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INPUT SOLAR WIND ENERGY TRANSFORMATION MODES DURING THE CDAW 9E EVENT

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ABSTRACT/RESUME

The relative importance of the possible modes of the input energy dissipation during the CDAW 9E substorm is examined here. In order to compute the magnetospheric energetics we have improved Akasofu's model (Ref. 1) by added two more terms in the total magnetospheric output energy funtion. The first one represents the energy consumpted for the tail reconfiguration, which was found to be the one third of the input energy. The second one computes the energy stored in the tail and/or returned to the solar wind. The 26% of the input energy has been explosively returned to the solar wind immediately after the onset of the expansion phase, indicating that the tail is in a lower energy state at the end of the substorm. The driven system has been grown in strength immediately after the arrival of the southward B_z-IMF component in the magnetopause, while two unloading events have been determined to occur at the expansion onset.

1. INTRODUCTION

As it is known the magnetosphere is a magnetohydrodynamic (MHD) dynamo which converts the solar wind energy into electric current energy or magnetic energy. The cross-tail current in the magnetotail is a resistive portion of the current solenoids driven by the MHD dynamo (Ref. 2). Because the substorm auroral electrojets are linked with magnetospheric currents, the near-earth portion of the cross-tail current is interrupted and diverted into the ionosphere at the onset of magnetospheric substorms.At the synchronous distance and in the near-earth magnetotail near the equatorial plane, magnetic field observations have indicated that the magnetosphere relaxes to a more dipolar field configuration during the substorm expansion (Refs. 3-6).

The energy that triggers the whole disturbance of a magnetospheric substorm is provided by the solar wind. Perreault and Akasofu (Ref. 7) have suggested an empirical formula which describes the input energy as a function of the interplanetary medium parameters. Akasofu (Ref. 8) has studied the processes of input energy during magnetic storms. His results supported the idea that solar wind energy is directly converted into storm energy without intervening storage in the tail. The process of direct input is probably important on longer time scales and during magnetic storms. Pytte et al. (Ref. 9) have distinguished between the sudden onset substorms and periods of direct conversion of solar wind energy. Fairfield et al., (Ref. 5) in a detailed analysis have confirmed the importance of the magnetotail in supplying energy for the sudden onset substorms. On the other hand they have noted cases of increasing tail energy density during some disturbances which indicate that direct dissipation of solar wind energy is another mode of input. However, the direct mode of input cannot explain the explosive dissipation of energy at substorm onset. Finally, Rostoker et al. (Ref. 10) have distinguished three physical processes in substorm disturbances: the driven process, the storage process and the release process.

The aim of this work is the study of the energy transformation modes and the determination of the relative magnitude of the competing processes during the substorm of the 8th May 1986 with the onset at 12:15 UT (CDAW 9E event). At first, we have established the sequence of the phenomena which occured during this substorm using ground, interplanetary and magnetotail measurements. The auroral elecrojets have been started to grow slowly immediately after the arrival of the B_z-IMF southward component at the magnetopause. Just after the expansion onset the magnetosphere rotated to a more dipolar state, which is a result of the cross-tail disruption. Secondly, in order to fit the Akasofu's model to the event studied here, which is an isolate substorm of weak solar wind coupling, we have introduced some necessary corrections in order to estimate the symmetric ring current injection rate. Moreover we have proposed an empirical formula to estimate the energy required for the field dipolarization, which was found to be the one third of the total input energy that triggers the substorm disturbance, while the energy which remains in the tail and it is probably returned to the solar wind was found to be the 26% of the input energy. The most important fact is that so the energy required for the field dipolarization as the energy which is returned to the solar wind have been dissipated in an explosive way. The inclusion of these two terms in the energy budget of the magnetosphere has led our system to a more unloading behaviour, which is in accordance to our observations.

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2. DATA PRESENTATION AND ANALYSIS

2.1. Auroral Electrojet Indices

The variations of 1-min values of AE and AO indices for the CDAW 9E event are given in the top panel of Fig. 1, while the corresponding values of AL and AU indices are shown in the lower panel of the same figure. A first decrease of the AL index is clearly observed at 11:30 UT, while at 12:15 UT a second sharp decrease is detected.

