Sustainable Humanosphere, vol. 11, p.1, 2015

REVIEW

Substorm: view from global MHD simulation and THEMIS observation

(Center for Exploratory Research on Humanosphere, RISH, Kyoto University)

Yao YAO

Abstract

In the geospace, a disturbance phenomenon called "substorm" are frequently observed, which can cause a great impact on elements in the humanosphere, such as radiation damage and surface charging on the satellite, health risk to astronauts due to the high-latitude radiation environment, and disasters in power transmission networks. To understand the physics of the substorm should be of prime importance, which helps us (1) to avoid such disasters by forecasting, and (2) to be a breakthrough in systematic understanding of the near-Earth environment from a global perspective, because the substorm is a global phenomenon whose signatures can be traced in most regions of the geospace. Triggering mechanism of the substorm expansion onset is one of the most important issues in the substorm research, which has not yet been exactly settled, though a number of models have been advocated previously. In this paper, I will firstly review the observational discovery of the magnetosphere that is the arena of the substorm phenomena, and then make a review on the triggering mechanism of the substorm onset, finally from a viewpoint of comparison between a global MHD simulation and multiple satellites observation the triggering mechanism will be reconsidered by the formation and evolution of high-pressure region origin from the magnetic reconnection site in the middle magnetotail.

1. Introduction

Effort of human beings to start the pace on utilization of near-Earth environment began with the launch of first satellite named "Sputnik 1" on October 4, 1957. After that numerous satellites were launched for exploring the near-Earth space. On the basis of these observations, we began to understand the near-Earth environment, which is more complicated as we speculated before. The near-Earth space environment is also known as the geospace that consists of the Earth's magnetosphere, ionosphere, upper region of the atmosphere, and the interplanetary space nearby. It is difficult to understand the geospace as a single system, because each region has different spatial scale, physical properties, and characteristic dynamic variations. The geospace is not as calm and peaceful as it looks. In the geospace, a disturbance phenomenon called "substorm" can be frequently observed. The substorm is a global phenomenon, whose signatures can be traced in the generation of high-energy particles in the magnetosphere, in aurora brightening and enhancement of the electrojet current in the ionosphere, and in heating of the thermosphere. Therefore, to understand the substorm phenomena could be a breakthrough in systematic understanding of the near-Earth space environment from a global perspective.

2. Magnetosphere

In solar system, interplanetary space is the space around the sun and other planets. The physical properties of the interplanetary space are defined by that of solar wind, which is a stream of plasma at supersonic speed ~400 km/s emanating from the upper atmosphere of the sun into the interplanetary space. The Soviet satellite Luna 1 launched on January 2, 1959 provided the first ever direct observations of the solar wind that was termed by Parker[1].

The Earth's magnetic field is not a simple dipolar field, when we consider the existence of the solar wind. It prevents the solar wind plasma from directly hitting surface of the Earth. The solar wind particles are mostly deflected around the Earth's magnetic field and cannot penetrate it due to the frozen-in theorem. The boundary separating the interplanetary space and the Earth's magnetic field is called magnetopause. On September 13, 1963 "Explorer 12" made the first obvious observations of the magnetopause[2]. Dynamic pressure of the solar wind plasma controls the outer part of the Earth's magnetic field generating a cavity called magnetosphere (Figure 1). The shape of the magnetosphere is very complicated, which is the direct result of the interaction between the solar wind and the Earth's magnetic field. In the dayside, the Earth's magnetic field is compressed by the solar wind dynamic pressure that is balanced by magnetic pressure of the Earth's magnetic field. However, in the nightside the magnetic field is stretched by the solar wind stream and shaped an approximation of teardrop shape with a long tail extending outward to the lunar orbit. This part of the magnetosphere is named magnetotail. The "IMP 1" satellite provided the first detailed measurements of the magnetotail at geocentric distances up to 31.4 Re in the nightside[4]. Near the deep tail (~220 Re), "ISEE 3" satellite found the magnetotail structure does not essentially change compared to the near Earth ones[5]. In the magnetotail, lobe region occupies the most volume, which is separated by plasma sheet into the northern and the southern tail lobes. The plasma sheet is a sheet-like region of denser plasma and weaker magnetic field compared to that in the lobe region. It is also a region of closed magnetic field lines around the equatorial magnetotail, whose inner edge can extend to the geosynchronous orbit at ~6.6 Re. The near-Earth plasma sheet consists of central plasma sheet and plasma sheet boundary layer. Plasma measurements obtained from the "AMPTE" satellite have brought us a statistical image of the structure and dynamics of the near-Earth plasma sheet between ~10 and ~20 Re[6]. The region from outer edge of the ionosphere to about the geosynchronous orbit is called inner magnetosphere. In the inner magnetosphere, the magnetic field is almost dipolar, which can trap the plasma particles origin from the solar wind and the ionosphere, and build the belts of energetic particles called radiation belts or Van Allan belts. It is James Van Allen who firstly discovered the existence of the radiation belt by "Explorer" satellite in the year 1958. On the other hand, up to about 4 Re the region is called plasmasphere that is occupied by the ionospheric origin low-energetic particles. Through the outer edge of the plasmasphere, electron density undergoes a sharp decrease from 10-100 cm^{-3} to 1-10 cm^{-3}. The direct observation on the plasmaspheric plasma was obtained from "OGO-5" satellite[7].

