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The role of the inner tail to midtail plasma sheet in channeling solar wind power to the ionosphere

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[1] In this article we use Cluster power density ($\mathbf{E} \cdot \mathbf{J}$) data from 2001, 2002, and 2004 to investigate energy conversion and transfer in the plasma sheet. We show that a southward IMF B_z is favorable for plasma sheet energy conversion, and that there is an increased particle and Poynting flux toward the Earth at times when Cluster observes an enhanced energy conversion in the plasma sheet. Conversion from electromagnetic to kinetic energy is increasingly dominant farther down-tail, while the generation of electromagnetic power from kinetic energy becomes important toward the Earth with a maximum at roughly $10 R_E$. By linking observations of the key quantity $\mathbf{E} \cdot \mathbf{J}$ to observations of the solar wind input and earthward energy flux, our results demonstrate the role of the inner tail to midtail plasma sheet as a mediator between the solar wind energy input into the magnetosphere and the auroral dissipation in the ionosphere.

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1. Introduction

[2] In the literature, there are many investigations suggesting that the plasma sheet energy conversion acts as an important mediator between the solar wind (SW) energy input into the magnetosphere and the auroral dissipation in the ionosphere. For example, high speed plasma flows in the plasma sheet have been shown to correlate well both with the orientation of the interplanetary magnetic field (IMF) [Juusola *et al.*, 2011] and with auroral activity as measured by the AE index [Angelopoulos *et al.*, 1994]. The results of these studies implicitly suggest a general energy transfer scheme from the SW, to the plasma sheet, and then to the ionosphere. However, to our knowledge, there is a lack of investigations directly linking the SW energy input and the energy flux toward the ionosphere to observations of the plasma sheet power density. The power density, $\mathbf{E} \cdot \mathbf{J}$ (where $\mathbf{E}$ is the electric field and $\mathbf{J}$ the current density), is a key quantity when investigating energy conversion issues. $\mathbf{E} \cdot \mathbf{J}$ corresponds to the amount of energy (per unit volume and per unit time) converted between its electromagnetic and

kinetic forms. A value $\mathbf{E} \cdot \mathbf{J} < 0$ indicates a generator, in which kinetic energy is converted to electromagnetic energy, and the electromagnetic energy density hence increases. For a load, $\mathbf{E} \cdot \mathbf{J} > 0$, and energy is transferred in the opposite direction. The interpretation of $\mathbf{E} \cdot \mathbf{J}$ can be verified from the Poynting theorem

$$\frac{\partial W_{EM}}{\partial t} = -\nabla \cdot \mathbf{S} - \mathbf{E} \cdot \mathbf{J}, \quad (1)$$

where W_{EM} is the electromagnetic energy density, and $\mathbf{S}$ is the Poynting vector.

[3] Due to the cross-tail current, and the dawn-dusk electric field, the plasma sheet corresponds to a load at large scales, converting electromagnetic energy to kinetic (thermal and plasma bulk) energy. On smaller scales, however, the plasma sheet shows a high level of fine structure in the energy conversion, hosting both load and generator regions. This complicated structure of the plasma sheet energy conversion has been verified both from numerical simulations [e.g., Birm and Hesse, 2005; Tanaka *et al.*, 2010] and from spacecraft observations [e.g., Hamrin *et al.*, 2009]. In Figure 1 we present a simple cartoon of the major energy transfer processes of the Earth's magnetosphere. It shows the plasma sheet as an important link in the long chain of processes eventually causing, e.g., auroral activity at lower altitudes.

[4] To our knowledge, the first experimental investigations of generator regions in the plasma sheet were presented in Marghиту *et al.* [2006], Hamrin *et al.* [2006], and Rosenqvist *et al.* [2006]. However, it is only recently that the overall behavior of the plasma sheet energy conversion has been investigated more intensely. Using Cluster $\mathbf{E} \cdot \mathbf{J}$ data

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Figure 1. A schematic cartoon showing some main features of the magnetospheric energy budget. See the text for details.

from several years, Hamrin *et al.* [2011] found that loads and generators regularly exist in the plasma sheet probed by Cluster. Load regions appear to be approximately three times as common as generator regions, and loads are generally observed closer to the neutral sheet, while generators often prefer locations toward the plasma sheet boundary layer (PSBL). In previous investigations, variations in $\mathbf{E} \cdot \mathbf{J}$ have also been linked to, e.g., earthward flowing plasmoids and magnetic flux ropes [Lui *et al.*, 2007; Zong *et al.*, 2007].

