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THE HALL'S AND COWLING'S CURRENTS CONTRIBUTION INTO THE WESTWARD AURORAL ELECTROJET DURING SUBSTORM UNLOADING PHASE

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Abstract

[1] We estimsted the Hall and Cowling current-caused contributions into the westward auroral electrojet (AEJ-W) during the substorm expansion phase, using data of two substorms. Between other, the data of field-aligned currents (FAC) were used, which were not available in past. As the main result, the major contributions in the unloading AEJ-W were caused by the Hall current that contradict to the conventional model. The physics behind this result is briefly discussed.

Introduction

[2] In the conventional concept, the *unloading AEJ-W* is caused by the Cowling current which amplifies its intensity by several times as compared with *convection AEJ-W* [e.g., Boström, 1974; 1975; Pudovkin et al., 1975; Akasofu, 1977; Untiedt, and Baumjohann 1993; Rostoker et al. 1987; Kamide and Baumjohann, 1993]. The ionospheric Cowling channel with a higher conductance, which is formed in the *unloading AEJ-W*, plays an important role in the substorm mechanism [e.g., Kan, 2007, and references therein]. In the substorm current wedge (SCW) model, the FACs, flowing from the tail disruption region, are closed in the ionospheric channel of higher conductance via the Pedersen or Cowling westward current of the unloading AEJ-W (zonal means westward or eastward, not southward or northward). This conclusion makes the main substorm current system, containing the unloading AEJ-W, by a Zonal Current System [McPherron et al., 1973; Boström, 1974. However, in recent years, has been developed the alternative approach, in which the principal role is played by the Meridional Current System, MCS, where the Pedersen meridional southward ionospheric current corresponds to the westward Hall current [e.g., Akasofu, 2003; Lui and Kamide, 2003; Liang and Liu, 2007]. Mishin et al. [2008a] has concluded under data of one case study, the Hall's (not Cowling's) current is the major component of the unloading AEJ-W. The present paper develops these results under data of two substorms.

Database and Method

[3] We studied two substorms, of 27 Aug 2001 and 01 Oct 2001, for which the s.w. parameters, AE-indices, and plots of the open tail magnetic flux Ψ are presented in Figure 1.
Vertical lines in the Figure mark the onsets of the two substorm active phases – the first active phase when Ψ is growing, and the second active phase when Ψ decreases. One can see, in the isolated 27 Aug 2001 substorm the second active phase is usual expansion phase initiated by the IMF turning northward and fast decrease of Ψ. The 01 Oct 2001 substorm is not isolated ones, and two active phases has no clear distinctions, the both are equally active.

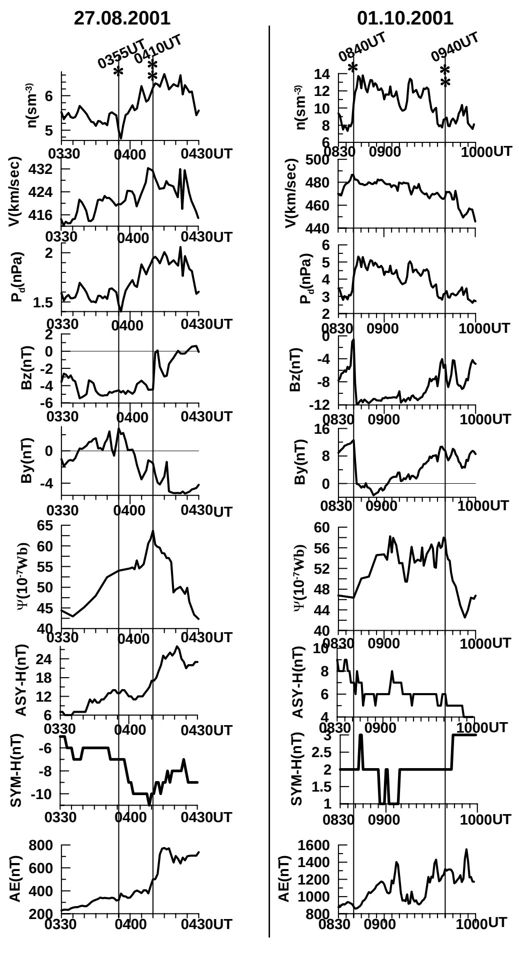

Figure 1. The solar wind parameters, AE-indices, and plots of the open tail magnetic flux Ψ for two substorms uder consideration.

