and y components $B_x = B_y = 0$, are the same for both simulation cases and do not vary in time. Both cases considered the same "startup" period for the IMF B_z component: at 00:00 the IMF B_z is southward ($B_z = -10$ nT), then at 01:05 the IMF turns northward ($B_z = 10$ nT) and stays this way for 3 hours. After that (1) In the simulation by *Kuznetsova et al.* [2007] at 0405 IMF B_z changes sign to southward direction, $B_z = -10$ nT, and remains so for the rest of the simulation, until 0900; (2) In the simulation without kinetic corrections IMF B_z changes sign at 0405 to southward direction, $B_z = -10$ nT, then at 0435 flips back to northward direction $B_z = 10$ nT, and repeats this flipping back and forth with the periodicity of 1 h.

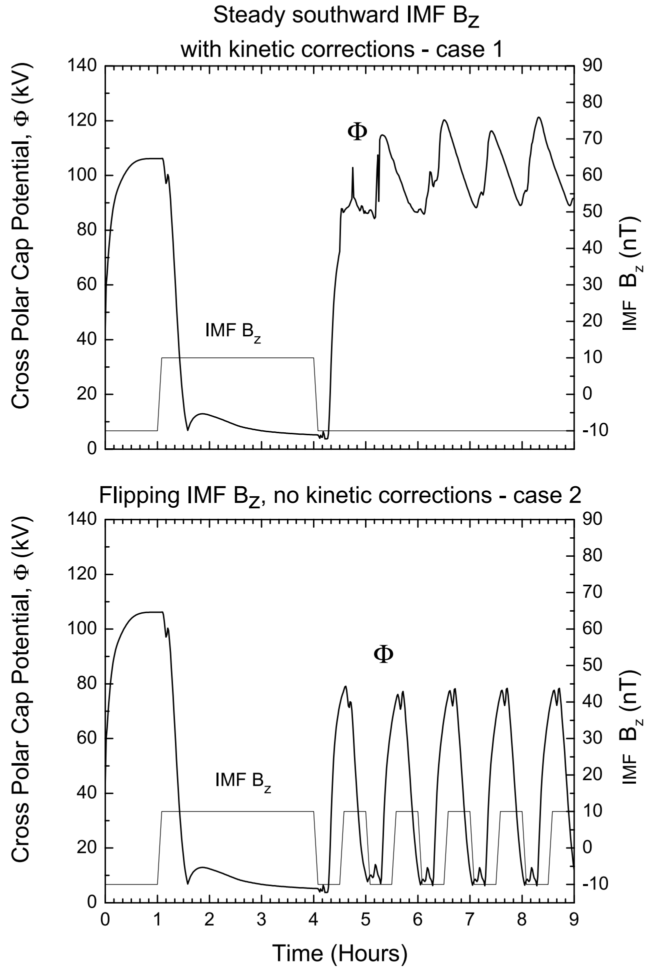

Figure 1. Cross polar cap potential (bold line) and interplanetary magnetic field (IMF) B_z component (thin line) during the whole simulation period. (top) The simulation for steady southward IMF B_z component with kinetic corrections in the magnetotail region, and (bottom) the simulation for flipping IMF B_z component without kinetic corrections.

[11] Figure 1 (top) corresponds to the first case and Figure 1 (bottom) corresponds to the second case. The thin line shows time behavior of the IMF B_z component, and the bold line shows the cross polar cap potential Φ, calculated by BATSRUS code. There is a characteristic drop of Φ for northward IMF B_z component and rapid growth as IMF B_z changes its sign to a southward direction at 0405 in both cases. After that, for the case of steady southward IMF B_z with cyclic loading-unloading in the magnetotail, Φ is high, oscillating with relatively small amplitude as a response to the periodical reconfiguration in the magnetotail. For the case of flipping IMF B_z, after 0435 Φ is lower than in the first case and, responding strongly to the IMF field variation, is oscillating with large amplitude.