2.2. Interplanetary medium data

The interplanetary magnetic field data (15.5 sec resolution) have been obtained from IMP-8 spacecraft which was launched in a circular geocentric orbit of ≈ $35R_E$. The separation between IMP-8 and the magnetopause results in a delay of 10 minutes between the measurements made at IMP-8 position and those that would be made at the earth's magnetopause, assuming a constant solar wind speed of 410 km/s. Time-plots of these interplanetary data are presented in Fig. 2. The B_z-component after an interval of drastic variations, returns to the south at 11:13 UT. At the same time a large discontinuity has been detected at all the three components of the interplanetary magnetic field. Nevertheless the southward IMF does not appear to determine the onset of the expansion phase, since it turns southward at 11:13 UT, while the expansion onset has been determined at 12:15 UT, as we will see in the following.

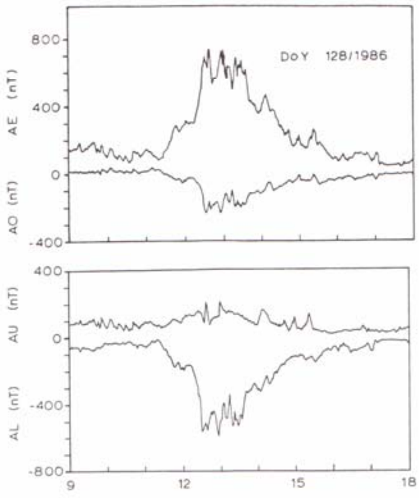

Figure 1. Time plots of the 1-min values of the Auroral Electrojet Indices during the CDAW 9E event.

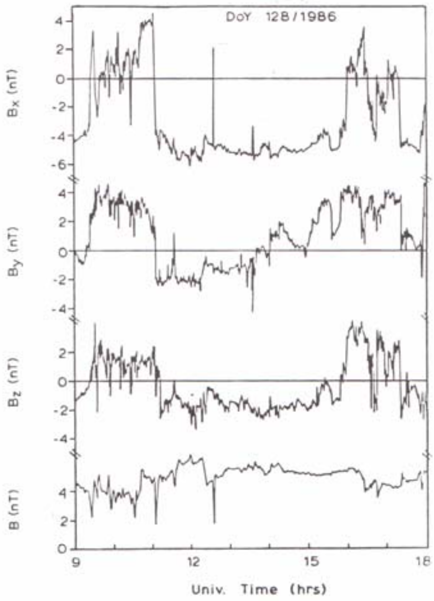

Figure 2. The B_x, B_y, B_z and B IMF components in SE coordinates for the CDAW 9E event measured by IMP-8 spacecraft.

2.3. Magnetotail data

In order to study the state of the tail prior to or during the early phases of the examined here substorm we have used the energy flux data and the magnetic field data measured from ISEE-1 spacecraft (Refs. 11-12). At 11:30 UT, ISEE-1 was located south of the neutral sheet at X = $-20R_E$ at 23:30 LT. The plasma sheet energy flux data (Fig. 3) indicate that the dropout begins at 12:12 UT. At 12:22 UT the plasma sheet vanishes leaving the spacecraft in the south lobe and remains very thin for about 30 min, while negative magnetic bays persist at auroral latitudes. It is known that the onset of the substorm expansion is accompanied by a rapid thinning at the distance of ISEE-1 (Ref. 13). Since at 12:22 UT the plasma sheet vanishes, we can conclude that the sudden decrease of the AL-index at 12:15 UT corresponds to the expansion onset. At 12:52 UT the plasma sheet began expanding over the spacecraft which was back in the plasma sheet boundary layer.

