A Unified Model for Explosive Thinning and Onset of Substorm

L. H. Lyu[1,2] and M. Q. Chen[1,2]

[1]Institute of Space Science, National Central University, Chung-Li, Taiwan 320-01, R.O.C.
[2]Department of Atmospheric Science, National Central University, Chung-Li, Taiwan 320-01, R.O.C.

Abstract

It is shown in this study that explosive thinning of near-Earth plasma sheet and onset of substorm can be modeled based on a similar physical process. Kinetic effects of ions and electrons are included in this study. Electric field is allowed to deviate from potential field in the ionosphere prior to onset of substorm. Based on our model, a vortex distribution of electric field followed by convergent electric field distribution should appear in the pre-midnight region of ionosphere at poleward edge of diffuse aurora near the end of growth phase. A downward field-aligned current resulted from these E-field distributions can trigger explosive thinning of near-Earth plasma sheet. Similar changes of electric field distribution can take place in the near-Earth plasma sheet as a result of localized explosive thinning and non-uniform distribution of energetic ions. An upward field-aligned current wedge can be formed as a result of these types of E-field distributions. The upward field-aligned current can trigger dipolarization of the thin current sheet. A positive feedback mechanism is identified after the initial dipolarization processes. Based on our model, onset of substorm expansion phase can proceed after the initial dipolarization if enough energetic ions have been accumulated in the near-Earth plasma sheet. Likewise, the substorm expansion phase will end when there are not enough energetic ions in the distant tail.

I. Introduction

Onset of substorm has been considered to be the most intractable problems in magnetospheric physics to date. Onset of substorm is defined by a sudden brightening of the most equatorward auroral form which is followed within a few minutes by an explosive expansion of the bright auroral bulge (Akasofu, 1964). Kaufmann (1987) summarized satellite and ground observations and described magnetotail configurations before and after onset of substorm as follows: (1) plasma sheet thinning during growth phase; (2) current disruption at near-Earth plasma sheet and formation of field-aligned current wedges at onset of substorm; (3) dipolarization of magnetic field inside the current wedges; (4) thinning of plasma sheet outside of the current wedges and tail-ward of the current wedges; (5) expanding of dipolarization region during substorm expansion phase.

To understand the triggering mechanism for substorm onset, observations at very high time resolution have been carried out by both ground observations (Pellinen and Heikkila, 1978) and satellite observations in the near-Earth plasma sheet (Ohtani et al., 1992). Pellinen and Heikkila (1978) found that quiet auroral arcs fade briefly in intensity, for about 1 or 2 minutes, just before breakup initiates the expansion phase of a substorm. Ohtani et al., (1992) have found two types of magnetic field reconfigurations: Type I without explosive thinning of current sheet, and Type II with explosive thinning of current sheet. They explained the observed magnetic field variations in Type I events in terms of expansion of current disruption region and expansion of post-midnight field-aligned-current wedge from earthward side to the tailward side and dawnward side of the spacecraft. The hot plasmas in Type I events also seems expand from earthward to the tailward of the spacecraft. However, they cannot explain why there is no explosive thinning associated with the Type I events. The Type II magnetic field reconfiguration events were observed mainly in the pre-midnight region. Since the observed magnetic field variations can not be explained by a simple change on the dawn-to-dusk current intensity in a thin current sheet, a rather complicated change of current intensity over entire flux tube was proposed to explain the changes in two of the three magnetic field components. However, the proposed model apparently still cannot explain the observed variations on the third component of magnetic field. Nevertheless, the observations by Ohtani et al. (1992) have provided very useful information that can help us to understand and to model the triggering mechanism of substorms in the magnetotail.

External trigger mechanisms have also been explored. Many observations (e.g., Kamide, 1991) have shown that substorms can be triggered by northward turning of interplanetary magnetic field (IMF). On the other hand, timing and possibility of substorm triggered by bursty bulk flows (BBFs) from distant magnetotail are still under examination.