[5] In this article we use Cluster data for discussing the role of the inner tail to midtail plasma sheet for the energy conversion between electromagnetic and kinetic energy forms, and for the energy transfer toward the ionosphere. To probe the energy conversion we will use the key quantity of the power density, $\mathbf{E} \cdot \mathbf{J}$. The multispacecraft Cluster mission [Escoubet *et al.*, 2001] is particularly favorable for observational investigations of the energy conversion. The reason is that at least four simultaneous magnetic field measurements (provided by the four Cluster spacecraft) are needed for estimating the current density $\mathbf{J}$.

[6] In section 2 we discuss relevant energy conversion and transfer processes in the magnetosphere. Section 3 contains a short overview of the data and methods used. In section 4.1 we analyze the response of the plasma sheet energy conversion in relation to the SW energy input (as probed by the IMF B_z direction). The relation between the plasma sheet energy conversion and the energy transfer toward lower altitudes (via BBFs and Poynting flux) is investigated in section 4.2. Our results are summarized in section 5.

2. Energy Conversion and Transfer in the Inner Tail to Midtail Plasma Sheet

[7] The SW kinetic energy flux is the major energy source for the magnetospheric energy budget. This flux is about 20 times larger than the SW Poynting flux at the distance of the Earth's orbit, but only a fraction of the available SW kinetic energy is needed to power the magnetospheric dynamics [Koskinen and Tanskanen, 2002]. Magnetic reconnection [Paschmann *et al.*, 1979] is a key process for controlling energy transfer into and within the magnetosphere [Dungey, 1961]. Locally, reconnection corresponds to a load where

free magnetic energy is transferred into accelerated particles and heat.

[8] Reconnection controls the transfer of SW energy across the magnetopause [Pulkkinen *et al.*, 2007]. The energy input depends foremost on the IMF direction and the SW speed [Pulkkinen *et al.*, 2008; Palmroth *et al.*, 2010]. For southward IMF, reconnection is expected to occur at the dayside magnetopause. The reconnected field lines are dragged down-tail by the SW, and in regions beyond the cusp, the magnetic tangential force acts against the SW flow, which causes energy from the SW to be transferred into magnetic energy density of the lobe magnetic field [Siscoe and Cummings, 1969]. Such magnetopause generators have recently been investigated by, e.g., Rosenqvist *et al.* [2008] and Palmroth *et al.* [2010].

[9] The energy stored in the tail magnetic field is released through tail reconnection [see, e.g., Sharma *et al.*, 2008, and references therein]. A near-Earth neutral line (NENL) is expected to form 20–30 R_E down-tail in the plasma sheet during substorm expansion [Nishida *et al.*, 1981]. The energy is transported away from the reconnection site as high speed plasma flows toward the ionosphere in the coupled magnetosphere-ionosphere (M-I) system, as well as into interplanetary space. For a long time, flows in the plasma sheet were considered to be rather smooth and laminar, but now we know that the plasma sheet is much more structured and complicated than initially anticipated. In the early 90s, bursty bulk flows (BBFs) were discovered, and soon it was observed that BBFs are commonly occurring in the plasma sheet [Angelopoulos *et al.*, 1992]. Typically, BBFs are expected to be caused by reconnection, and they correspond to bursty high speed flow events observed on a 10 min timescale, and composed of individual flow burst (≥ 400 km/s) on shorter timescales [e.g., Scholer *et al.*, 1984; Angelopoulos *et al.*, 1992; Chen and Wolf, 1993]. While observed about a tenth of the time in the plasma sheet, they contribute approximately to half of the circulated mass, energy, and flux [Sergeev, 2005]. BBFs are related to auroral phenomena at the ionospheric end of the M-I system, e.g., auroral expansions, localized brightenings, and auroral streamers [e.g., Amm and Kauristie, 2002; Sergeev, 2005].

[10] The energy transferred into the magnetosphere is eventually dissipated through various processes such as ring current dissipation, auroral Joule heating, and charged particle precipitation into the ionosphere. It has been found that the plasma sheet dissipates (in the form of plasma heating and plasmoid ejection) comparable amounts of energy during substorms [Jeda *et al.*, 1998; Slavin *et al.*, 1993]. The energy conversion in the plasma sheet is hence an important factor for the magnetospheric energy budget.

