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A study on the multi-component substrom current

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Abstract A new technique of eigen mode analysis, Method of Natural Orthogonal Components (MNOC) is used to analyze the ionospheric equivalent current systems obtained on the basis of magnetic data at six meridian magnetometer chains in the northern hemisphere during March 17－19, 1978. The results show that the whole current pattern for any given instant consists of a few eigen modes with different intensities. The first eigen mode exhibits a two-cell current construction, characterizing the large-scale magnetospheric convection and directly driven process, while the second eigen mode shows a concentrated westward electrojet at midnight sector, characterizing the substorm current wedge and the loading-unloading process. The first mode consistently exists whenever during quiet periods or at substorms, and its intensity increases from the beginning of the growth phase of substorms, then quickly intensifies in the expansion phase, followed by a gradual decrease in the recovery phase. On the other hand, the intensity of the second mode remains to be near zero during both quiet time and the growth phase of substorms. Its rapid enhancement occurs in the expansion phase. These characteristics in the current patterns and the intensity variations coincide with the defined physical processes of the directly driven and loading-unloading components.

Key words substorm, equivalent current system, method of natural orthogonal components (MNOC).

1 Introduction

Large-amplitude transient magnetic variations occurring in the nightside high latitudes have increasingly attracted the attention of space scientists since people realized that they were associated with the growth of the terrestrial ring currents during periods of magnetic storms. These polar magnetic perturbations were called polar magnetic substorms, and the related auroral signatures were termed auroral substorms (Akasofu 1964). All the auroral and ionospheric disturbances together with their magnetospheric counterparts come under the overall name magnetospheric substorm (Rostoker 1996).

As Akasofu (1979) pointed out and most space scientists have accepted, the magnetospheric substorm consists of two components, the directly driven component (DD) and loading-unloading component (LU). In DD component, the energy derived from the solar wind deposits directly in the ionosphere, ring current and elsewhere with an appreciable time delay. The LU component involves a storage of the solar wind energy in the magnetotail and its sudden release into the auroral ionosphere and into the ring current.

In fact, there may be other processes which are involved in substorms.

The DD and LU components in substorms were recognized firstly on the basis of the ionospheric equivalent current system (IECS) of substorms made by using ground-based magnetic data. In IECS of a substorm the overall features in the spatial construction and temporal evolution of the magnetic dispersions during the substorm are clearly shown: the directly driven component exhibits a two-cell construction, referred by the terms DS, S_q^p and DP2, while the unloading component has a single vortex involving a longitudinally confined westward ionospheric electrojet located in the midnight sector, referred to as DP1. At any instant these two major components and other minor components are superposed together. Our task is to separate them quantitatively.

Clauer and Kamide (1985) and Kamide and Kokubun (1996) tried to separate these two components by different methods. However, they needed some objective assumption or additional knowledge about the ionospheric electric field and conductivity.

In this paper we use Method of Natural Orthogonal Components (MNOC) to analyze the ionospheric equivalent current systems during substorms and obtain fundamental orthogonal basis set . Then we compare the obtained eigen modes of the current systems with DP1 and DP2 in order to determine their physical meanings.

2 Method of eigen mode analysis

Method of Natural Orthogonal Components (MNOC) is a technique of eigen mode analysis widely used to separate the contributions to an event from several different physical processes (Kendall and Stuart 1976).

In the following deduction the original data $X(t_i, \boldsymbol{r}_j)$ are the substorm current functions at time $t_i (i = 1, 2, \ldots m)$ in a two-dimensional grid net of the ionosphere, where $\boldsymbol{r}_j$ $(j = 1, 2, 3, \ldots. n)$ is the location vector of the j-th grid (colatitude and longitude). Thus we have m samples, each of which includes n elements. The original data can be written as a matrix $\boldsymbol{X}_{m\times n}$.