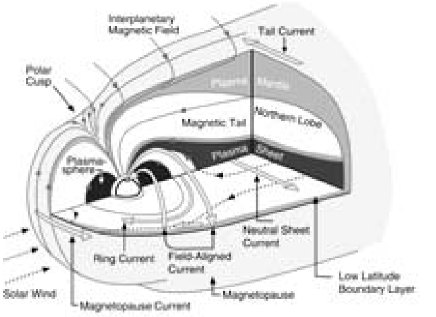

Figure 1. Schematic illustration of the Earth's magnetosphere (after De Keyser et al., 2005[3]).

3. Substorm

Aurora is one of the most beautiful phenomena mostly seen at the high latitudes of the Earth. To understand the physics of the aurora we have to introduce a transient phenomenon named "substorm". The substorm is a brief disturbance occurs in the Earth's magnetosphere. It is a significant process that can release solar wind energy stored in the magnetotail drastically into the inner magnetosphere, and the high latitude ionosphere causing sudden brightening and poleward movement of the aurora arcs. The substorm has three phases: growth phase, expansion phase, and recovery phase, which can be identified by the Auroral Electrojet (AE) index (Figure 2) that measures the global electrojet activity in the auroral zone. The interplanetary magnetic field (IMF) especially Z component is a key parameter that can affect the whole magnetosphere and ionosphere of the Earth. When the IMF B_z turns southward, the dayside reconnection will allow the solar wind particles and energy to be transferred into the magnetosphere. To our knowledge, part of the energy will be stored in the Earth's magnetotail by means of the stretched tail-like magnetic field configuration resulting in thinning of the plasma sheet. After substorm onset, the expansion phase begins and the energy will be drastically released from the magnetotail into the ionosphere, which can have a great impact on element in the humanospheric environment. The Earth-orbiting satellites are the direct sufferer mostly due to the radiation damage, or/and spacecraft charging, for example AT&T Telstar 402R geosynchronous communications satellite[8]. The high latitude radiation environments (solar energetic particles and relativistic electrons in the Earth's outer radiation belt) during a Space Particle Events (SPE) may increase a health risk to astronauts[9]. During a

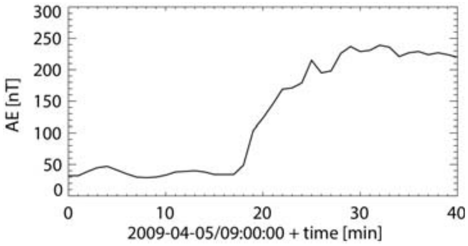

Figure 2. AE index recorded on Apr. 5, 2009.

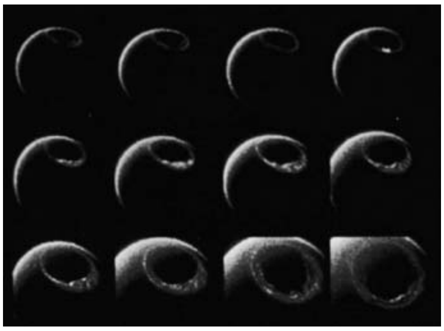

Figure 3. Consecutive false-color images of the auroral oval around the onset in a substorm on 2 April 1982 during the period 0529 through 0755 UT recorded by Dynamics Explorer 1 spacecraft (after Pfaff Jr., 2012[11]).

great storm of March 1989, a complete collapse of the Hydro-Quebec electric-power grid occurred in Canada due to sudden increase of the auroral electrojet current, and leaving nine million people without electricity for about 9 hours.