II. A New Model for Substorm Onset

Theoretical models for substorm onset can be classified into three categories: (1) models based on magnetic reconnection (e.g. Hones, 1979; Baker and McPherron, 1990; Lui, 2000 and references therein), (2) models based on local instabilities without magnetic reconnection (e.g. Lui, 2000, and references therein), and (3) models based on global magnetosphere-ionosphere (M-I) coupling (e.g., Kan et al., 1988; Kan and Sun, 1996). The original M-I model (Kan et al., 1988) can produce a signature of substorm growth phase, but fail to generate an onset signature. Kan et al. (1994) have proposed an unloading instability to trigger onset of substorm, but did not include kinetic effects in the near-Earth plasma sheet.

A new M-I coupling model for substorm onset is proposed in this study. Both ions' and electrons' kinetic effects are included in this model. The strong electrostatic ionosphere boundary condition assumed in previous M-I coupling model is removed in order to incorporate small-scale phenomena in the ionosphere prior to onset of substorm.

1. Global convection enhancement during growth phase of substorm

The new M-I coupling model for substorm onset follows the traditional way to explain the global enhancement of dawn-to-dusk electric field during the growth phase of substorm. Namely, southward turning of IMF can lead to magnetic reconnection at dayside magnetopause. Dawn-to-dusk induced electric field launched from the reconnection site can propagate across magnetic field line by fast mode waves and along magnetic field line by Alfvén waves to enhance global plasma circulation in both ionosphere and magnetosphere.

2. Formation of vortex distribution of electric field at the poleward edge of diffuse aurora

Reflection of Alfvén waves at the E-region ionosphere can lead to left-hand rotation of electric field with respect to the background magnetic field due to presence of Hall conductivity in this region. Non-uniform distribution of diffuse aurora can lead to non-uniform distribution of conductivities in the night-side E-region (except during the summer time). Conductivities in the night-side E-region ionosphere are expected to be low in 70˚–75˚ MLAT, but relatively high around 65˚ MLAT (e.g., Kamide, 1991). Thus electric fields at 65˚ MLAT region will rotate faster than those in 70˚–75˚ MLAT region.

According to previous study of substorm growth phase (Kan et al., 1988), the conductivities in the ionosphere also enhanced locally in the pre-midnight region due to presence of upward field-aligned current in the quiet time auroral arc. As a result, a vortex distribution of electric field can be formed at the poleward edge of diffuse aurora in the pre-midnight region, with axis of the vortex anti-parallel to the background magnetic field.

Note that enhancement of convection can slow down the rotation of electric field, whereas, reduction in convection can indeed speed up the formation of electric field vortex. This process is analogous to the daily experience that we have to decelerate our car in order to make a sharp turn on the road.

3. Formation of downward field-aligned current in the pre-midnight region

The vortex distribution of electric field at the poleward edge of diffuse aurora in the pre-midnight region can result in convergent movement of electrons. This high-density electrons in the center of the vortex can result in field-aligned electron beam, which moves upward to the near-Earth plasma sheet. This high density electrons can also turn the vortex electric field distribution to a convergent distribution, which can also lunch Alfvén waves with strong down-ward field-aligned current (FAC) at the center of the convergent E-field. The changes of E-field distribution from a vortex to a convergent distribution can also be considered as part of the left-hand rotation process of the electric field due to presence of anisotropic conductivities. The downward FAC, either due to electron beam or carried by Alfvén waves can lead to explosive thinning in the near-Earth plasma sheet.

4. Effective Hall conductivity and Pedersen conductivity in the near-Earth plasma sheet

Due to enhancement of global convection, the magnetic fluxes in the tail lobes increase during the growth phase of substorm. Increasing of magnetic pressure in the lobes can lead to thinning of plasma sheet and increasing of diamagnetic current in the plasma sheet boundary layers.

Nonadiabatic motion of ions in the thin current sheet can change their drift direction from earthward to dusk-ward. Based on Tsyganenko 1989 magnetosphere model, a preliminary test particle simulation has been carried out. Our results (not shown) indicate that this direction change occurs mainly around x=–15~–8 Re.