It is assumed that there are h different processes contributing to the substorm current system, their contributions can be written as follows:

$$\boldsymbol{F}^k_{m\times n} = \boldsymbol{A}^k_{m\times 1}\Phi^{kT}_{n\times 1} \qquad k = 1, 2, \cdots, h \tag{1}$$

where $\Phi^{kT}_{n\times 1}$ represents the normalized current pattern produced by the k-th process, and $\boldsymbol{A}^k_{m\times 1}$ is the corresponding intensity. The total current system can be represented as the sum of these contributions:

$$\boldsymbol{X}_{m\times n} = \sum_{k=1}^{h} \boldsymbol{F}^k_{m\times n} = \sum \boldsymbol{A}^k_{m\times 1}\Phi^{kT}_{n\times 1} \tag{2}$$

From $\boldsymbol{X}_{m\times n}$ we can construct the covariance matrix:

$$\boldsymbol{V}_{n\times n} = \boldsymbol{X}^T_{m\times n}\boldsymbol{X}_{m\times n} = \sum_{k=1}^{h}\sum_{l=1}^{h} \Phi^k_{n\times 1}\boldsymbol{A}^{kT}_{m\times 1}\boldsymbol{A}^l_{m\times 1}\Phi^l_{n\times 1} \tag{3}$$

If assuming that

$$\begin{aligned} \Phi^{iT}_{n\times 1}\Phi^j_{n\times 1} &= \left| \begin{array}{ll} 1 & i = j \\ 0 & i \neq j \end{array} \right. \\ \boldsymbol{A}^{iT}_{m\times 1}\boldsymbol{A}^j_{m\times 1} &= \left| \begin{array}{ll} \lambda_i & i = j \\ 0 & i \neq j \end{array} \right. \end{aligned} \tag{4}$$

we can get from equations (3) and (4)

$$V_{n\times n}\Phi^{p}_{n\times 1} = \lambda_p \Phi^{p}_{n\times 1} \qquad p = 1, 2, \cdots, h \tag{5}$$

From equation (5) we have

$$A^{k}_{m\times 1} = X_{m\times n}\Phi^{k}_{n\times 1} \tag{6}$$

It means that the eigen vectors of the covariance matrix $V_{n\times n}$ describe the current patterns created by these processes, and the eigen values indicate their current intensities.

3 Data and results

The samples analyzed in this paper are 864 ionospheric equivalent current systems (IECS) for each 5 minutes during 3 days of March 17 – 19, 1978, which are calculated on the basis of the magnetic records at 71 stations in the northern high latitudes. We consider the latitudinal range of 50° – 90° with a 2° interval and the longitudinal range of 0° – 360° with a 15° interval (or 1 hour). Thus the number of elements in each sample is 480. A piece of time series of IECS (1100 – 1255 UT on March 19, 1978) is shown in Fig. 1. in which the contour interval is 30 kA.

A quiet two-cell pattern can be seen clearly in Fig. 1 before 1130 UT. At 1140 UT an enhancement of westward electrojet of substorm appeared in nightside, which was dominant.

The method described in section 2 is used in this data set, in which $m = 864$, $n = 480$. The eigen modes are calculated from these samples, and ordered according to magnitude of eigen-values. The first 6 eigen modes are shown in Fig. 2, from which we found that the first two modes dominate over the rest, and their patterns seem to be meaningful.

In order to determine the physical meanings of the first and second modes we compare these modes with the substorm current systems obtained by other authors (Rostoker 1969). It can be seen that the first mode has a two-cell current pattern, and seems to characterize the directly driven process. The second mode shows a concentrated westward electrojet at midnight sector, which resembles the auroral electrojet appearing during substorms corresponding to the unloading process.