The maps of the equivalent currents and FAC density spatial distribution in the ionosphere were used, obtained using the magnetogram inversion technique, MIT, [Mishin, 1990; Kamide and Baumjohann, 1993]. The inputs were data of >100 magnetometers in the geomagnetic latitudes $\Phi > 60^o$, and the ionospheric conductance model by Mishin et al. [1986]. The solar wind parameters (s.w.) [CDAWeb, Goddard Space Flight Center; http://cdaweb.gsfc.nasa.gov/cdaweb/sp_phys/] and activity indices [WDCC2 for Geomagnetism, Kyoto and MIT on 45-65 magnetometers in the geomagnetic latitudes $\Phi > 60^o$-75^o] were used as well.

[4] The well-known is, mentioned in Introduction, the Z<u>onal</u> Current System of SCW, where the Pedersen current, closing the pair R1 FACs, flows westward. Lui and Kamide [2003, and references therein] introduced the notion MCS - <u>Meridional</u> Current System. It is the three-dimensional current system, consisting of a pair of FACs and the Pedersen ionospheric meridional current, which closes this FAC pair. Mishin et al. [2008b, this issue] have described three types of such systems. In the present work, we consider only one of them, the MCS-1, comprising the unloading AEJ-W near midnight and downward and upward FACs on its north and south borders (see Figures 2 and 3). These downward and upward FACs belong (in MCS-1) to Iijima's Potemra (I-P) Regions I and 2, respectively. It will be shown that the unloading AEJ-W can be observed in both above current systems, MCS-1 and SCW. We name these two types of the unloading AEJ-W as Hall' and Cowling' types (or contributions in AEJ-W), respectively.

[5] It will be shown in paragraph [7] that the Hall's current contribution in AEJ-W can be presented by equation $J^*_H = kJ_{MCS}(L_{NS}/L_{MCS})$, where MCS is MCS-1 and other denotations are as follows: the intensity of the FAC pair, which frame the unloading AEJ-W, is J^*_{MCS}; the longitudinal (MLT) and latitudinal sizes of the electrojet under consideration are L_{MCS}, and L_{NS}, respectively. We compared the observed intensity of the unloading electrojet near midnight, J_w, with the calculated contributions into it of Hall's (J^*_H) and Cowling's (J_c) current. The initial supposition was that the unloading electrojet is a part of MCS-1 in the auroral oval near midnight, where the AEJ-W is expanded during the substorm unloading phase. In the above equation, $\kappa = \Sigma_H/\Sigma_p$ is the ratio of the Hall and Pedersen height-integrated conductance; J_{MCS} is the intensity of the two FAC sheets, framing the unloading AEJ-W; and L_{NS} and L_{MCS}, arethe north-south and longitudinal (by MLT) sizes, measured on the maps of the equivalent currents and FAC density spatial distribution, respectively.

[6] When calculating J^*_H we used the value $\kappa = \Sigma_H/\Sigma_p = 2$. According to the MIT conductance model used for the events under consideration, it is typical k value in the midnight sector of the unloading AEJ-W. The probable $\kappa = \Sigma_H/\Sigma_p$ values lie within the interval 2 to3 [e.g., Kamide and Baumjohann, 1993]. We also determined the intensity J_w of the unloading electrojet on the equivalent current maps. Having J^*_H and J_w, we fitted the values $\kappa = \kappa^*$ in each UT instant to provide the equality of the $J^*_H = J_w$. On such a base, we considered the events, when the coincidence of $J^*_H = J_w$ within 10% took place with $2 < k^* < 3$, to support the hypothesis "the unloading electrojet is the Hall current." The events when the equality $J^*_H = J_w$ took place with $\kappa^* > 4$ were considered to support the hypothesis "the unloading electrojet is the Cowling current." The transitions from one regime to the other were observed as strong deviations of J^*_H from J_w. The amplitude of deviations was so large that the timing of the named transitions did not cause significant doubts (see Figure 4).