[12] The outputs of the BATSRUS model for these two model conditions were used as an input to the Fok ring current (FRC) model [*Fok et al.*, 1995; *Fok and Moore*,

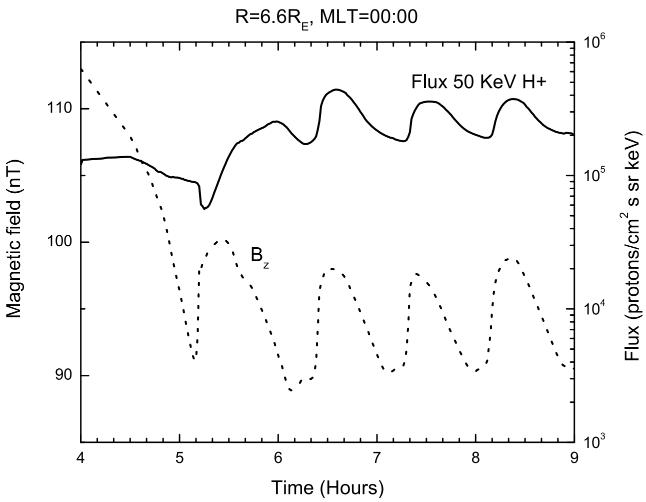

Figure 2. The 50 keV proton flux (solid line) and magnetotail B_z field component (dotted line) at the geosynchronous orbit point $R = 6.6\ R_E$, MLT = 0000, for the case of steady southward IMF B_z component with kinetic corrections in the magnetotail region.

1997]. The FRC model calculates the differential particle fluxes for protons and electrons up to 300 keV by solving a bounce-averaged Boltzmann transport equation for a phase space distribution function along magnetic field lines. The phase space distribution is assumed to be constant along magnetic field lines for given values of the first and second adiabatic invariants. The advection terms include gradient-curvature drift and $\mathbf{E} \times \mathbf{B}$ drift, which includes both corotation and the convection. In addition, the model calculates losses due to charge exchange. The initial source population uses the quiet time ion composition compiled by *Sheldon and Hamilton* [1993], which were obtained using Active Magnetospheric Particle Tracer Explorer/Charge Composition Explorer/Charge-Energy-Mass instrument. However, the initial composition is not that important for our analysis because of the ‘‘loss of memory’’ of the initial distribution, due to the charge-exchange losses, drift-out of the particles in the growth phase of the substorm, and later inflowing of the energized particles accelerated during the loading-unloading cycles in the magnetotail. After the initial setup, the FRC uses as an input temperature and density at the outer boundary of the model (10 R_E on the nightside and the last closed field line on the dayside) and ionospheric potential and magnetic field calculated by BATSRUS code. The pitch angle distribution on the boundary is assumed to be isotropic.

3. Simulation Results

[13] In this section we discuss the results of running of the FRC model simulations for the two above-mentioned cases of the BATSRUS code outputs. We will focus more in detail on the results of the first case, steady southward IMF B_z component with kinetic corrections in the magnetotail region, analyzed by *Kuznetsova et al.* [2007]. We believe that quasi-periodic loading-unloading cycles (multiple reconnection) in the magnetotail obtained in this simulation can explain the ‘‘sawtooth’’ profile, quasi-periodic, large-amplitude oscillations of energetic particle fluxes, often detected at the geosynchronous orbit during prolonged intervals of steady southward IMF B_z component.

[14] In Figure 2 we present the results of the FRC analysis based on the BATSRUS simulation by *Kuznetsova et al.* [2007]. The dotted line corresponds to time variation of the magnetotail B_z field component and solid line to 50 keV proton flux averaged over all pitch angles produced by the FRC model, both calculated at the midnight MLT of the geosynchronous orbit R = 6.6R_E. The drop of the flux at approximately 0510 following the 3 h quiet period of northward IMF B_z is a characteristic ‘‘growth phase dropout’’ caused by the deenergization of the ring current particles in the growth phase of the substorm: the southward turning of the IMF B_z at 0405 causes tailward stretching of the Earth’s magnetic field and particle energy drop due to the conservation of the adiabatic invariants. This dropout occurs just before the first loading-unloading (reconnection) event starts in the magnetotail and is followed by large amplitude oscillations of the geosynchronous flux for the rest of the simulation period.

[15] Therefore, in contrast to the result of *Keller et al.* [2005], geosynchronous flux oscillations are not necessarily caused by IMF B_z flipping/cross polar cap potential variations, but can be the result of spontaneous loading-unloading (multiple reconnection) in the magnetotail for steady southward IMF B_z. The clear correlation between tail magnetic field and flux oscillations indicates that the cause of flux oscillations is bursty injection of energetic particles from the tail. Particles are energized by the inductive electric field generated during magnetic field variation in the course of the periodic loading-unloading in the magnetotail.