The three components Bx, By and Bz of the tail magnetic field in solar magnetospheric coordinates (SM), together with the total field magnitude B_T, are shown in Fig. 4. The effect of the total field magnitude decrease detected from 12:40 UT until 13:15 UT, is primarily due to the large decrease in |Bx| component, and this was first reported by Camidge and Rostoker (Ref. 14) to be the predominant effect in substorm disturbances on the tail. During the growth phase of the substorm in

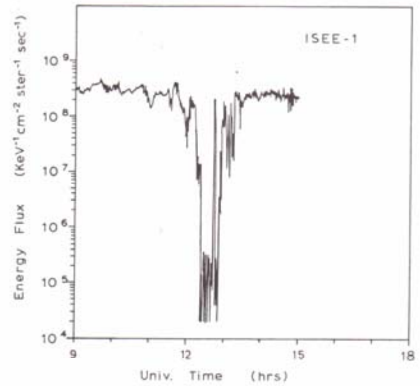

Figure 3. The 6keV electron flux measured by ISEE-1 spacecraft with a 4sec resolution for the examined here event.

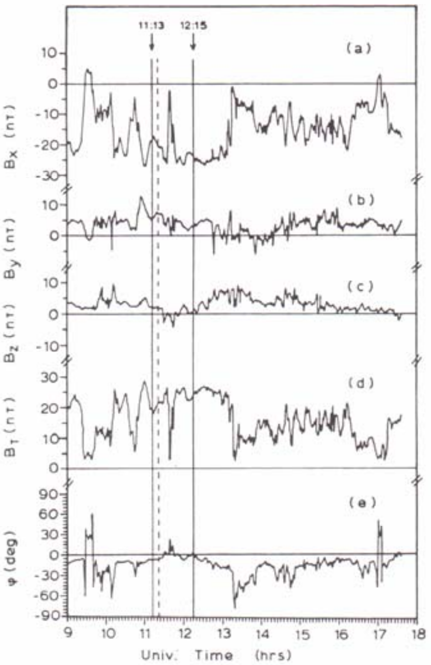

Figure 4. Time plots of the Bx, By, Bz and B_T components of the tail magnetic field, from ISEE-1 in SM coordinates and the time plot of the angle φ calculated as it is described in the text.

the magnetotail, between 11:23 UT and 12:15 UT the Bz component of the tail field presents some variations near zero and just before the expansion onset, Bz component was almost zero. At this time |Bx| component was larger than 25 γ. Consequently the field orientation was essentially parallel to the neutral sheet. Such an orientation is typical for the tail lobe. The beginning of the increase in Bz appears to be associated with the onset of the expansion phase, while the |Bx| component decreases. These changes indicate a rapid rotation of the field from a taillike to a more dipolelike configuration. Therefore in order to determine more precisely the time of rotation of the field from a taillike to a more dipolelike shape we have ploted the angle φ, which is the angle between the projection of the field's vector in the XZ plane and the equatorial plane. The time plot of the angle φ is shown in Fig. 4(e). It is obvious that just after the expansion onset the angle φ starts to increase which means that the field rotates to a more dipolar configuration. This angle takes generally small values during the substorm growth, while it is almost zero some minutes before the onset. This means that just before the onset the field's configuration was extremely taillike.

In summary the sequence of the phenomena which compose this substorm have been established as follows: The beginning of the growth phase in the tail corresponds closely with the appearing of a southward component of the interplanetary magnetic field (IMF) which reaches the magnetopause at 11:23 UT. Just before the expansion onset ISEE-1 at $20R_E$ downstream detects a) an increase of the field magnitude in the lobe of the tail, b) a decrease in Bz component of the tail field and c) the development of a taillike field configuration. Immediately after the onset of the expansion phase a) the magnitude of the angle φ began to decrease and the field starts to rotate slowly to a more dipolelike configuration and b) the plasma sheet thins.

3. MAGNETOSPHERIC ENERGETICS

In order to determine the mechanisms by which the energy input has been dissipated in the magnetosphere we have studied the energy budget of the magnetosphere during this isolate substorm. In the following, we have supposed that the rate of solar wind energy input into the magnetosphere is expressed by the solar-wind magnetosphere coupling parameter ε, proposed by Perreault and Akasofu (Ref. 7):

$$\varepsilon = VB^2\sin^4(\theta/2)l_o^2 \qquad (1)$$

where, B is the magnitude of the interplanetary magnetic field, V is the solar wind bulk speed, θ is given by $\tan^{-1}(B_y/B_z)$ or by the angle's supplement for $B_z<0$ and l_o^2 is an effective cross-sectional area of the magnetosphere, where l_o denotes the linear dimension of the cross-sectional area and it is equal to $7R_E$.

