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On principal factors in substorm models

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Abstract This paper gives a brief account of substorm modeling with different key elements or factors. The progress of our understanding of substorms consists of three chief stages during this century. Nine previous substorm models are briefly recapitulated, and then a recent two neutral-points model by Prof. C. T. Russell is introduced. In order to test or to strengthen this new model, several correlated examples of meaningful data are duly given in this short paper.
Key words substorm, modeling, correlated analysis.

1 Introduction

The progress of our understanding of the magnetospheric substorms consists of three chief stages during this century. In the first stage from 1900 to 1930 Birkeland-Stormer's solitary particle theory prevailed. Birkeland (1908) was the first to make an extensive geomagnetic observation in the polar region and to deduce a new kind of magnetic disturbance, the "elementary polar magnetic storm" with a typical time scale of half an hour. Further, with Stormer, he examined motions of individual charged particles in the vicinity of a dipole field. The second stage (1931 - 1953) centered in the Chapman-Ferraro's plasma (ID) theory. They (1931) argued that the solar "corpuscular stream" in the vicinity of the earth should be treated as a plasma, not motions of individual charged particles. This effort led them to the first theory on the formation of the magnetosphere. Chapman (1935) also made an extensive study of geomagnetic records and resolved the storm's disturbance field D into three parts, one of them is the polar disturbance field DP. Another important point is that Chapman devised the two-dimensional equivalent current system which is mathematically unique. Lastly, the discovery of the Van Allen belts in 1958 inaugurated the era of space exploration, since then many astonishing advances have been made relating to magnetospheric physics. For instances, the discovery of the plasmasphere by Storey (1953), Dungey's open magnetosphere and Axfort-Hines' plasma convection both in the year 1961, the discovery of different plasma regions, the cusp, central plasma sheet (CPS), boundary plasma sheet (BPS), mantle, low-latitude boundary layer (LLBL), etc., roles of IMF B_z, field-aligned currents and multiple reconnections, together with plasmoids, flux transfer events (FTEs), O^+ flow, all occurred during the third development stage. For more detailed description of the history, please refer to Akasofu (1991).

In this paper, we first recapitulate briefly several substorm models in section 2, then in section 3 introduce a recent substorm model made by Prof. Russell (2000), and in subsequent sections some correlated data analyses are quoted. Dealing with key factors or elements in substorm modeling, it is necessary to differentiate the external (IMF B_z, Field-aligned currents) against the internal (Earth field, plasma sheet), space structure (Bow shock, plasma regions) and time variation (Growth, expansion, recovery), local (magnetospheric crossing) against global (M-I coupling), and also cause-effect relationship, phenomenological features or physical processes. In short. substorm modeling may be made in many different ways.

2 Previous substorm models

A.T.Y. Lui (1991 and refs therein) has made an extensive study of existing substorm models together with his own synthesis substorm model. The list of contending substorm models includes (a) the near-Earth neutral line model (Hones 1979) —— Formation of the near-Earth neutral line, (b) the boundary layer model (Rostocker and Eastman 1987) —— Kelven-Helmholtz instability from enhanced reconnection at the distant neutral line, (c) the thermal catastrophe model (Smith *et al*. 1986; Goertz and Smith 1989) —— Resonant absorption of Alfven waves in the plasma sheet boundary layer, (d) the current disruption model (Chao *et al*. 1977; Lui 1979) —— Deflation of plasma sheet from rarefaction waves launched by reduction in cross-tail current, (e) the interchange or ballooning instability model (Liu 1970; Roux 1985) —— Unstable surface wave between dipolar-like and tail-like region, (f) the wave-induced precipitation model (Parks *et al*. 1972; Kropotkin 1972), (g) the magnetosphere-ionosphere coupling model (Kan *et al*. 1988; Rothwell *et al*. 1988) —— Intense field-aligned current from divergence of both Hall and Petersen currents in the ionosphere, (h) Lyons-Nishida model (1988) —— Description of substorms in the tail incorporating boundary layer and neutral line effects, (i) the synthesis substorm model (Lui 1991) —— Synthesizing the various substorm models (a) to (f), and (j) configuration instability model in the presence of a plasma flow (Hong *et al*. 1997; Pu *et al*. 1999) —— Effects of midtail high plasma flow on the configuration instability of the near-Earth tail. The former seven models account for part of the entire substorm sequence, but the last three attempt to produce synthesis models. Among all these ten models, the near-Earth neutral line model (a) and the current disruption model (d) have been well known for long time, but judging from observations and physical processes, it seems the coupling or synthesis models, such as (g), (i), (j) should be appreciated. Indeed, other alternative substorm models may exist or be propounded in the future, and still newer direction of research on magnetospheric substorms have also just begun.