[16] Figure 3 shows time series of the geosynchronous proton flux averaged over all pitch angles for three energy channels, 50, 100, and 150 keV at MLT = 1800. All fluxes

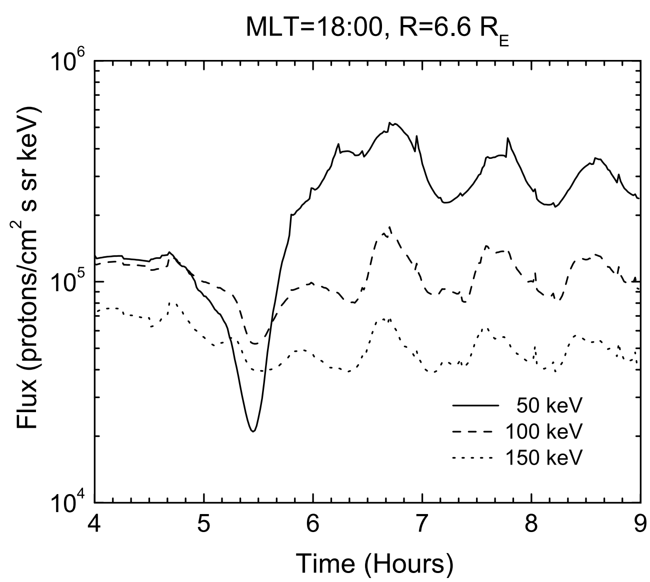

Figure 3. Geosynchronous orbit proton fluxes at MLT = 1800 for three different energy channels, 50 keV (solid line), 100 keV (dashed line), and 150 (dotted line) keV, for the case of steady southward IMF B_z component with kinetic corrections in the magnetotail region.