The dusk-ward-drift ions will gain kinetic energy from the dawn-to-dusk convection electric field. Since electrons' motion in the plasma sheet still follows $E \times B$ drift, it can result in effective Hall conductivity, Hall current, and Hall electric field in the near-Earth plasma sheet. On the other hand, non-adiabatic motion of ions can result in effective Pedersen conductivity, Pedersen current, and Pederden electric field in the near-Earth plasma sheet. The dawn-to-dusk electric field will begin to rotate left-handed with respect to the background magnetic field due to the presence of effective anisotropic conductivities.

It is commonly accepted that there are more energetic ions at the inner edge and in the pre-midnight region of the near-Earth plasma sheet (e.g., Ohtani et al. 1992, and references therein). Non-uniform distribution of energetic ions in the near-Earth plasma sheet can lead to non-uniform rotation of electric field at the end of substorm growth phase.

5. Formation of upward field-aligned current in the pre-midnight region

Since the effective conductivities increase with increasing ion kinetic energy, or with decreasing magnetic strength, or with decreasing current sheet thickness, the explosive thinning due to downward FAC lunched from ionosphere can enhance the effective conductivities in the near-Earth plasma sheet. Thus, in addition to the non-uniform distribution of energetic ions as described in the last subsection, the localized explosive thinning can also enhance non-uniformity of effective conductivities in the near-Earth plasma sheet. Based on a similar process described before in the ionosphere, a vortex distribution of electric field can be formed in the pre-midnight region of near-Earth plasma sheet, with axis of vortex anti-parallel to the background magnetic field. This vortex electric field can result in convergent movement of electrons and result in a high density electron cluster in the pre-midnight region after explosive thinning. This high density electrons in the center of the vortex can result in field-aligned electron beam moves toward the ionosphere. This high density electrons can also turn the vortex electric field distribution to a convergent distribution, which can also lunch Alfvén waves with strong FAC at the center of the convergent E-field. The upward FAC, either due to electron beam or carried by Alfvén waves can trigger dipolarization of substorm onset.

6. Positive feedback for substorm expansion phase

According to our model, the cross-tail current in the thin current sheet consist of diamagnetic current, effective Hall current, and effective Pedersen. The intensity of diamagnetic current depends on the density gradient at plasma sheet boundary layer, whereas the intensity of the effective Hall current and Pedersen current depends on the ratio between ion gyro radius and current-sheet thickness. As a result, after initial dipolarization, the effective Hall current and Pedersen current will decrease with increasing current sheet thickness. However, this process can take place only if enough energetic ions have been accumulated in the near-Earth plasma sheet. This process can provide a positive feedback mechanism for further dipolarization of the thin current sheet. The diamagnetic current can also provide some positive feedbacks to enhance the dipolarization process but in a much slow MHD time scale.

Enough energetic ions in the thin current sheet are also important for expansion of aurora after onset. Hot ions and relatively cold electrons from the plasma sheet can result in strong electrostatic field-aligned potential drop at top of the ionosphere to accelerate electrons (e.g., Wagner et al., 1980, Han and Lyu, 1996). Electrons can also be accelerated along the field line due to expansion of hot ions nearly perpendicular to the magnetic field. Thus, if there are not enough energetic ions in the near-Earth plasma sheet, there may be no expansion phase for the active auroral display.

7. Changes of electric field direction and electric current direction due to anisotropic conductivities in the near-Earth plasma sheet

In all types of classical MHD substorm models, the electric field and currents in the near-Earth plasma sheet are always in the dawn-to-dusk direction. However, in our model, both vortex distribution and convergent distribution of electric field described above infer changes of the E-field directions in the near-Earth plasma sheet prior to the onset of substorm. Changes of the E-field directions may also occur in the duskward side of the upward field-aligned current wedge during substorm expansion phase.