The physical process of sudden energy release associated to the substorm expansion phase is one of the most wonderful processes, which could not be found in laboratory experiments and other observable phenomena. The expansion phase begins from the substorm onset that is widely known as the time of a sudden brightening of the aurora[10] (Figure 3). However, what process triggers the onset, when and where the onset is triggered is still far from understood. Triggering mechanism of the substorm onset is one of the key issues in the substorm research. Numerous models have been proposed to explain causal relationship between the substorm associated processes in the magnetosphere, however, it is still in the debate. There are two potent candidates, one is the near-Earth neutral line (NENL) model[12] (Figure 4), in which the time sequence could be considered as, first a neutral line is formed in the near-Earth magnetotail, then magnetic reconnection begins at $X_{GSM}\sim -20$ Re. The reconnection results in earthward bursty bulk flow (BBF)[13] that can transport mass, energy, and magnetic flux to the near-Earth region. Pileup of the magnetic flux at the inner edge of the plasma sheet causes the dipolarization, and substorm current wedges that lead to the enhancement of the auroral electrojet. The other candidate is the current disruption (CD) model[14] (Figure 5), in which the ballooning instability[15] or the cross-field current instability[16] is predicted to cause the current disruption at $X_{GSM}\sim -10$ Re leading to the dipolarization, and finally the increase in the auroral electrojet. On the basis of these two models, two significant features can be extracted, the magnetic reconnection that occurs near the tailward edge of the thin current sheet[17], and the dipolarization that were observed by numerous satellites within a X_{GSM} range from $X_{GSM}\sim -6.6$ to -16 Re[18, 19]. The difference between these two models is which process causes the other one. The NENL model also known as outside-in model indicates that the outmost magnetic reconnection causes the innermost dipolarization. Other triggering models are founded on the basis of these two models, for example, Pu et al.[20] proposed a synthesis of tail reconnection and current disruption model, in which the fast flow caused by the reconnection resulting in the current disruption leading to the dipolarization. In a catapult current sheet relaxation model, Machida et al.[21] suggested that enhancement of the pointing flux toward the plasma sheet center at $X_{GSM}\sim -12$ Re causes an earthward convective flow that induces a ballooning instability or other instability causing the current disruption, the relaxation of a stretched catapult current sheet itself could develop the boundary of the stretched dipole field into the magnetic neutral line then leading to the magnetic reconnection. Current observations from multiple satellites seem to support the NENL model, that is, the magnetic reconnection in the mid-magnetotail is the trigger of the substorm onset[22].

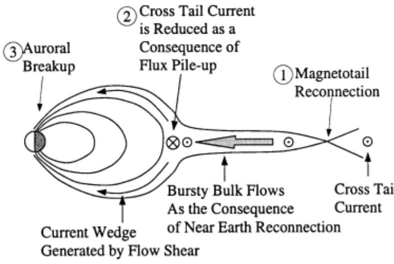

Figure 4. Near-Earth neutral line (NENL) model[34].

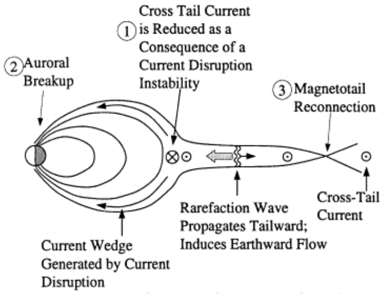

Figure 5. Current disruption (CD) model[34].

4. Evolution of high-pressure region around the substorm onset

The substorm is a global phenomenon that could couple both the magnetosphere and the ionosphere.

However, one-point satellite observations only reveal local features of the substorm. The current Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission[23] launched on February 17, 2007 provided a unique opportunity to investigate the evolution of near-Earth plasma sheet during the substorm, which has five probes covering a wide spatial range in Sun-Earth direction. Although the THEMIS mission can provide multiple-point observations, it is still difficult to restore a whole global image of the substorm.