3 A new substorm model

Recently Russell (2000) has proposed a two neutral points model to explain northward turnings of the interplanetary magnetic field (IMF) triggering the expansion phase of substorms. Several elements are involved in understanding this triggering: the existence of two neutral points, the rope type nature of plasmoid, factors controlling the rate of reconnection, and the near-Earth neutral point begins on closed field lines prior to the expansion onset. The whole scenario of Russell's model is shown in Fig. 1, in a rather qualitative manner.

In this model a southward turning initiates merging of the IMF with the magnetospheric field at a rate M. This transports flux into the open field line of the tail and increases the flux Φ in lobe. At this point convection from the nightside to the dayside, C, increases slowly to replace the magnetic flux eroded from the subsolar magnetopause region. This occurs out of the noon-midnight plane sketched in the top panel. This convection reduces the magnetic flux in the night plasma sheet, Φ_{NPS}. Assume that the distant reconnection rate, R_D, is similar to the merging rate, M, but certainly changes will be somewhat delayed further down the tail. After a significant amount of flux is added to the tail and it stretches in the anti-solar direction, a second neutral point forms with reconnection rate, R_N, that gradually increases but remains low as long as it reconnects on closed field line and the plasmoid remains trapped. With time the plasmoid flux, Φ_{PM}, increases. With the IMF turns northward, the dayside merging, M, drops to zero followed quickly by the reconnection rate at the distant neutral point, R_D. The flux in the distant plasma sheet Φ_{DPS} is reconnected by the near-Earth neutral point and the plasmoid is released to go down the tail. When the near-Earth neutral point reaches the open field lines of the lobe, reconnection proceeds rapidly.