Evidence of changes on electric field directions can be seen from both ground and satellite observations. A northward electric field in the south lobe has been observed by CRRES satellite (Kozelova et al., 2000). The equator-ward electric fields are commonly observed in the ionosphere (Kamide, 1991). They are responsible for the formation of westward electrojet in the midnight region.

The effective Hall current and Pedersen current in the plasma sheet also change their directions according to the local electric field direction. It can be shown (Lyu and Chen, 2000) that the D and V components of magnetic field variations in Type II events observed by Ohtani et at. (1992) can be associated with the effective Hall current and effective Pedersen current of a dusk-to-dawn electric field in either vortex shape or convergent shape of electric field distribution in the near-Earth plasma sheet.

8. Formation of downward FAC in the post-midnight region.

Formation of downward field-aligned current in the post midnight region can be considered as a nature consequence of the current disruption in the midnight region of plasma sheet. The downward field-aligned current is formed at the boundary between dipolarized magnetic field and the tail-like magnetic field in the post-midnight region.

The downward field-aligned current in the post-midnight region can also be associated with the westward electrojet in the ionosphere as discussed in the last subsection. Closure of this westward electrojet in the post-midnight sector can lead to formation of downward FAC in the post-midnight region. Since no explosive thinning has been found in the Type I events observed by Ohtani et al. (1992), we suggest that most of the FACs in the post-midnight region are resulted from low-frequency waves at the leading edge of westward electrojet (Baumjohann, 1991) and the post-midnight boundary of the dipolarization region.

III. Summary and Discussion

In summary, we have shown in this study that explosive thinning of near-Earth plasma sheet and onset of substorm can be modeled based on a similar physical process. According to our model, at the end of growth phase, non-uniform and anisotropic conductivities in the night-side ionosphere can result in a vortex distribution of electric field at pre-midnight and poleward edge of diffuse aurora. This E-field distribution can result in a local enhancement of electron density near the center of the vortex and lead to a downward FAC. This FAC can lead to explosive thinning of near-Earth plasma sheet at dawnward side of this FAC. Non-uniform distribution of energetic ions in the thin current sheet can result in non-uniform distribution of effective Hall conductivity and Pedersen conductivity in the near-Earth plasma sheet. This non-uniformity of effective conductivities increases after explosive thinning. Based on a similar process, a localized intense FAC can be formed, which is associated with electrons flowing from magnetosphere to ionosphere. This FAC can trigger dipolarization of thin current sheet. A positive feedback mechanism has been identified for dipolarization and expansion onset of substorm.

One of the very unique results obtained in this study is the existence of an unusual downward FAC in a very localized region and in very short duration prior to onset of substorm. We have no idea on how to establish observational evidence for this proposed process. However, we believe that the fading of quiet aurora arc prior to onset of expansion phase observed by Pellinen and Heikkila (1978), may have provided some clues for this proposed phenomena.

Our model can also provide a possible explanation for the observed pseudo onset. Since northward turning of IMF can reduce convection in the ionosphere, it can speed up E-field rotation as will as the formation of the downward FAC. The downwad FAC can still result in explosive thinning of near-Earth plasma sheet and lead to another upward FAC for the initial brightening of the most equator-ward auroral arc. However, if there are not enough energetic ions accumulated in the near-Earth plasma sheet prior to the northward turning of IMF, there will be no expansion phase but only a pseudo onset.

In our model, we have introduced effective anisotropic conductivities to describe the plasma kinetic effects in the plasma sheet. However, there are also wave-wave and wave-particle interactions that may result in low-frequency large-scale impact on the global field configuration (e.g., Lyu et al., 2001). Modulation effects from these high-frequency interactions have not been included in our model. Previous theoretical studies of substorm onset have provided useful information in these areas (e.g., Lui, 2000, and references therein). It can certainly improve our understanding of substorm onset process if we can incorporate these wave-wave and wave-particle interactions in our model in the future.

IV. Acknowledgment

This research is supported by NSC grant 89-2111-M-008-054 to the National Central University.