However the energy input is not immediately dissipated within the ionosphere and experiences a series of transformations. Following the Akasofu's model (Ref. 2) the magnetosphere dissipates the input solar wind energy into the ionosphere and the symmetric ring current with the driven process. So, the total energy consumption rate of the magnetosphere, U_T, is given by the sum of the auroral particle flux U_A, of the Joule heat production rate in the ionosphere U_J and of the ring current energy injection rate U_{RC}, given by the equations:

$$U_A = AE \times 10^{15} \text{ erg s}^{-1} \quad (2)$$

$$U_J = 2 \times 10^{15} \text{ AE erg s}^{-1} \quad (3)$$

$$U_{RC} = 4 \times 10^{20}(dDst/dt + Dst/\tau_S) \text{ erg s}^{-1} \quad (4)$$

where τ_S is the life time of the symmetric ring current particles. So, we can write

$$U_T = U_A + U_J + U_{RC} \quad (5)$$

In this study in order to determine a more realistic function for the output magnetospheric energy U_T we have introduced the following improvements in the Akasofu's formula (Eq. 5):

At first we have supposed that during the whole process, the life time of the symmetric ring current particles remains constant and equal to 10 hrs (Ref. 15) since the examined here substorm is produced by a weak solar wind coupling (Dst>-30 γ, $\varepsilon < 3\times10^{18}$ erg s^{-1}).

Moreover in order to compute the ring current energy injection rate in the Akasofu's empirical formula (Ref. 2), we have substituted the Dst-index by the normalized values of the H-component from the San Juan Observatory (not presented here) which is a low latitude station located in the day-side magnetosphere. This station is subjected to the symmetric ring current response.

According to the above mentioned improvements the ring current energy injection rate (Eq. 4) can be corrected using the following equation:

$$U_{RC} = 4 \times 10^{20}(dH_D/dt + H_D/\tau_S) \text{ erg s}^{-1} \quad (6)$$

where H_D denotes the 1-min values of the normalized H-component from the San Juan Observatory.

Continuously, as we have shown in the previous section, the magnetosphere rotates from taillike to dipolelike configuration after the onset of the expansion phase. The dipolarization of the field is due to the enhancement of the cross tail currents which drive the FAC. Honolulu magnetic station is an Observatory which is subjected to the symmetric and also to the partial ring current, as it was located very close to the midnight meridian at the onset of the expansion phase of this event. Therefore in order to estimate the energy consumption rate due to the dipolarization, the following equation may be used:

$$U_{DIP} = 4\times10^{20}(dH_N/dt - dH_D/dt + H_N/\tau_A - H_D/\tau_S) \text{ erg s}^{-1} \quad (7)$$

where, H_N denotes the 1-min values of the normalized H-component from Honolulu Observatory (not presented here) and τ_A is the mean life time of the particles which compose the asymmetric ring current, taken equal to 4 hours (Ref. 10).

Finally it is known that the tail energy changes during a substorm disturbance. Fairfield et al. (Ref. 5) have confirmed the importance of the tail storage in producing substorms. Whether the tail energy increases or decreases will depend on the relative magnitude of the two competing processes, that is the storage process and the unloading process. Therefore in order to have a measure of the amount of energy stored or released from the tail, U_{MT}, we have substracted the sum of the values U_A, U_J, U_{RC} and U_{DIP} from the corresponding values of the input energy ε, using a time delay of 10 min:

$$U_{MT}(t) = \varepsilon(t-10) - U_{IM}(t) \quad (8)$$

$$\text{where } U_{IM}(t) = U_A(t) + U_J(t) + U_{RC}(t) + U_{DIP}(t) \quad (9)$$

The time plots of the energy functions ε, U_A, U_J, U_{RC}, U_{DIP} and U_{MT} estimated for the exanined here event are given in Fig. 5. The southward turning of the interplanetary magnetic field at 11:13 UT has as a result the immediate increase of the energy input ε. At 11:23 UT the energy that remains in the magnetotail takes positive values, while the energy dissipated for the dipolarization of the field is negligible. This is in accordance with our real data (Fig. 4e), since during the growth phase the angle φ takes very small values, which means that the magnetosphere is close to a taillike configuration and therefore the energy U_{MT} which is stored in the tail goes into the cross-tail currents enhancement. However, in the same time and especially after 11:35 UT, the energy dissipation rates U_A and U_J, presented in Fig. 5(b) and 5(c) respectively, are slowly increased, indicating that a part of the input energy has been directly converted in driving the auroral electrojets.