Equations

[7] We denote the intensity of the FAC pair which is closed in the ionosphere via the unloading AEJ-W, as well as the longitudinal (MLT) and latitudinal sizes of the electrojet under consideration, J^*_{MCS}, L_{MCS}, and L_{NS}, respectively. Then, the Pedersen ionospheric meridional current density is $j^*_P = J^*_{MCS}/L_{MCS,}$ and the Hall current density is $J^*_H = J^*_H/L_{NS} = j^*_P \cdot k$, where $k = \Sigma_H/\Sigma_P$ and J^*_H are the model intensity of the Hall unloading electrojet. The sizes L_{MCS} and L_{NS} are determined by using the maps of FAC spatial distribution and maps of equivalent currents. Denoting also **E** and **B** as the vectors of the magnetic and electric fields, and accepting some obvious simplifications, we have the following equation system.

$$j^*_P = \Sigma_P E \qquad (1)$$

$$j^*_P = J^*_{MCS}/L_{MCS} \qquad (2)$$

$$E = J^*_{MCS}/(\Sigma_P\ L_{MCS} \qquad (3)$$

$$j^*_H = \Sigma_H[E,B]/B \qquad (4)$$

$$j^*_H = \Sigma_H E \qquad (5)$$

$$j^*_H = kJ^*_{MCS}/L_{MCS} \qquad (6)$$

$$k = \Sigma_H/\Sigma_P \qquad (7)$$

$$J^*_H = j^*_H L_{NS} \qquad (8)$$

$$J^*_H = kJ_{MCS}(L_{NS}/L_{MCS}) \qquad (9)$$

When calculating the J^*_H we used the value

$$k = 2 \qquad (10)$$

Results

[8] The maps of the FAC spatial distribution and maps of equivalent currents are presented in Figures 2 and 3. The typical examples of each of the two regimes of the unloading AEJ-W are given, of the Hall's regime (top panel) and the Cowling's one (bottom panel).

Using Figures 2 and 3, let us note, first, the common features of the two types. Unlike the convection jet, localized in the dawn sector, the unloading AEJ-Ws of both types are observed near midnight and also they take late evening hours, i.e., the AEJ-W is expanded westward during the unloading. The Hall's or Cowling's current, forming the unloading electrojet near midnight, both flows between the downward FAC of Region 1 (R1) and upward FAC of the Iijima and Potemra (I-P) R2. The Pedersen's corresponding ionospheric current, closing the couple of FACs, is southward along the meridian. Such a current system (couple of FACs, Pedersen ionospheric current, and the magnetospheric current closing the FACs) was termed three-dimensional MCS-1 [Mishin et al., 2008 b].

Numeral 1 in this term is the number of the I-P FAC Region of the downward FAC.

To north-west of MCS-1, the MCS-1 adjoined by the MCS-0 system, which also contains a (smaller) portion of the unloading AEJ-W.