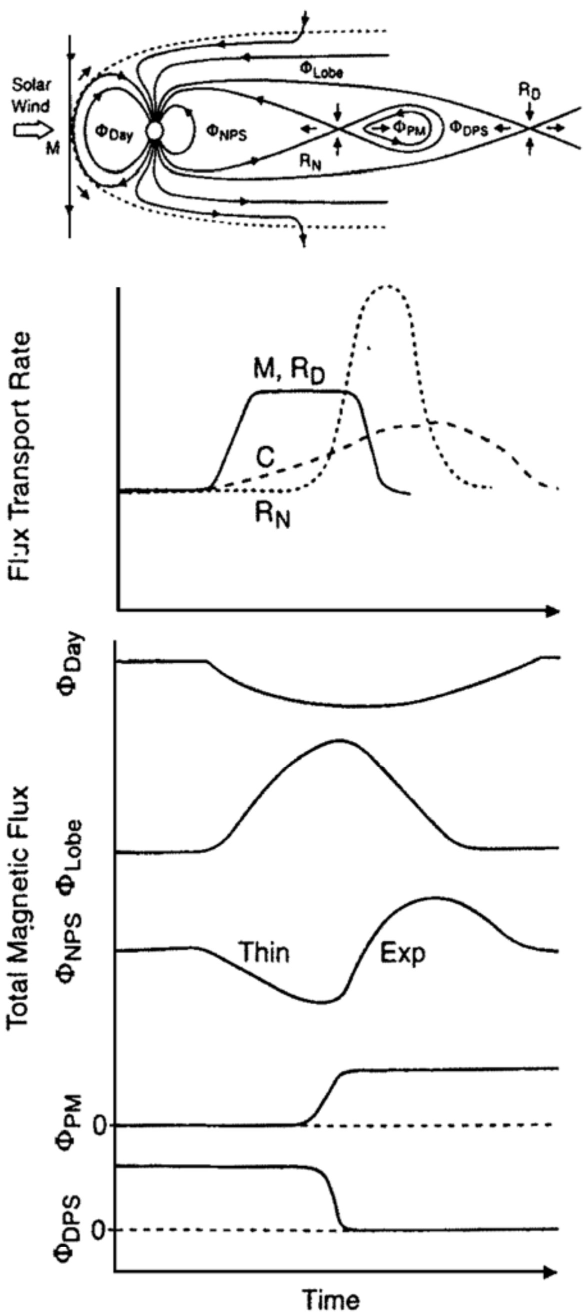

Fig. 1. The two neutral point model, see text (Russell 2000).

4 Correlated data analysis

At first glance Russell's model is very simple and self-consistent. However, due to the very complex, many factors interacting nature of the development of substorm and storm, it seems the model should be tested and much well done by previous and future studies of many useful solar-terrestrial data and theoretical work. The following are some meaningful examples.

(1) The first example comes from the work by Pulkkinen *et al.* (1998). They present observations of two sequential substorm onsets on May 15, 1996, as shown in their Fig. 2a, b. The first event occurred