In order to examine the contributions of the different modes to the total currents, the time variation of the intensities of the first 6 modes are shown in Fig. 3. We found that the first mode consistently exists during both quiet periods and substorms, its intensity increases from the beginning of the growth phase of substorms, and then further intensifies after the onset of the expansion phase, and reaches its maximum value about the peak time of the substorm, followed by a gradual decrease in the recovery phase. On the other hand, the intensity of the second mode remains to be near zero during both quiet time and the growth phase of substorms, its rapid enhancement occurs in the expansion phase. It reaches its maximum value at the peak time of the substorm. These characteristics are physically in good agreement with the directly driven process and loading-unloading process, which are associated, respectively, with the magnetospheric convection

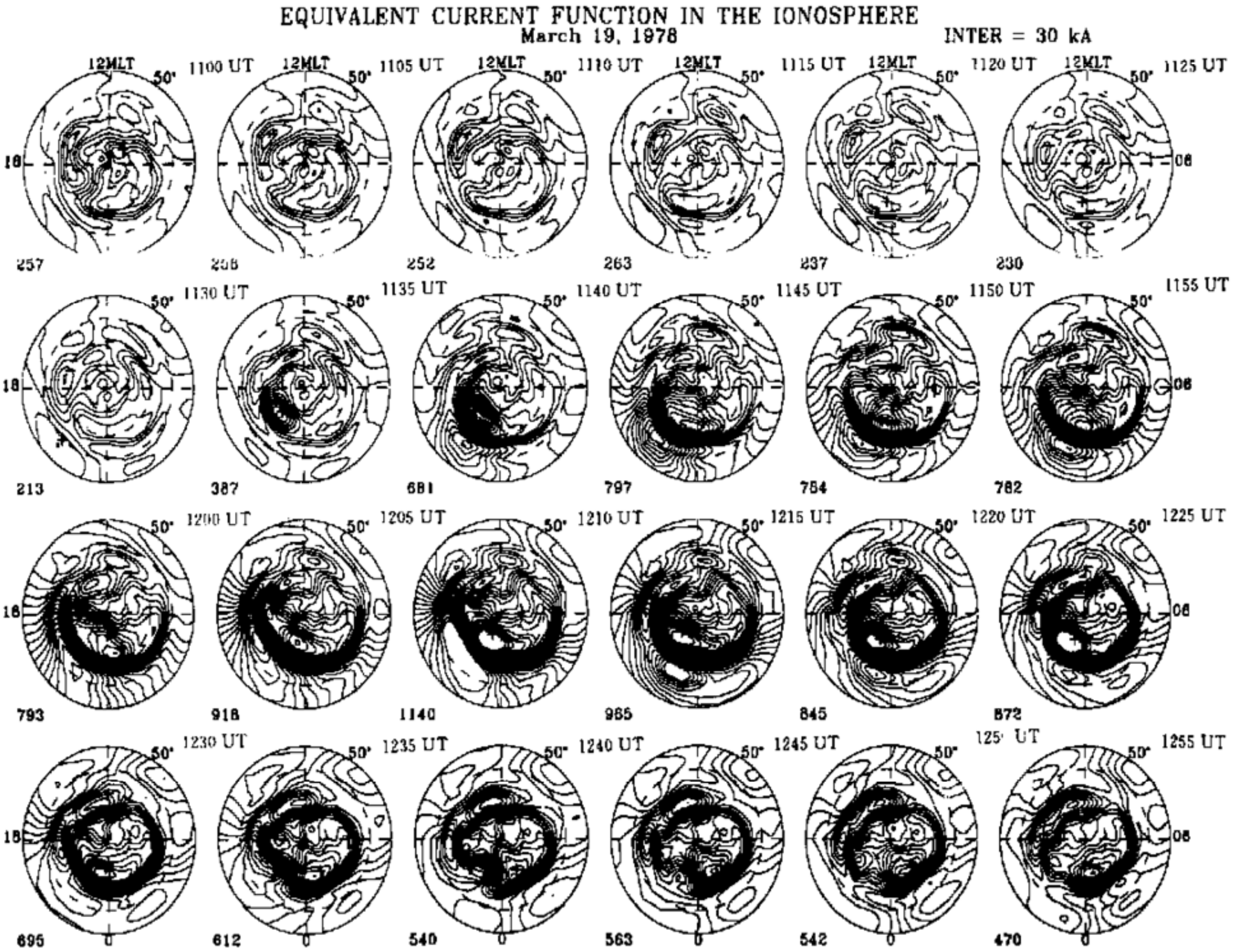

Fig. 1. Sequence of IECS during a period from 1100 UT to 1255 UT on March 19, 1978.