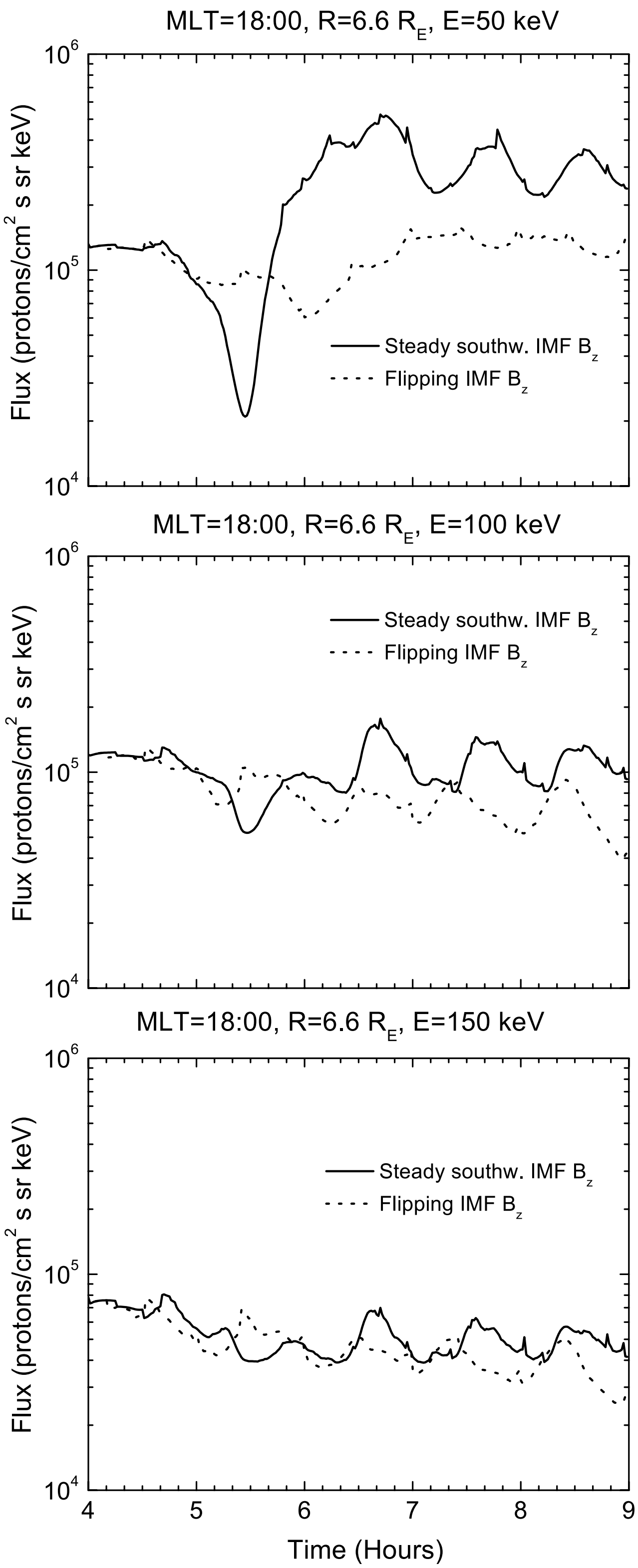

Figure 4. Comparison of geosynchronous orbit proton fluxes at MLT = 1800 for the two simulation cases considered, showing (top) 50 keV, (middle) 100 keV, and (bottom) 150 keV. Solid line corresponds to the case of steady southward IMF B_z component with kinetic corrections in the magnetotail region, and dotted line corresponds to the case of flipping IMF B_z component without kinetic corrections.

exhibit strong oscillations. Note that fluxes for higher energies have more "sawtooth"-like shape than fluxes for lower energies.

[17] The essential question is, which of the two mechanisms is theoretically more important for geosynchronous flux oscillations and ring current buildup: multiple reconnection in the tail, or multiple changes of the sign of the IMF B_z component. To answer this question, we performed the Fok ring current model analysis for the same values of the solar wind input conditions as in the first case, but without kinetic corrections and for periodically flipping of IMF B_z direction (see Figure 1, bottom).

[18] The geosynchronous proton fluxes averged over all pitch angles at MLT = 1800 calculated by the FRC model in this second case are shown in Figure 4 with dotted line for three energies, 50, 100, and 150 keV. For comparison, is plotted with the solid line the flux calculated in the first case (the same as in Figure 3). We can clearly see that the fluxes and their oscillation amplitude are higher for the quasi-periodic loading-unloading in the magnetotail. The difference is especially strong for lowest energy E = 50keV, exhibiting very weak oscillations due to the flipping IMF B_z component. This is in contrast to the result of *Keller et al.* [2005] which demonstrated strong flux oscillations for the lowest energy considered in their simulations, E = 62.5 keV. But, in *Keller et al.* [2005] the value of the flipping IMF B_z component was 2 times higher than in our simulations and solar wind density was taken much higher too (varying from 15 to 20 per cm^{-3}). While the "sawtooth" oscillations are usually observed for low solar wind densities, we suggest that our result strongly indicates that cyclic loading-unloading in the magnetotail for steady southward IMF B_z plays a dominant role in geosynchronous particle fluxes.

[19] The same conclusion can hold for the ring current buildup dynamics. The Fok ring current model allows calculating particle number and energy content within geosynchronous orbit, $R = 6.6R_E$. The time evolution of these quantities for the two cases considered is shown in Figure 5. The solid line corresponds to the first case, and the dotted line corresponds to the second case.

[20] Figure 5 (top) shows the number of protons as a function of time. There is a sharp increase after the first reconnection event at approximately 0510 for the first case. The growth continues after the second reconnection event and is followed by a slow decrease with superimposed weak oscillations due to the subsequent loading-unloading cycles in the tail (solid line). The high level of the number of particles within geosynchronous orbit is maintained by quasi-steady convection into the ring current for steady southward IMF B_z component. The slow decrease is caused by the increasing losses due to charge exchange and magnetic field variation. The number of particles for flipping IMF B_z component (dotted line) also increases in our simulation but remains smaller than in the first case until after the fifth flipping, which is rather unlikely to happen in reality.

[21] Figure 5 (bottom) shows total proton energy within geosynchronous orbit as a function of time. For the first case there is overall growth due to quasi-steady convection with superimposed oscillations due to multiple reconnection (solid line). This combined action of quasi-steady convective and bursty inductive electric fields is in agreement with