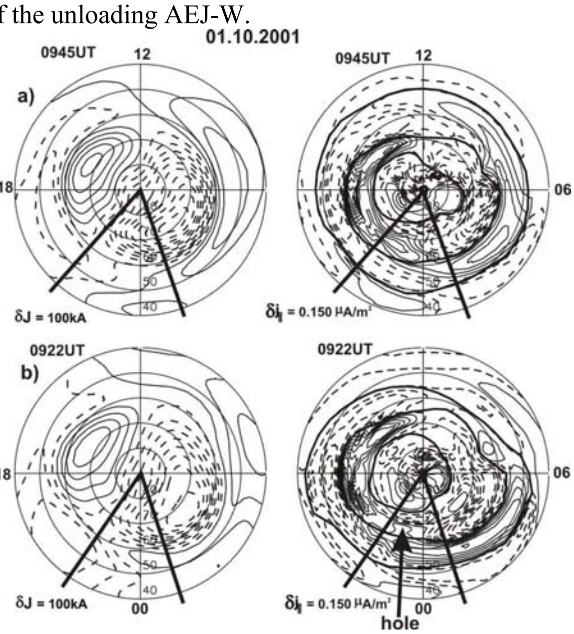

Figure 2. Typical examples of the current systems with the prevailing contribution into the unloading AEJ-W of the Hall current (Figure 2a, top), or the Cowling current (Figure 2b, bottom). One can see in Figure 2b near midnight, there is the couple of FACs, framing the electrojet on north and south. In Figure 2a, such a couple is absent ('hole"!), and dominates the SCW effect which creates the westward electric field and the Cowling's current prevailing contribution in the AEJ-W. Two meridians, constraining from east and west the MCS-1 under consideration, are shown.

The calculations of J^*_H, based on the equations (1) to (10), were performed in the present study using only data for the MCS-1. The sizes L_{NS} and L_{MCS} of this MCS-1 in the ionosphere were determined for each UT separately, by using the maps of the equivalent currents (L_{NS}) and FACs (L_{MCS}).

[9] The difference between the Hall type and the Cowling ones is particularly evident in Figure 4a.

First, let us compare the J_w and J^*_H values, calculated at κ=2 for 01 Oct 2001 substorm. It is well seen these two values agree within < 10% in the temporal interval (0940-1000) UT. For (1000-1030) UT, the J_w and J^*_H values also agree within 10% when 2<κ≤2.6. Keeping in mind the k=2 value as most probable one, and the range of the probable values is *k=2 – 4*, we conclude that for (0940-1030) UT, 01 Oct 2001, that is, over the bulk of the substorm expansion phase under consideration, the Hall current contribution was prevailing, not the Cowling ones. Indeed one can see, the J_w and J^*_H calculated values coincide for this interval, if we vary the k values from 2 to 2.6 when calculating. On the other hand, within the temporal interval (0915-0924) UT, the J_w и J^*_H values are impossible to reconcile by *fitting* k within 2 to 4. Hence, within this interval (0915-0924) UT, the prevailing contribution into the unloading electrojet was produced by the Cowling current.

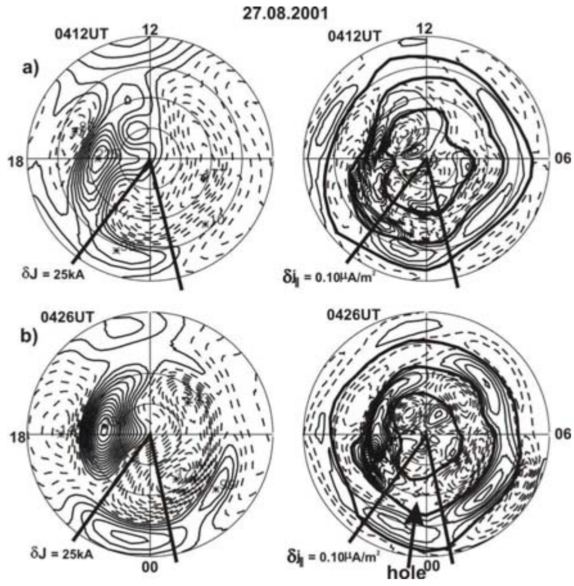

Figure 3. See caption in Figure 2

[10] The similar analysis of the data for the 27 Aug 2001 substorm (Figure 4b) leads to the conclusion that in this event the Hall current contribution prevails within the interval (0400-0422) UT, and the Cowling current contribution prevails within (0424-0430) UT.