As the performance of computer hardware is being incredibly improved, the numerical simulation has become an important research method after theoretical research and observation. Tanaka et al.[24] developed a global magnetohydrodynamics (MHD) model that has a capability in reproducing many observable manifestations of the substorms, such as the formation of a near-Earth neutral line[12], earthward flow in the plasma sheet, stretching and dipolarization of magnetic field, sudden intensification of a westward electrojet at the auroral latitudes. In spite of the suggestion that non-MHD processes trigger a substorm[25], the global MHD simulation reasonably describes the global structure and dynamics of the magnetosphere that evolves self-consistently to satisfy mass, momentum, and energy equations.

Variation of plasma pressure in the near-Earth magnetotail is a characteristic feature around the substorm expansion onset. Statistical studies were previously carried out in the plasma sheet[6, 26, 27]. Baumjohann[28] indicated that adiabatic convective motion would lead to greatly high plasma pressure of associated flux tubes closer to the Earth. Observation in the inner magnetosphere was reported to show simultaneous pressure enhancement and magnetic depression at the onset by CRRES satellite[29]. Xing et al.[30] showed that a substantial duskward enhancement in the plasma sheet pressure gradient at 11 Re near the onset on the basis of THEMIS observations could be associated with enhanced upward field-aligned current during the late growth phase. Xing et al.[31] further found that within 2 min prior to the onset, the ion distribution function showed a substantial earthward shift, which agrees with the ion acceleration ahead of the earthward convection dipolarization front.

On the basis of a global MHD simulation, Tanaka et al.[24] pointed out that the sudden intensification of the westward auroral electrojet can be explained in terms of a substantial increase of the plasma pressure caused by the state transition (change in the force balance) in the plasma sheet. During the growth phase, about 6 minutes before the substorm expansion onset a near-Earth neutral line forms and results in the force imbalance between plasma pressure gradient force and magnetic tension force. It is always over tension in the mid-magnetotail region just before the onset, since the reduction of the pressure gradient force. The over tension state brings out earthward tension force that can accelerate the particles and generate earthward fast flow. The convergence of the fast flow contributes to the pressure enhancement that leads to the generation of high-pressure region (HPR). In other words, the plasma is squeezed in the near-Earth plasma sheet resulting in the formation of the HPR. It can also be said that the plasma implodes earthward. As a consequence, the HPR moves earthward, and reaches the inner region from $X_{GSM}= -6$ to -8 Re within 3 or 4 min before the onset. The generation of the HPR causes diamagnetic current that can result in an intensification of the Region 2 field-aligned currents, together with the Region 1 currents on the nightside. Then, auroral electrojets are intensified in the polar ionosphere on the nightside, which is regarded as a manifestation of the substorm onset. After the onset, the region where the plasma is squeezed spreads tailward. As a consequence, the HPR retreats tailward. From previous

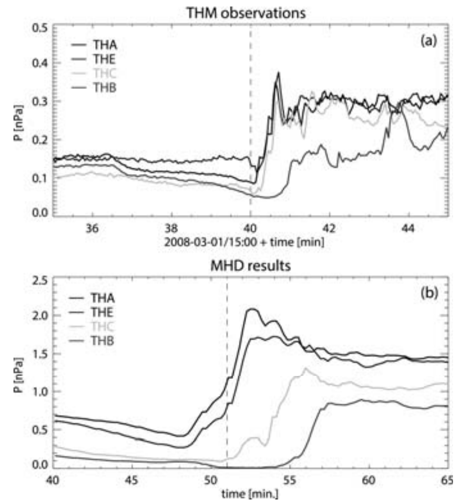

Figure 6. Comparison of plasma pressure between (a) THEMIS observations and (b) MHD simulation (after Yao et al., 2015[32]).