[11] Processes important for both the energy and mass transport within the coupled M-I system, as well as for the ultimate energy dissipation in the auroral ionosphere, have been investigated extensively. See for example Paschmann *et al.* [2002] for a review. Recent investigations suggest that energy conversion regions (ECRs) in the plasma sheet, in the form of both loads and generators, are often associated with BBFs [Hamrin *et al.*, 2011; Marghita *et al.*, 2010; O. Marghita *et al.*, manuscripts in preparation, 2012]. The results from Hamrin *et al.* [2011] suggest a rather complicated structure of the plasma sheet energy conversion, with the possibility of multiple conversion back and forth between the kinetic (thermal and plasma bulk) and electromagnetic energy forms before the energy eventually is dissipated in the ionosphere.

[12] Electromagnetic power generation and dissipation along auroral field lines was addressed by Angelopoulos *et al.* [2002]. By using conjugated data from the Polar and Geotail satellites, they observed that the earthward particle energy flux is about ten times as large as the electromagnetic energy flux at the same altitude. Moreover, most electromagnetic energy density generated at $\sim 18 R_E$ is found to be dissipated before it reaches the Polar altitude of $\sim 5 R_E$ (above the auroral acceleration region). However, the Poynting flux observed by Polar is still more than enough for explaining the auroral particle acceleration below the spacecraft. Moreover, even if only a small part of the BBF energy couples to Alfvén waves and is radiated away, it is nonetheless sufficient for powering the auroral acceleration during substorms. The results presented by Angelopoulos *et al.* [2002] indicate that there must exist mechanisms corresponding to the loss of electromagnetic energy along the field lines, and BBF-generated Alfvén waves were suggested as a possible candidate. Comparing with the results of Hamrin *et al.* [2011], we note that such an electromagnetic energy conversion mechanism could well be described by the existence of ECRs along the field lines between the reconnection site (load) and the auroral acceleration and ionospheric dissipation (loads).

3. Method and Data

[13] In this investigation we use Cluster data from 2001, 2002, and 2004 to investigate the plasma sheet energy conversion and transfer through the evaluation of $\mathbf{E} \cdot \mathbf{J}$. For these years, the Cluster spacecraft configuration was favorable (approximately an equilateral tetrahedral with scale size 1000–4000 km). During 2003, the scale size was of the order of, or smaller, than the typical ion gyro radius, while the configuration was in a multiscale mode in 2005 and later years. Magnetic field measurements from the FGM magnetometer instrument are used for obtaining the current density by using the curlometer method. The electric field is derived

from the two CIS ion instruments, CODIF and HIA, on the assumption that the $\mathbf{E} \times \mathbf{B}$ drift is dominant. Electric field estimates from the EFW double-probe instrument are used for double-checking the results. For a detailed discussion of the Cluster mission and instruments, see Escoubet *et al.* [2001, and references therein].

[14] Near the Earth (in the inner tail to midtail plasma sheet) the space plasma is mostly well described by ideal MHD, where $\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$, and the $\mathbf{E}$ parallel to the magnetic field, $E_{\parallel}$, is assumed to be zero. Then $\mathbf{E} \cdot \mathbf{j} = \mathbf{E}_{\perp} \cdot \mathbf{j}_{\perp}$. This assumption can break down in small regions, where then also the term $E_{\parallel} \cdot j_{\parallel}$ potentially contributes to $\mathbf{E} \cdot \mathbf{j}$. In this study we use the ion velocity $\mathbf{v}$ and $\mathbf{B}$ measured by instruments on satellites to estimate $\mathbf{E}_{\perp}$, and cannot directly detect any regions where $E_{\parallel} \neq 0$. However, considering the timescale of our ion measurements, of about 10 s ($\gtrsim 4s$), this contribution is likely to be negligible most of the time. We therefore assume that the contributions of $E_{\parallel} \cdot j_{\parallel}$ to the overall power density is not significant, and we neglect it.

[15] The power density is evaluated in the GSM frame of reference. Picking a correct reference frame is very important since the power density is not invariant under coordinate transformations. The choice of frame should be based on the relevant energy conversion processes within the system, e.g., (a) the reconnection X-line load, (b) load and generator regions within the highly structured plasma sheet (possibly related to BBFs), (c) the load in the auroral acceleration region, and (d) the load corresponding to the ionospheric Joule heating. As discussed in Hamrin *et al.* [2011], the GSE/GSM frame is the optimal one in our case.