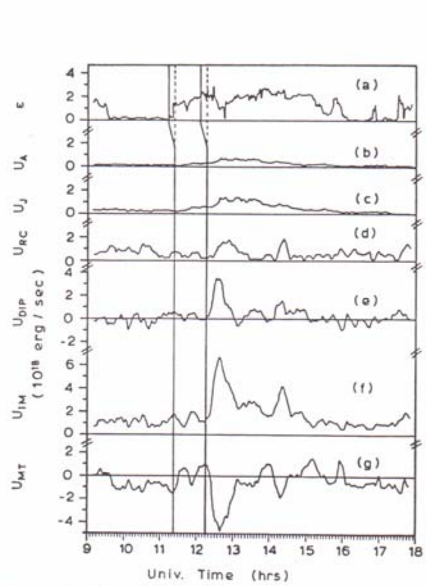

Figure 5. Time plots of the energy functions ε, U_A, U_J, U_{RC}, U_{IM}, and U_{MT} estimated for the studied here event, computed according to Eqs. (1), (2), (3), (6), (7), (9) and (8) respectively.

In conclusion, from the start of the substorm at 11:13 UT until 11:35 UT, the input solar wind energy is stored directly into the tail. From 11:35 UT until 12:15 UT a part of the input energy is dissipated for the growth of the driven system, while the rest of the input energy is continuously stored into the tail.

At 12:15 UT, the energy stored in the tail during the growth phase, has been dissipated explosively in the inner magnetosphere – ionosphere according to the following way: First of all the U_{DIP} energy rate has been increased very sharp, immediately after the onset, indicating that the cross-tail currents have been diverted into the ionosphere. The U_A and U_J energy rates increase more rapidly after 12:15 UT indicating that from that moment the auroral electrojets are fed by the FAC. This explosive dissipation of the tail energy indicates that the unloading process is the dominant mode of energy dissipation at the expansion onset. Finally we have to note that the ring current energy injection rate U_{RC} was not considerably increased since the level of the U_{RC} after the onset did not exceed the U_{RC} level during the quiet period before the growth phase.

A cross correlation analysis between the parameter ε and the energy rate dissipated in the inner magnetosphere U_{IM} gave us a best correlation coefficient equal to 0.54 for time lag 30 min. Taking in consideration the time delay of 10min during which the information propagates from the IMP-8 satellite position to the earth's magnetopause, the time lag for the best correlation coefficient becomes 20 min. This last result confirms the unloading behaviour of the magnetospheric response.

In order to have a more quantitative view of the energy balance we have computed the integrals of the quantities appeared in Fig. 5, over each one phase of this event. The energy required for the field dipolarization at the expansion phase is equal to 4.79×10^{21} erg. This amount is comparable to the solar wind energy coupling which was input during the substorm growth and was found equal to 5.75×10^{21} erg. In other words, during the growth phase the 83% of the input energy has been stored in the tail while the rest has been used for the growth of the driven system electrojets. This fact supports the idea that the tail is an important source of substorm energy. We have to note that the increase of the auroral electrojets intensity at 12:15 UT did not begin from quiet conditions since appreciable auroral currents were flowing prior to the onset time (AE=300γ), while the tail energy was increasing ($dU_{MT}/dt>0$). This fact support the idea that a part of the input energy must have been directly converted during a convection bay (Ref. 9,8,5) and this is the reason why the energy consumpted in the ionosphere during the expansion phase (7.42×10^{21} erg) is greater than the energy required for the field dipolarization (4.79×10^{21} erg). Finally according to our calculations it is resulted that the total energy required for the field's dipolarization is the one third of the input solar wind energy, while the 26% of the input energy has been explosively returned to the solar wind.