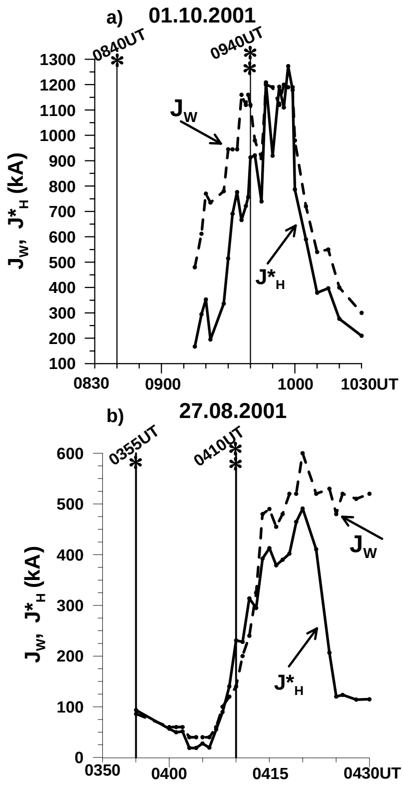

Figure 4. The observed (J_w) and calculated (J_H*) values of the unloading electrojet intensity.

[11] Let us return to Figure 2. Considering first the top panels, one can see that the Hall type prevails in the unloading electrojet, when the two oppositely directed sheets of FACs are observed north and south of this jet *over all the length of MCS-1 near midnight, and they are closed in the ionosphere via the Pedersen meridional current*. The last fact contradicts to the classic model of the substorm current wedge, in which the Pedersen or Cowling zonal westward current corresponds to the unloading AEJ-W [McPherron et al.1973]. The lower panel of Figure 2 present the example of the unloading electrojet with the Cowling's type prevailing. The main peculiarity of this regime, as compared to the Hall's regime, is that the pair R1 FACs of the opposite signs does not closed near midnight, but a "hole" separating the downward and upward R1 FACs is observed. The meridional component of the Pedersen current, observed in the case of the Hall regime, is absent in the "hole." *The electric field in the "hole" has the westward zonal component.* This can be the key fact to understand the cause of the transition from the Hall regime to the Cowling one.

Discussion and Conclusion

[12] Following Boström [1975], we will consider the ionospheric area of the unloading AEJ-W near midnight in the form of a rectangular drawn east to west, with the Hall and Pedersen conductance high inside the rectangular and zero outside it. If the initial westward electric field E_0 is given in this area, the Pedersen westward current $j_p= E_0\Sigma_p$ arises, as well as the Hall meridional northward current $j_{H,1}=E_0\Sigma_H$, which is compensated by the Pedersen equal and oppositely directed current $j_{p,2}=E_p \Sigma_p$, where E_p is the southward polarization field. With zero conductance out of the rectangular, we have $j_p= j_{H,1}$, from which it follows $E_p=E_0(\Sigma_H/\Sigma_p)$. The polarization field E_p produces the Hall secondary westward current $j_{H2}=E_0(\Sigma^2{}_H/ \Sigma_p)$. In general, the Cowling current $j_c=E_0(\Sigma_p+ \Sigma^2{}_H/ \Sigma_p)$ is produced in the rectangular under consideration. It is the model of the Cowling type unloading electrojet.

[13] It is evident from the above, that gradients of the ionospheric conductance on the northern and southern boundaries of this field and westward electric field E_0 are necessary to form the Cowling type. Fulfillment of the first condition is evident in the maps of the ionospheric conductance (are not shown). The second condition is also fulfilled according to data of paragraph [10]: the electric field in the "hole" has the westward zonal component. Thus, the identification of the Cowling regimes, as the ones with the "hole" is acknowledged.

[14] The observed (equivalent) current density of the Cowling' or Hall' mode can be expressed $j_{w,c}=E_w(\Sigma_P+\Sigma_H{}^2/\Sigma_p)$ or $j_{w,H}=E_s\Sigma_H$, respectively. Here, E_w has cased by generation of the I-P FACs R1 and by the electric potential transport in the ionosphere from the tail disruption region. The E_s is caused as the joint effect of plasma ejection Earthward from the tail disruption region, and by generation of the I-P R1 also R2 FACs. The latter causes also the partial ring current DRP. Thus, the Hall' and Cowling's modes of the unloading AEJ-W have the different physics in the terms of the electric potential transport in the ionosphere, and R2 FACs/DRP generation.

Authors of this paper continue the study of the problem under consideration.

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