A KINETIC M-I COUPLING MODEL WITH UNLOADING INSTABILITY AT ONSET OF SUBSTORM

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ABSTRACT

Onset of substorm due to unloading instability is proposed in this paper based on a kinetic M-I coupling model. Nonadiabatic motion of energetic ions in the near Earth plasma sheet can lead to an effective Hall conductivity in the plasma sheet similar to the Hall conductivity in the E-region ionosphere. Hall conductivity can lead to left-hand rotation of electric field with respect to the background magnetic field. Nonuniform distribution of diffuse aurora in ionosphere and nonuniform distribution of energetic ions in plasma sheet can result in nonuniform distribution of Hall conductivity. Nonuniform Hall conductivity can lead to nonuniform rotation of electric field. As a result of M-I coupling process, a southward curl-E field distribution can be found in the premidnight region of near Earth plasma sheet prior to the onset of substorm. An electron time scale dynamo process in response to the southward curl-E field distribution can lead to formation of premidnight upward field-aligned current. The premidnight upward field-aligned current can initiate dipolarization in the midnight region and trigger unloading instability. Unloading instability will grow if there are enough energetic ions in the near Earth plasma sheet at onset of substorm. Enough energetic ions in the plasma sheet imply that the cross-tail current is mainly contributed by the Hall current. Positive feedback between thickening of current sheet and reduction of Hall current leads to amplification of current disruption and onset of substorm expansion phase. Our model can explain the observed magnetic field signature during explosive thinning prior to onset of substorm. Our model can also explain onset of substorm due to northward turning of IMF.

1. 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 wedge at onset of substorm; (3) dipolarization of magnetic field inside the current wedge; (4) thinning of plasma sheet outside of the current wedge and tail-ward of the current wedge; (5) expanding of dipolarization region and current wedge during substorm expansion phase. Current theoretical models for substorm onset can be classified into three categories: models based on magnetic reconnection, models based on local instabilities without magnetic reconnection [e.g., Lui, 2000], and models based on global coupling and/or global instabilities [e.g., Kan and Sun, 1996]. The kinetic magnetosphere-ionosphere (M-I) coupling model proposed in this paper belongs to the last category.

2. THE M-I COUPLING UNLOADING INSTABILITY

The M-I coupling processes have been studied extensively by the Alaska substorm research group in the past 15 years [e.g., Kan and Sun, 1985; Kan et al., 1988; Kan and Sun, 1996]. Their original 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 based on the M-I coupling process. The tail current is believed to be disrupted by an incident Alfvén wave from ionosphere and cause a substorm onset. However, without considering plasma kinetic effects in the near Earth plasma sheet, it has been shown that the MHD version of M-I coupling unloading instability model is unable to produce an instability to trigger substorm onset (L. Chen, private communications, 1994).

To improve Kan et al.’s 1994 model, the ion and electron kinetic effects in the thin current sheet are included in the present study. The reason to include ions’ kinetic effects is that the thinning of plasma sheet during growth phase can result in nonadiabatic motions of energetic ions in the near Earth plasma sheet. The E × B drift is no longer applicable to the energetic ions in a thin current sheet. The reason to include the electron kinetic effect is simply because that the substorm onset is taking place on an electron time scale.

Our model starts from a simple idea that, according to the Faraday’s law, dipolarization at substorm onset must result from a southward curl-E field distribution. Therefore, to determine an M-I coupling process that can produce a southward curl-E field distribution in the near Earth plasma sheet will be the first step of this study.
From the Faraday’s law and the Ampere’s law, one concludes that the curl-E and curl-J are in the opposite directions in the source region of a changing magnetic field. Namely, there must be a “dynamo” process in the source region to trigger dipolarization. Therefore, our second step is to find an electron time scale “dynamo” process in response to the southward curl-E field distribution to trigger substorm onset.

Our final step is to find a positive feedback mechanism that can enhance current disruption and dipolarization to result in substorm expansion onset.

2.1. Southward Curl-E Distribution: A Result of M-I Coupling

Southward turning of IMF can lead to magnetic reconnection at dayside magnetopause. Dawn-to-dusk induced electric field launched from the reconnection site will propagate across the polar cap to the night-side ionosphere. M-I coupling through Alfvén waves can enhance global plasma circulation in ionosphere and magnetosphere. 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. Nonuniform distribution of diffuse aurora can lead to nonuniform 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.