V. References

Akasofu, S.-I., 1964: The development of the auroral substorm, *Planet. Space Sci.*, **12**, 273.

Baker, D. K., and R. L. McPherron, 1990: Extreme energetic particle decreases near geostationary orbit: A manifestation of current diversion within the inner plasma sheet, *J. Geophys. Res.*, **95**, 6591.

Baumjohann, W., 1991: Electrodynamics of active auroral forms: westward traveling surges and omega bands, in *Auroral Physics*, p. 361, edited by C.-I. Meng, M. J. Rycroft, and L. A. Frank, Cambridge University Press, Cambridge.

Han, J. R., and L. H. Lyu, 1996: Simulation study of field-aligned potential drop in discrete aurora, *Proceedings of the Fifth (1996) Atmospheric Science Symposium*, June 26-29, 1996, Tao-Yuan, Taiwan, R.O.C., pp. 116-121.

Hones, E. W., Jr., 1979: Transient phenomena in the magnetotail and their relation to substorms, *Space Sci. Rev.*, **23**, 393.

Kamide, Y., 1991: The auroral electrojets: Relative importance of ionospheric conductivities and electric field, in *Auroral Physics*, p. 385, edited by C.-I. Meng, M. J. Rycroft, and L. A. Frank, Cambridge University Press, Cambridge.

Kan, J. R., L. Zhu, and S.-I. Akasofu, 1988: A theory of substorms: Onset and subsidence, *J. Geophys. Res.*, **93**, 5624.

Kan, J. R., L. H. Lyu, and C. F. Kennel, 1994:Unloading instability triggered by Alfvén waves disrupting the cross-tail current in the near-Earth plasma sheet, in *Substorms-2, Proceedings of the Second International Conference on Substorms, Fairbanks, Alaska, March 7-11, 1994,* edited by J. R. Kan, J. D. Craven, and S.-I. Akasofu, p. 183, Geophysical Institute, University of Alaska Fairbanks.

Kan, J. R., and W. Sun, 1996: Substorm expansion phase caused by an intense localized convection imposed on the ionosphere, *J. Geophys. Res.*, **101**, 27,271.

Kaufmann, R. L., 1987: Substorm currents: Growth phase and onset, *J. Geophys. Res.*, **92**, 7471.

Kozelova, T. V., B. V. Kozelov, and L. L. Lazutin, 2000: Substorm large impulsive electric fields observed by CRRES, *Proc. 5th International Conference on Substorms*, St. Petersburg, Russia, 16-20 May 2000 (*ESA SP-443*, July 2000).

Lui, A. T. Y., 2000: Substorm expansion onset mechanism debated, *EOS*, **81**, 70.

Lyu, L. H., and M. Q. Chen, 2000: A kinetic M-I Coupling model with unloading instability at onset of substorm, *Proc. 5th International Conference on Substorms*, St. Petersburg, Russia, 16-20 May 2000 (*ESA SP-443*, July 2000) pp. 315-318.

Lyu, L. H., M. Q. Chen, and W. H. Tsai, 2001: A theoretical model for cross-scale simulation of collisionless plasmas in space, *Proceedings of the seventh (2001) Atmospheric Science Symposium*, September 26-29, 2001, Taipei, Taiwan, R.O.C.

Ohtani, S., K. Takahashi, L. J. Zanetti, T. A. Potemra, R. W. McEntire, and T. Iijima, 1992: Initial signatures of magnetic field and energetic particle fluxes at tail reconfiguration: Explosive growth phase, *J. Geophys. Res.*, **97**, 19,311.

Pellinen, R. J., and W. J. Heikkila, 1978: Observations of auroral fading before breakup, *J. Geophys. Res.*, **83**, 4207.

Wagner, J. S., T. Tajima, J. R. Kan, J. N. Leboeuf, S.-I. Akasofu, and J. M. Dawson, 1980: V-potential double layers and the formation of auroral arcs, *Phys. Rev. Lett.*, **45**, 803.