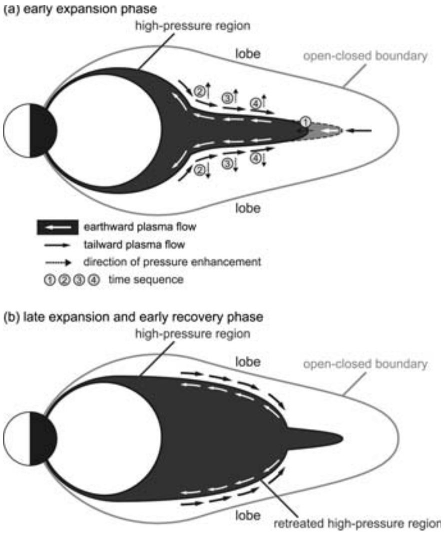

Figure 7. Schematic diagram illustrating the processes resulting in the pressure enhancement in the noon-midnight (Y_{GSM}= 0 Re) meridinoal plane (after Yao et al., 2015[32]).

studies, the evolution of the HPR in the near-Earth plasma sheet has not been clear identified, though the importance of the HPR has been indicated by Tanaka et al.[24].

During a substorm event on 1 March 2008, four THEMIS probes aligned along the Sun-Earth line, and observed a sudden pressure enhancement (SPE) from inner most probe to outer ones, which implies tailward retreat of the high-pressure region. By visual inspection, Yao et al.[32] determined the coincident position of the THEMIS probes in the MHD domain. It is found that the simulation results can reproduce the similar tailward retreat of the high-pressure region at approximate positions of the THEMIS probes in the simulation domain (Figure 6). The results of the simulation also show that at off-equator (Z_{GSM}= −1.5 Re) only the tailward retreat of the SPE can be seen in the presented case. However, at the equator there is an earthward propagation of the SPE seen firstly before the substorm onset. From viewpoint of the force balance, the tailward retreat of the SPE could be explained by the propagation of high-pressure region in $-Z_{GSM}$ direction, and from the inner to the outer along $-X_{GSM}$. The combination of the convergence of the plasma flow (velocity divergence along Z_{GSM} axis) and the pressure gradient force account for the propagation of the HPR along $-Z_{GSM}$. This process is illustrated in Figure 7.

In an isolated substorm event occurred on 5 April 2009, the earthward implosion of the HPR before the substorm onset as predicted by the global MHD simulation was identified[33], which was not identified in the study reported by Yao et al.[32]. It is found that there are two peaks of the ion pressure observed by the THEMIS probes located at X_{GSM}~ −11 Re near the equatorial plane. The first peak took place just before the substorm onset, and the second one took place just after the onset. The duration of the two pressure peaks is shorter in the inner region than that in the outer region. This is consistent with "V" structure (Figure 8) of the plasma pressure in a distance-time diagram shown from the MHD simulation. These results may provide observational evidence of the sequence of the substorm as predicted by the MHD simulation[24]. The convergence of the plasma flow caused by the change in the force balance (state transition in the plasma sheet) plays an important role in the enhancement of the plasma pressure around the substorm onset.

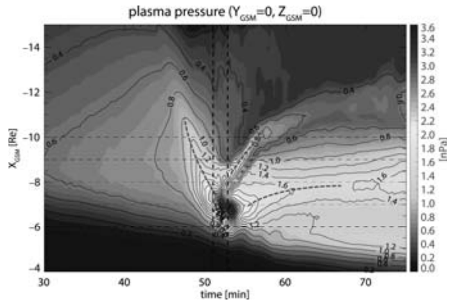

Figure 8. Temporal variation of simulated plasma pressure as a function of X_{GSM} in the equatorial plane (Y_{GSM}= 0 and Z_{GSM}= 0 Re) (after Yao et al., 2015[33]).

5. Summary

Numerical simulation has been developed into an important way after traditional theoretical research and observation. In the magnetospheric substorm study, the MHD simulation[24] gradually shows its power in understanding the physics of the substorm from a global view. Some substorm signatures have been reproduced by the MHD simulation, at the same time some significant manifestations seen from the

MHD simulation have also been identified by observational evidences.

Although the MHD simulation did not exactly simulate the substorm events reported by Yao et al.[32, 33], the simulation results seems to well reproduce what observed by the THEMIS probes. Therefore, we might believe that the MHD simulation could show us the common features of the substorm, which does not change for different substorm events. To know the whole process of the substorm in the magnetosphere-ionosphere system may help us further understanding its important impact on the region below the ionosphere, which is the core region of the humanosphere.

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