Ions in the plasma sheet will gain kinetic energy from the dawn-to-dusk convection electric field as their drift direction changes from earthward to duskward. A preliminary test particle simulation, based on Tsyganenko 1989 magnetosphere model, indicates that this direction change occurs mainly around $x=-15$–8 Re. Since electrons’ motion in the plasma sheet still follows $E \times B$ drift, we can expect to have effective Hall conductivity, Hall current, and Hall electric field in the near Earth plasma sheet. Nonuniform distribution of energetic ions in the near Earth plasma sheet can further enhance the nonuniform rotation of electric field at the end of substorm growth phase. We expect that there are more energetic ions at the inner edge of plasma sheet and in the premidnight region of the near Earth plasma sheet.

Convection electric field in the region with magnetic field connected to the plasma sheet is mainly maintained by plasma flow in the F-region ionosphere. F-region ionosphere is characterized by relatively high density plasma (higher than the density in the magnetosphere), but relatively low Hall and Pedersen conductivities (lower than the conductivities in the E-region ionosphere). The cross-polar-cap convection flow in the F-region will reduce the rotation of electric field. Therefore, it takes time (~30 minutes) to reach a southward curl-E distribution in the premidnight region of near Earth plasma sheet as shown in Figure 1.

Our final step is to find a positive feedback mechanism that can enhance current disruption and dipolarization to result in substorm expansion onset.

2.2. Triggering Mechanism in Electron Time Scale

The end of growth phase is characterized by incident Alfvén waves carrying non-uniformly rotated electric field to make a southward curl-E distribution in the premidnight region of near Earth plasma sheet. Within a few electron gyro periods, the $E \times B$ drift of electrons can lead to a convergent movement of electrons and convergent Hall electric field in this region. Thus, a field-aligned potential drop is formed in electron time scale. This potential drop will accelerate electrons and result in an intense upward field-aligned current in the premidnight region. This should be the cause of sudden brightening of the most equatorward auroral arc.

2.3. Positive Feedback Mechanism due to Ion Kinetic Effect in the Plasma Sheet

The formation of premidnight upward field-aligned current can trigger dipolarization in the midnight region of near Earth plasma sheet. A positive feedback mechanism is needed to produce an expansion phase of substorm. From the sketches of pre-onset electric field and current distributions shown in Figure 1, we can see that the dawn-to-dusk cross-tail current is mainly contributed by the Hall current in the near Earth plasma sheet. Since the effective conductivities in the near Earth plasma sheet is strongly depend on the effective current sheet thickness, when the thickness of current sheet increases after the initial dipolarization, the effective conductivities in this region will reduce, and
the dawn-to-dusk Hall current will be disrupted. The disruption of dawn-to-dusk Hall current will further increase current sheet thickness. This is a positive feedback mechanism for the substorm expansion phase.

2.4. Formation of Field-Aligned Current in the Post-Midnight Region

Formation of downward field-aligned current in the post midnight region is associated with the current disruption in the midnight region and the formation of westward electrojet in the ionosphere. The downward field-aligned current is located at the boundary between dipolarized magnetic field and the tail-like magnetic field in the post-midnight region. Aurora electrons in the premidnight and midnight region will drift eastward to form a strong westward electrojet due to the presence of equatorward electric field in that region [e.g., Kamide, 1991]. The mapping of this equatorward electric field to the near Earth plasma sheet is the earthward electric field shown in Figure 1. Mapping of this electric field can also lead to a northward electric field in the south lobe, as has been observed by CRRES satellite [Kozelova et al., 2000].

3. DISCUSSION

3.1. Magnetic Field Signature during Explosive Thinning

Explosive thinning of near Earth plasma sheet prior to onset of substorm has been observed by Ohtani et al. [1992]. Our model can explain the observed magnetic field signature during the explosive thinning events.

According to our model, Hall current and Pedersen current distribution at the inner edge of plasma sheet prior to the onset of substorm are shown in Figure 1. The sunward Hall current can result in a dawnward perturbed magnetic field (δBx < 0) in the north lobe, but duskward perturbed magnetic field (δBx > 0) in the south lobe. The dawnward Pedersen current can result in antisunward perturbed magnetic field (δBy < 0) in the north lobe, but sunward perturbed magnetic field (δBy > 0) in the south lobe.

To compare our predictions with the observed four explosive thinning events given in the paper by Ohtani et al. [1992], we have to change the H, V, D components in their paper to the Bz, –Bx, and –By components in the GSM coordinates. The north and south lobes can be determined from the sign of the x-component of background magnetic field, Bxo. For Bxo>0, three events (1985 5/23, 5/30, 6/29) are observed in the north lobe. For Bxo<0, one event (1985 6/13) is observed in the south lobe. It can be shown that magnetic field variations observed in all the four events are consistent with the above predictions.