4. DISCUSSION AND SUMMARY

Generally in this work we have regarded the magnetotail as an energy reservoir, whose input is controlled by the IMF and from which energy is lost to the ionosphere, to the inner magnetosphere and to the solar wind. During the growth phase the tail magnetic field shows a more stressed configuration as it is obvious from the variations of the angle φ (Fig. 4e). This change reflects the buildup of a strong cross-tail current in the midnight sector at $20R_E$ downstream. The same feature has been observed to occur during the growth phase in the near-Earth region typically at 7 to 15 R_E downstream (Refs. 16-19). This may be due to the predominance of the parallel component of the pressure and the increase in field line curvature as suggested by Kaufmann (Ref. 6) and by Lui et al. (Ref. 18).

At the onset of the expansion phase the strong cross-tail current, produced during the growth phase, suddenly becomes reduced drastically. The diverted current is flowing along preexisting auroral arcs because they provide better conductivity channels. Auroral breakup therefore occurs on one of the preexisting arcs. In this breakup longitudinal sectors the removal of the intense cross-tail current and the creation of a loop through the ionosphere cause a sudden relaxation of stretched magnetic field, producing an earthward convection surge whereby the stretched magnetic field line becomes dipolelike (Ref. 20). It is interesting that our model predicts with a satisfactory time accuracy that the energy U_{DIP} dissipated for the rotation of the tail field to dipolelike configuration increases drastically just after the expansion onset. Plasma tailward of current disruption region is partially evacuated by the convection surge. This leads to a thinning of the midtail plasma sheet (Ref. 20) observed at 12:22 UT by ISEE-1 at 20 R_E downstream.

In order to adjust the Akasofu's model to our isolate substorm of weak solar wind coupling, we have taken the life time τ_s of the symmetric ring current particles to be constant during the whole substorm disturbance and equal to 10 hours. Moreover by substituting the Dst-index by the normalized values of the H-component from a low latitude Observatory located in the dayside magnetosphere, we have isolated the contributions of the symmetric ring current. The present Dst-index, due to the sparsity of stations from which is computed, cannot distinguish between contributions from the symmetric ring current (containing energy deposited during the development of the substorm) and the asymmetric ring current (containing energy which is eventually deposited during the decay of the driven system) (Ref. 10). Each of these currents has quite different time constants, with the decay of the storm-time ring current requiring several tens of hours and the decay of the asymmetric ring current requiring at most 2-4 hours.

The addition of the terms U_{DIP} and U_{MT} is the most important improvement concerning the computation of the energy needs in triggering the dynamic processes observed in magnetotail leading up and following the expansion onset. It is of significant importance to distinguish the meaning between the rates U_{DIP} and U_{MT} used in the present model. The first one describes the energy needed for the tail field dipolarization after the onset of the expansion phase which is due to the partial disruption and diversion of the cross-tail current into the ionosphere to form the substorm current wedge. The second one estimates from one hand the energy stored in the magnetotail during the storage process of the substorm which consequently is transformed to U_{DIP} energy during the decay of the driven system and from the other hand the energy which is injected back to the solar wind during the release process.

The improved energy function for the total magnetospheric energy output, which is proposed in this work, has provided more realistic results in the energy consideration of the examined here substorm.

1. It was established the importance of the magnetotail in supplying the energy for the sudden expansion onset at 12:15 UT.

2. The one third of the input solar wind energy has been explosively dissipated at 12:15 UT for the diversion of the cross tail currents to the ionosphere.

3. The tail energy changes during this substorm. The rate of the energy stored in the tail became minimun at 12:40 UT (Fig. 5g) when the ionospheric currents have drained the tail of much of its energy since AE was maximum at that time. A considerable amount of energy which is the 26% of the input energy has been explosively returned to the solar wind, immediately after the onset of the expansion phase. This fact indicates that the tail is in a lower - energy state at the end of the substorm expansion.

4. Apart from the two mentioned unloading events, occured at the expansion onset, a considerable amount of the input energy has been used for the growth of the directly driven system, continuously from 11:35 UT until 12:40 UT.

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