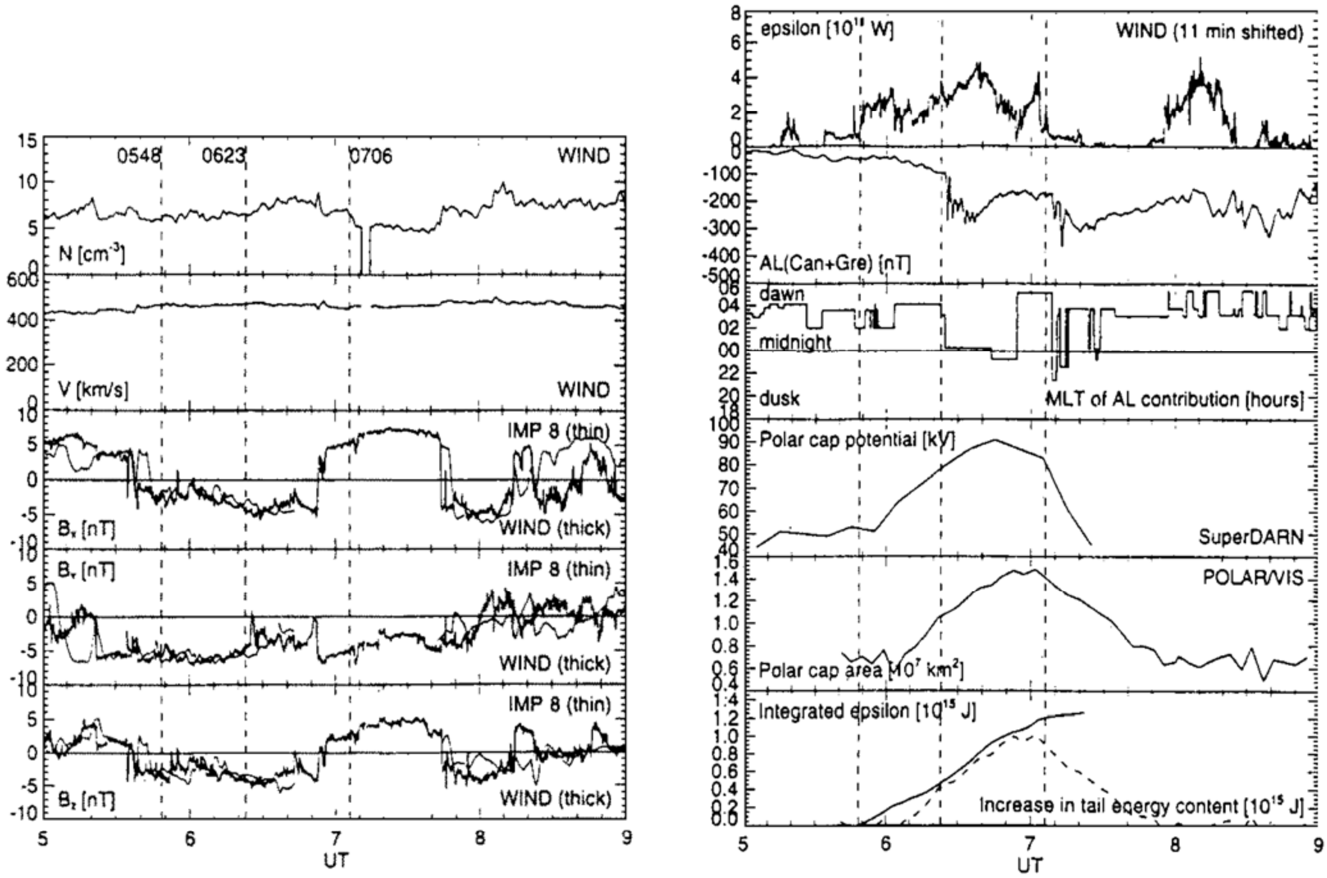

Fig. 2. Observations of two sequential substorm onsets on May 15, 1996 (From Pulkkinen *et al*. 1998). (a) Solar wind data from Wind. Panels from top to bottom: Solar wind density, velocity, interplanetary magnetic field B_x, B_y, B_Z. The thin lines show IMF components from IMP8; (b) (top to bottom) The $\epsilon(= 10^7 V B^2 l_0^2 \sin^4(\theta/2))$ in units of 10^{11} W. Auroral electrojet index created from magnetometers in Canada, Greenland, and Scandinavia in nanoteslas. Polar cap potential deduced from SuperDARN observations and model. Polar cap size in units of 10^7 km^2 as deduced from the Polar/VIS auroral images. Time-integrated ϵ (beginning from 0548UT) and tail energy content as deduced from the Polar cap area variations.

during persistently negative IMF Bz, where the second expansion followed a northward turning of the IMF. While the first remained localized, the second event led to a major reconfiguration of the magnetotail. The two very different events are contrasted, and it is suggested that the IMF direction controls the evolution of the expansion phase after the initial onset. Evidently, this example is in support of Russell´s model, though Pulkkinen *et al*. have analyzed the observation data in great detail, relating to onset, expansion, and global consequences. In their paper, magnetic field modeling and field-aligned mappings are used to find the high-altitude source region of auroral features and currents giving rise to ground magnetic disturbance. It is shown that the auroral brightening is related to processes near the inner edge of the plasma sheet but that the initial field-aligned currents couple to the midtail region.

(2) The second example deals with the separation of directly driven (DD) input of energy from the solar wind and unloading (UL) of stored magnetotail energy in the development of magnetospheric substorms. In two papers Sun *et al*. (1998; 2000) have developed an improved method of determining the time variations of

directly driven (DD) and unloading (UL) components, combining the correlation method with MNOC (Method of Natural Orthogonal Component). Data are taken during the substorm of 0000 – 0500 UT March 18, 1978, and substorm during 1500 UT November 3 to 0200 UT November 4 1993. Their results of separating two components in the ionospheric equivalent currents during substorms are well shown in their Figures 1 – 9 of second paper, from which we adapt them into one figure here depicted (Fig. 3). Results show that the contribution from the unloading component is zero during the growth phase and dominates during the expansion phase of substorms. Although we have long associated its cause with release of energy stored in the magnetotail, its time variations have now been revealed for detailed theoretical research.