The electric current distribution shown in Figure 1 can bend magnetic field duskward in the near Earth plasma sheet. If magnetic reconnection does occur in the explosive thinning region, our model suggests a duskward plasma flow, instead of tailward plasma flow, in the near Earth premidnight region.

3.2. Possible Cause of Explosive Thinning

The formation of premidnight upward field-aligned current at aurora substorm onset is due to convergent movement of electrons in the near Earth plasma sheet in response to the southward curl-E field. The same electric field distribution should have been appeared in the ionosphere a few minutes ago. A similar electron movement is expected in the ionosphere. Therefore, there may be a downward field-aligned current (ionosphere-to-magnetosphere electron flow) in the premidnight region prior to the onset of substorm. This downward field-aligned current in the premidnight region may be responsible for the explosive thinning observed by Ohtani et al. [1992]. To our knowledge, we have not seen any report on this type of downward field-aligned current in the premidnight region that is about 65˚ MLAT with time scale between electron time scale to Alfvén wave traveling time (from ionosphere to magnetosphere) prior to the onset of substorm. It will be interesting to compare the ground observations with the satellite observations during the explosive thinning events.

3.3. Northward Turning of IMF

Northward turning of IMF can trigger “recovery phase” of magnetic storm, but trigger “onset” of magnetic substorm [e.g., Kamide, 1991]. According to a recent EOS article [Lui, 2000], there are at least ~50% of substorms are triggered by IMF changes that lead to reduction in convection! Based our model, if sufficient amount of energetic ions have been built up in the near Earth plasma sheet prior to the changes of IMF, reduction in convection can indeed speed up the rotation of electric field and result in onset of substorm. 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.

3.4. Pseudo Substorm Onset

If the southward IMF does not last long enough before it changes sign, there will be not enough energetic ions in the near Earth plasma sheet. If there are not enough energetic ions in the current sheet, there will be no Hall current disruption. Without the positive feedback mechanism, there will be no expansion phase but only a pseudo onset [e.g., Kan et al., 1994] of bright aurora arc.

3.5. Time Delay Between Substorm Onset and Expansion Onset

Our model can also explain the time delay between substorm onset and expansion onset [e.g., Kan et al., 1994]. According to our model, the substorm onset is
occurred at electron time scale. The field-aligned potential drop along the premidnight upward field-aligned current can accelerate electrons all the way to the ionosphere. Whereas, expansion onset will occur at ion time scale plus the plasma traveling time along the magnetic field line without electrostatic acceleration except at the end of their trip. Based on the electrostatic aurora acceleration model [e.g., Wagner et al., 1980], injection of plasmas with hot ions from plasma sheet can build up a field-aligned potential drop above the ionosphere due to convergence of magnetic field line and the huge difference between ion’s and electron’s gyroradii.

3.6. Expansion Phase and Recovery Phase

If similar triggering and unloading processes proceed in the thinning region outside the current wedge, we can expect to see the development of expansion phase and a westward traveling surge of aurora in the premidnight ionosphere. The interactions between the westward electrojet, and the precipitating electrons and hot ions from the dipolarized plasma sheet may lead to very complicate field-aligned current distributions in the post-midnight region [e.g., Baumjohann, 1991]. The aurora acceleration mechanism in the morning sector may be different from the electrostatic accelerations in the midnight and premidnight region.

If there are not enough energetic ions in the distant tail, there will be no Hall current disruption. Without this positive feedback mechanism, the substorm will turn into recovery phase. This may be the cause of substorm recovery phase.

4. SUMMARY

In summary, we have proposed a cross-scale kinetic M-I coupling model with unloading instability at onset of substorm. The MHD scale M-I coupling process leads to a southward curl-E distribution in the premidnight region of near Earth plasma sheet. The electron scale dynamo process leads to formation of upward field-aligned current in the premidnight region. This premidnight upward field-aligned current can trigger unloading instability by increasing Bz in the midnight region. Unloading instability grows due to a positive feedback effect between thickening of current sheet and reduction of Hall current. The Hall current in the plasma sheet is a result of ion kinetic effect. Nonadiabatic motion of energetic ions in a thin plasma sheet with finite normal magnetic field component can lead to a Hall effect similar to the Hall effect in the E-region ionosphere. Current disruption in the midnight region of near Earth plasma sheet is a consequence of unloading instability in our model.

Our model predicts that northward turning of IMF can trigger aurora substorm onset but not guarantee an expansion onset. Our model can explain the observed magnetic field signature during the explosive thinning events and provide a possible mechanism for the explosive thinning prior to the substorm onset.

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