[16] Using the $\mathbf{E} \cdot \mathbf{J}$ data we have identified 555 ECRs from the years of interest. The identification is made by an automatic routine, and only clearly identifiable regions with significant $|\mathbf{E} \cdot \mathbf{J}| > 0$ above the surrounding fluctuations are selected. To be accepted by the routine, every event must fulfil a set of instrumental and physical criteria. In total, 428 Concentrated Load Regions (CLRs) and 127 Concentrated Generator Regions (CGRs) have been identified. In addition to this, we have randomly selected almost 2500 reference events with random time extent between 100 s and 500 s. The only selection criterion for these RAND events is that the spacecraft instruments are fully operational. There are no extra requirements on, e.g., measurable energy conversion. The RAND events are expected to capture the general behavior of the plasma sheet energy conversion. For a discussion about the data, the selection routine, and a more theoretical motivation for the use of the power density quantity, we refer to Hamrin *et al.* [2011, and references therein].

[17] In this article we analyze the occurrence of ECRs in relation to the north-south direction of IMF B_z , to the plasma sheet bulk flow, and to the Poynting flux. For the IMF investigation, we use 64 s averages of the ACE SW data [Chiu *et al.*, 1998; Smith *et al.*, 1998] time shifted to the nominal magnetopause ($10 R_E$). The plasma bulk flow is obtained from the HIA and CODIF instruments (with the assumption that all ions are H⁺). In the computation of the Poynting flux, the background magnetic field (a polynomial fit) has been subtracted from the total magnetic field to obtain the wave contribution. However, no background electric field has been subtracted. To be consistent with the

Figure 2. The occurrence of plasma sheet load (red) and generator (blue) regions for southward ($B_z < 0$) and northward ($B_z > 0$) IMF, respectively. We only include events which correspond to a constant southward or northward IMF during an extended 60 min interval before the starting time of the ECRs. No extra time delay between variations in the IMF and the ECR response is assumed. The ratio between the number of ECRs with $B_z < 0$ and $B_z > 0$ is indicated at the top of the $B_z < 0$ bar.

power density calculation, the Poynting flux has been computed in the same frame of reference as $\mathbf{E} \cdot \mathbf{J}$, i.e., GSM.

4. Observations

4.1. ECR Response to SW Input

[18] SW energy input is known to be efficient under conditions of southward IMF B_z , even though investigations show that reconnection also operates during northward IMF, but at higher latitudes [e.g., Reiff and Burch, 1985]. In this section we investigate the response in the plasma sheet energy conversion with respect to variations in the GSM IMF B_z component.

[19] It is reasonable to assume that the plasma sheet energy conversion is not responding instantaneously to variations in the IMF. The histogram in Figure 2 therefore shows the occurrence of ECRs for conditions of steady northward and southward IMF B_z during intervals ≥ 60 min before the starting time of the ECRs. The timescale of 60 min is reasonable for including a possible time lag between the SW energy input and the plasma sheet response [see, e.g., Bargatze et al., 1986]. The ratio between the number of events with $B_z < 0$ and $B_z > 0$ ($N_{B_z < 0}/N_{B_z > 0}$) is indicated at the top of the CLR and CGR bars. We see that CLRs and CGRs are observed during southward IMF 3.3 and 1.2 times as often as during northward IMF, and we find confirmed that a southward IMF is favorable for plasma sheet energy conversion at Cluster altitudes.

[20] The response to the IMF B_z sign is seen to be stronger for CLRs than for CGRs. This effect could be traced back to variations in the CLR and CGR spatial distributions in xyz space (Figure 3) as probed by Cluster, and in relation to the general plasma sheet motion, thinning, and expansion during the substorm cycle. Note that loads can be expected to exist for example rather close to the reconnection site where the plasma is accelerated, while generators may well be more common closer to the inner boundary of the plasma sheet, in the region of braking and diversion of earthward plasma flows. In addition to this, we may also expect that loads and generators may appear in different regions of the BBF channels (e.g., the front side, rear side or the flanks).

[21] In Figure 3a we indicate the expected occurrence of plasma sheet loads and generators as a general function of x . A schematical Cluster orbit is shown in Figure 3b. Due to properties of the orbit, plasma sheet data from various

regions in xyz space (from regions closer to the neutral sheet as well as from regions in the PSBL and closer to the flanks) are included in this investigation — see also Hamrin et al. [2011] for a discussion of the xyz distributions of CLRs and CGRs. For x values below $\sim 14 R_E$, Cluster data are obtained near the flanks. For larger distances, we may expect that Cluster in general probes the plasma sheet near the NENL, in regions where we are more close to the maximum of the load distribution, but toward the declining tail of the generator distribution. Consequently, the data in this investigation can be used to verify the difference between the spatial distributions of CLRs and CGRs in xyz space as probed by Cluster.