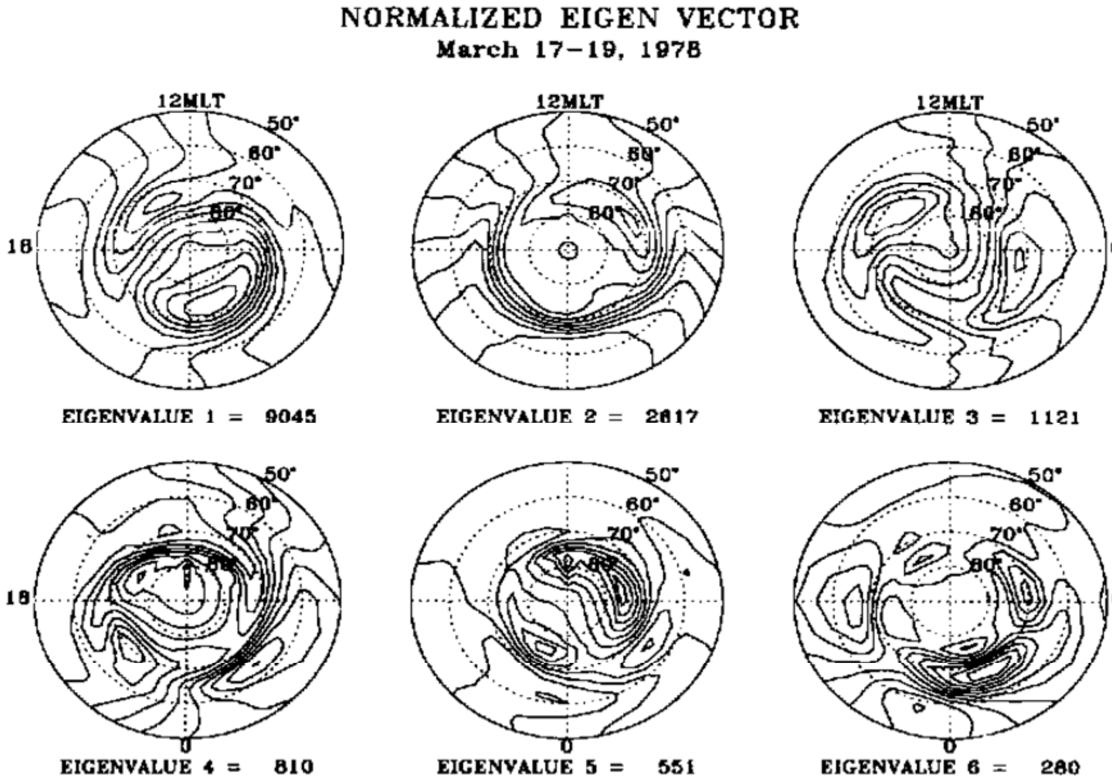

Fig. 2. The normalized current patterns for the first 6 eigen modes of IECS during March 17-19, 1978. The eigen-values are shown below each pattern.

and the sudden formation of the substorm current wedge.