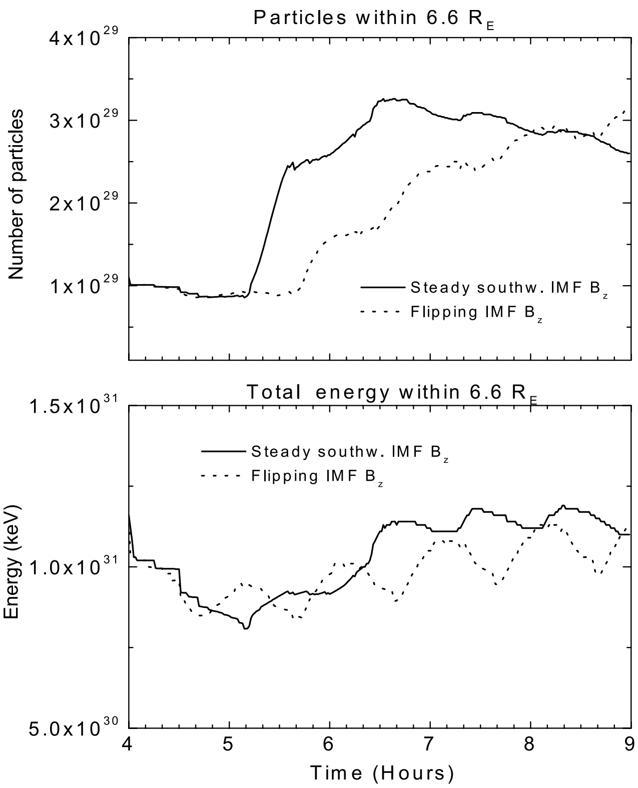

Figure 5. (top) Total number and (bottom) total energy of protons within geosynchronous orbit as a function of time for the two considered cases. Solid line corresponds to simulation for steady southward IMF B_z component with kinetic corrections in the magnetotail region, and dotted line corresponds to simulation for flipping IMF B_z component without kinetic corrections

observations of the ring current during "sawtooth" geosynchronous injections [*Reeves et al.*, 2004] for steady southward IMF B_z component. The energy content for the flipping IMF B_z component (dotted line) also increases in our simulation but remains smaller than in the first case.

[22] Therefore, the analysis of the FRC model results for the two considered cases clearly shows the dominant role of the quasi periodical loading-unloading in the magnetotail (multiple reconnection) for steady southward IMF B_z component over flipping IMF B_z/cross polar cap potential variation in the formation of geosynchronous energetic particle fluxes and ring current buildup.

4. Summary

[23] Using the global magnetosphere MHD code BATS-RUS and the Fok ring current model we demonstrated that proton fluxes in the ring current experience strong quasi-periodic oscillations due to a quasi periodical loading-unloading process in the magnetotail when kinetic effects are taken into account in the reconnection region. Bursty inductive electric fields produced due to magnetic field variations cause quasi-periodical injection of particles into the ring current and corresponding geosynchronous flux oscillations. This mechanism is different from the mechanism considered by *Keller et al.* [2005]. Therefore we demonstrated that geosynchronous flux oscillations are not necessarily caused by IMF B_z flipping/cross polar cap potential variations.

[24] We also studied the relative importance of these two mechanisms for the geosynchronous flux and the ring current buildup. The comparison clearly shows the dominant role of quasi-periodic loading-unloading in the tail over the role of flipping IMF B_z component in the formation of geosynchronous fluxes for various energies. The difference is especially strong for lower energies, for which we obtained rather weak oscillations due to flipping IMF B_z. This is in contrast to the result of *Keller et al.* [2005] which demonstrated strong flux oscillations for relatively low energies. The reason for this discrepancy is that in our simulation the values for the flipping IMF B_z component and the solar wind density are much lower than in simulations by *Keller et al.* [2005]. The "sawtooth" profile injections are usually observed for low solar wind densities. Therefore, our results indicate that quasi periodical loading-unloading in the magnetotail for steady southward IMF B_z is likely to be the mechanism responsible for geosynchronous flux "sawtooth" profile oscillations.

[25] The dominant role of quasi-periodical loading-unloading in the tail in ring current buildup is clear also from the comparison of particle number and energy content within geosynchronous orbit for the two mechanisms. Ring current energy grows in time and oscillates due to combined effect of quasi-steady convective and bursty inductive electric fields for steady southward IMF B_z condition, which is in agreement with observations [*Reeves et al.*, 2004].

[26] In conclusion, we demonstrated that quasi-periodic loading-unloading in the magnetotail for steady southward IMF B_z is able to explain "sawtooth" profile oscillations. However, the period between each tail loading-unloading process and resulting flux oscillations obtained in our simulations (~1 h), is shorter than usually observed "sawtooth" oscillation characteristic time (2–4 h). This disagreement may be associated with a number of additional factors, including conditions in the solar wind and in the inner magnetosphere and ionosphere, that are missing in the simulation with the idealized settings used by *Kuznetsova et al.* [2007]. The further development of the simulation technique includes the use of less diffusive numerical schemes, higher resolution simulation grids, improved representation of inner magnetosphere physics and magnetospheric convection. This is a subject of future work.

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