[22] After the discussion above we can also explain why CGRs respond more weakly to IMF B_z than CLRs (see Figure 2). The general magnetotail configuration is expected to vary with, e.g., the SW input and the substorm cycle. After prolonged intervals of southward IMF we may expect a substorm expansion, with a resulting tail-ward motion of the NENL [Baumjohann et al., 1999]. A few minutes before onset, reconnection occurs at x approximately between $-16 R_E$ and $-20 R_E$ [Miyashita et al., 2009], i.e. in the region of the Cluster plasma sheet crossings in 2001, 2002, and 2004. (Note that Cluster mostly probes the earthward side of the NENL according to our data - see the discussion in relation to Figure 4 below.) The relative position between the NENL and the Cluster spacecraft will vary during the substorm cycle. On the average, Cluster is probing regions near the NENL (generally on the earthward side), i.e. regions which are dominated by earthward plasma acceleration (at the peak of the CLR distribution and the tail of the CGR distribution in Figure 3a). The location of the NENL depends on the SW [Nagai, 2006], and it has been shown that the neutral line occurs closer to the Earth under strong solar wind conditions [Miyashita et al., 2009]. For such conditions, this would hence push the Cluster plasma sheet crossings further toward an increasing (a decreasing) CLR (CGR) distribution as shown in Figures 3a–3b, i.e., toward an even weaker response of the CGRs. In summary, the Cluster location close to the peak (tail) of the CLR (CGR) distribution, together with the magnetotail dynamics with respect to the IMF and the substorm cycle, could explain why the occurrence of CGRs seems to be less affected by the IMF B_z direction.

Figure 3. (a) Schematic variation of the occurrence of load and generator regions in the plasma sheet. (b) Schematic Cluster orbit. Note that effects from the Cluster orbit imply that a rather extended region in GSM xyz space is probed. (c) Observed occurrence of CLR, CGR, and RAND events versus GSM $-x$.

[23] In Figure 3c we present the occurrence of CLR, CGR, and RAND events as a function of GSM $-x$. The data are normalized to one and binned so that there is an equal sampling between the bins (the same number of RAND events in all bins). We see that the expected variation in the spatial distribution of CLR and CGR is indeed observed, with CGRs generally occurring closer to the inner boundary of the plasma sheet. Presenting the CLR and CGR distributions only over the x coordinate rather than in full 2D or 3D space does perhaps not give us the complete picture, since, for example, data obtained at smaller x tend to originate from regions closer to the flanks or the PSBL. However, this does not change the general conclusion that spatial (xyz) variations in the CLR and CGR distributions affect the obtained IMF response as displayed in Figure 2.

4.2. Relation Between ECRs and Energy Transfer

[24] Figures 4a–4c show the variation of the plasma sheet energy conversion in relation to (a) the observed plasma flow in the GSM x direction (V_x), (b) the total plasma flow ($|V_{tot}|$), and (c) the Poynting flux along the GSM x direction (S_x). Note that the horizontal axis is reversed so that positive values are to the left. The third bin from the left in all panels corresponds to small values ($-50 \leq V_x < 50$ km/s, $|V_{tot}| < 50$ km/s, and $-0.05 \leq S_x < 0.05 \mu\text{W/m}^2$).

[25] From Figure 4a we see that the plasma sheet flow in the x direction typically is rather low — see the large gray RAND data bar in the third bin from the left. From the RAND reference data set it can also be seen that Cluster

more often observes plasma flows toward the Earth ($V_x > 0$) than away from the Earth ($V_x < 0$). This is consistent with the Cluster satellites generally probing regions earthward of the NENL during the years of interest. Moreover, since the CLR and CGR bars dominate in the two leftmost bins, we note that both CLR and CGR are associated with high speed flows, V_{tot} , especially toward the Earth.

[26] It should be noted that we mainly study in this section the correlation between the ECR occurrence and the energy transfer along the GSM x direction. Detailed investigations regarding the energy transfer in full 3D space is outside the scope of the present article, but it is the focus for a future investigation. However, our data show that the V_x component often gives a dominant contribution to the total plasma flow velocity when ECRs are observed, even though there are several ECRs where the V_y and/or V_z contribution cannot be neglected. This can be verified from Figure 4b where we show the ECR occurrence versus $|V_{tot}|$.