(3) The third example extends substorms to geomagnetic storms in lower latitudes. This implies that Russell's model might also lead two-step development of geomagnetic storms. Using the D_{st} index, more than 1200 geomagnetic storms, from weak to intense, spanning over three solar cycles have been examined statistically (Kamide *et al.* 1998a, b). IMF and solar wind data have also been used in the study. They found that for more than 50% of intense magnetic storms, the main phase undergoes a two-step growth in the ring current. That is, before the ring current has decayed significantly to the prestorm level, a new major particle injection occurs, leading to a further development of the ring current, and making D_{st} decrease a second time. In this way the storm is called type 2, in distinct to the conventional storm of type 1. Thus intense magnetic storms may often be the result of two closely

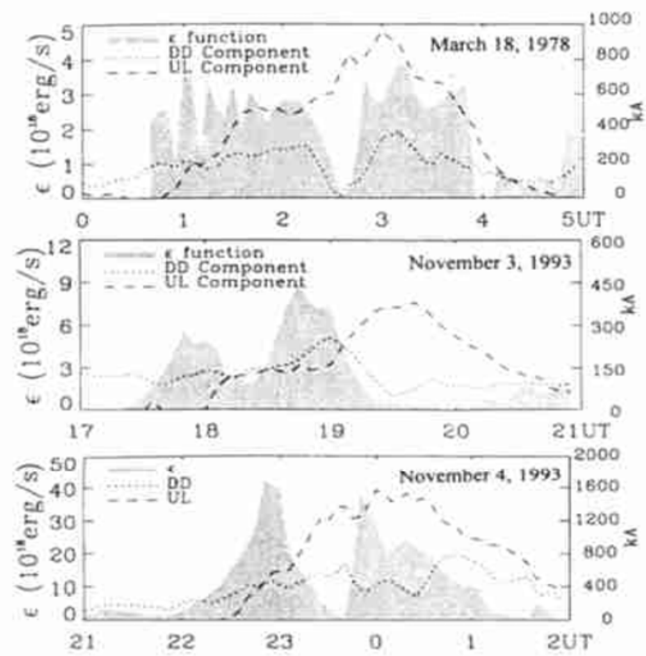

Fig. 3. Results during substorm for time variation of the directly driven component (dotted curve), the unloading component (dashed curve), and $\epsilon = VB^2\sin^4(\theta/2)l_0^2$ derived from solar wind parameters with appreciable time delay (adapted from Sun *et al.* 2000).

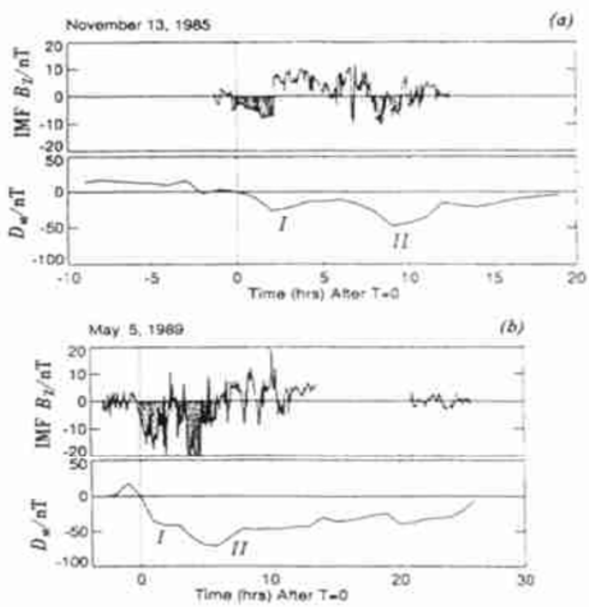

Fig. 4. Two typical examples of type 2 magnetic storms on (a) November 13, 1985 and (b) May 5, 1989, along with the corresponding B_Z component variations in the interplanetary magnetic field (From Kamide *et al.* 1998a).

spaced moderate storms. The corresponding signature in the interplanetary medium is the arrival of double-structured southward IMF at the magnetosphere. Figure 4 shows two examples of type 2 storms. In figure 4a the two peaks in D_{st} (labeled as Ⅰ and Ⅰ Ⅰ) are separated by 7 h, while those in Figure 4b are separated by only 4 h. This difference in separation time is also clearly identified in the corresponding B_Z component of the IMF, although both cases include other fluctuations as well.

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