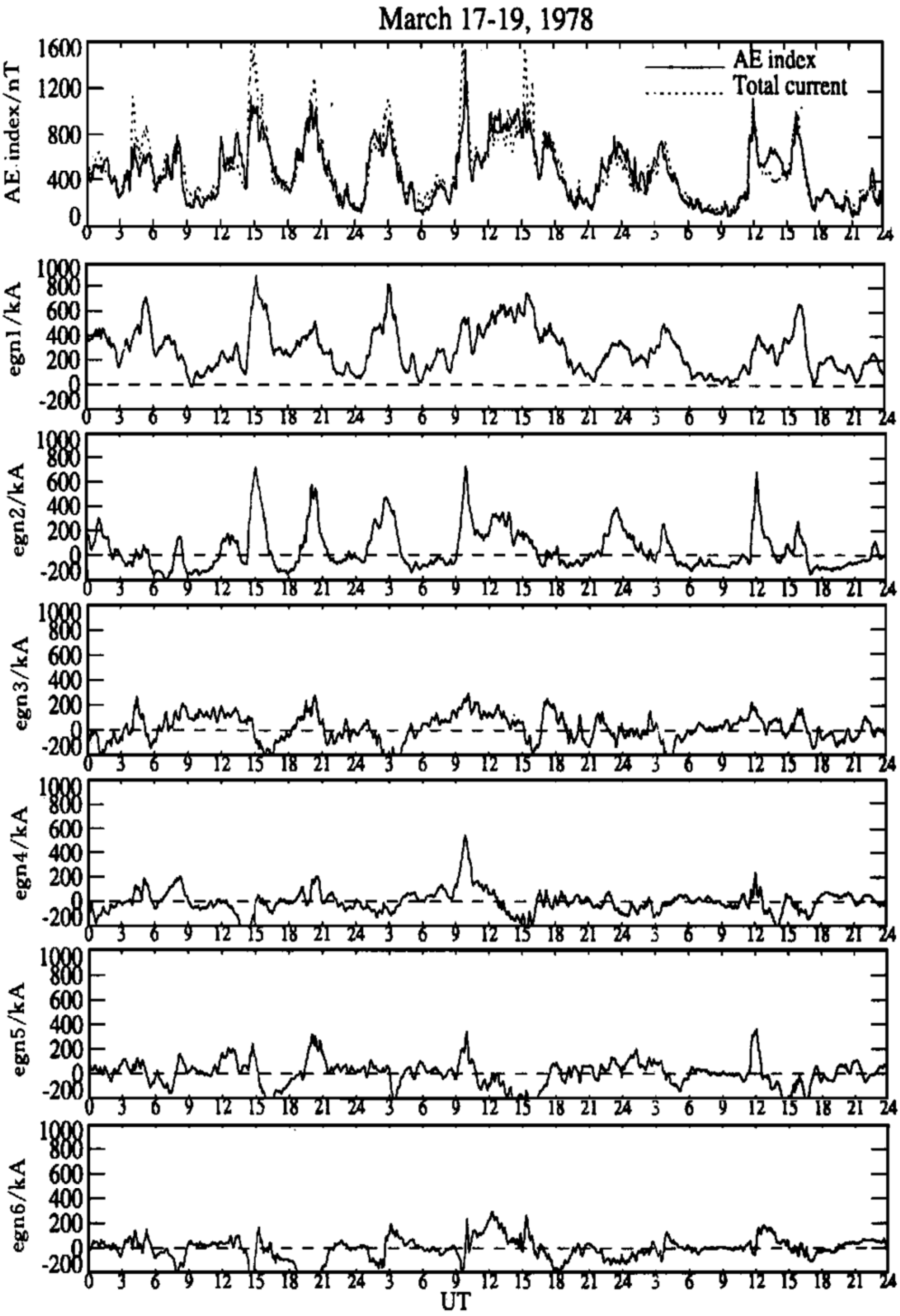

Fig. 3. Time variations of the intensities of the first 6 modes.

4 Conclusion

(1) The equivalent ionospheric current pattern of substorms consists of a few eigen modes with different intensities for any given instant.

(2) The first eigen mode exhibits a two-cell current construction, characterizing the large-scale magnetospheric convection and directly driven process, while the second eigen mode shows a concentrated westward electrojet at midnight sector, characterizing the substorm current wedge and the loading-unloading process.

(3) The first mode consistently exists whenever during quiet periods or at substorms, and its intensity increases from the beginning of the growth phase of substorms. The second mode remains to be zero during both quiet time and the growth phase of substorms, its rapid enhancement occurs in the expansion phase.

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