[27] Analyzing the RAND reference data set in Figure 4c, we see that the x component of the Poynting flux is dominantly directed toward the Earth. This is consistent with the expectation that Cluster probes regions earthward of the NENL, and that a large part of the energy is ultimately dissipated in the ionosphere. Moreover, typical values of the RAND data are small, $-0.05 \leq S_x < 0.05 \mu\text{W/m}^2$. CLR and CGR, on the other hand, are often correlated with a stronger Poynting flux toward the Earth. The Poynting flux observed by Cluster is likely to be a superposition, originating from both local and distant sources. Preliminary event studies

Figure 4. CLR, CGR, and RAND occurrence versus (a) plasma flows V_x , (b) $|V_{tot}|$, and (c) Poynting flux S_x . Note that the V_x and S_x axes are reversed so that positive values (fluxes/flows toward the Earth) are to the left.

[Constantinescu *et al.*, 2010] suggest that conditions inside ECRs favor the generation of low frequency waves, while plasma is much more stable outside these regions. Although in the explored cases the detected waves originated from both types of ECRs, the local component appeared to be stronger for CLR. In order to check if these features represent general properties of the ECRs, a statistical investigation is planned for a future study.

5. Summary and Discussion

[28] The plasma sheet energy conversion has recently been investigated in detail through the analysis of the key quantity, $\mathbf{E} \cdot \mathbf{J}$ [see, e.g., Hamrin *et al.*, 2011, and references therein]. Through these investigations, it has been shown that spacecraft estimates of $\mathbf{E} \cdot \mathbf{J}$ can indeed be used for probing the plasma sheet energy conversion. By using

Cluster observations in the plasma sheet at a geocentric distance of about 15–20 R_E , Hamrin *et al.* [2011] have compiled and presented a consistent picture of the energy conversion between the electromagnetic and kinetic energy forms. Issues such as the occurrence, location, size, and strength of the energy conversion, as well as a likely relation to auroral activity at lower altitudes, have been addressed. The results are consistent with large scale MHD simulations [Birn and Hesse, 2005].

[29] ECRs are suggested to be related to BBFs [Marghitu *et al.*, 2010; Hamrin *et al.*, 2011]. In the present investigation we have mainly considered the relation between ECRs and the plasma flow in the GSM x direction, but as mentioned in section 4.2, contributions from V_y and V_z may also be important. Even though we expect a relation between ECRs and BBFs, preliminary investigations have shown that far from all BBFs are related to ECRs. On the other hand, a

majority of the ECRs are observed in correlation with significant plasma flows V_{tot} (see Figure 4b). Only about 10% of the identified ECRs are observed under slow flow conditions. This is significantly different from the RAND events, which are more often correlated with slow flows. The cause for the slow flow CLRs and CGRs need to be analyzed thoroughly. Investigations of this issue as well as the detailed relationship between ECRs and BBFs are, however, outside the scope of the present article, but is planned for a future study.

[30] In the present investigation we add to the acquired knowledge about the plasma sheet energy conversion by including information about the role of the plasma sheet in transferring energy, originally coming from the SW, toward the Earth's ionosphere. We use Cluster data to show that a southward IMF B_z is favorable for plasma sheet energy conversion. We also show that there is an energy flow (both as Poynting flux and as plasma flows) toward the Earth. Our data confirm that at the tail-ward end of the investigated region (down-tail to about $20 R_E$) power conversion from electromagnetic to kinetic and thermal power is dominant, while near the Earthward end this kinetic power is partially converted back to Poynting flux, from where it would then be available to power nightside auroral activity. The correlation between the plasma sheet $\mathbf{E} \cdot \mathbf{J}$ and auroral activity was discussed in Hamrin et al. [2011]. They found that the occurrence frequency of CLRs and CGRs increases with increasing geomagnetic activity as measured by the Kp and AE indices. Detailed investigations of conjugate events based on high-altitude Cluster data and low-altitude FAST data, suggest as well a strong relationship between CGR observations by Cluster and auroral activity probed by FAST [Hamrin et al., 2006].

[31] To our knowledge, this is the first time that actual responses in the plasma sheet $\mathbf{E} \cdot \mathbf{J}$ have been linked to the SW energy input at the magnetopause and the energy transfer in the plasma sheet toward the ionosphere. Since a minimum of four simultaneous measurements of the magnetic field are needed for estimating the full current density, thorough investigations of $\mathbf{E} \cdot \mathbf{J}$ have not been possible until the multispacecraft Cluster mission was available (last ~ 10 years).

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