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Key Points:

- The fluxtube integrated conductance in the conjugate hemispheres is inversely proportional to the night-time westward electrojet
- The relative locations of field-aligned current (FAC) and auroral electrojets during substorms are presented statistically based on CHAMP observations
- The efficiency of the Cowling channel increases in the night-time during substorm periods

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Effects of Solar Illumination and Substorms on Auroral Electrojets Based on CHAMP Observations

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Abstract We investigate the effects of solar illumination and the substorm process on the auroral electrojets using CHAMP high-resolution magnetic field data obtained over a period of 10 years. The eastward electrojet was found to be proportional to the ionospheric conductance induced by solar irradiation over the whole day. More notably, a stronger westward current was detected in times of lower fluxtube-integrated conductance in both hemispheres. The relative spatial distribution and evolution of the westward electrojet and field-aligned current (FAC) during the substorm periods were also investigated. The position of the westward current coincided with that of the upward FAC in 2000–2200 magnetic local time (MLT), in keeping with the structure of a westward traveling surge. Furthermore, the upward FAC in the local time sector of the poleward of the westward electrojet was supplied mostly by the remote closure current. The downward FACs in the poleward and upward FACs in the equatorward of the westward electrojet existed in the MLT sectors after 2200 h. Finally, the ratio of the peak intensity of the westward electrojet to that of the meridional Pedersen current, in the 2000–2200 MLT sector increased by about 250%, and the value in the 2200–0200 MLT increased by about 10%–20%. These results provide observational evidence of the increased efficiency of the Cowling channel in the night-time during substorm periods and contribute to our understanding of the formation mechanism of the auroral electrojet.

1. Introduction

Auroral electrojets flow eastward at dusk and westward around the midnight and at dawn in the auroral zone. They play an important role in the magnetosphere-ionosphere coupling process and in the space weather study (i.e., geomagnetic induce current). Using magnetic data from ground-based magnetometers and low-orbit satellites, scientists have studied the variation in auroral electrojets with local time and season, as well as their reactions to the solar wind, interplanetary magnetic field (IMF), and geomagnetic activity (e.g., Gromova et al., 2018; Huang et al., 2017a, 2017b; Pulkkinen et al., 2011; Shue & Kamide, 2001; Singh et al., 2013; Vennerstrom & Moretto, 2013; Wang et al., 2008). These studies have been pivotal to our understanding of the spatial distribution and formation mechanism of the auroral currents.

The auroral electrojet is influenced primarily by the ionospheric electric field and conductivity. The ionospheric conductivity originates from both solar EUV radiation and high-energy particle precipitation. Previous studies (Wang et al., 2005) have established a good correlation between the intensity of daytime field-aligned currents (FACs) and the solar illumination induced conductivity, indicating voltage source-like characteristics of the magnetospheric dynamo. However, the influence of solar illumination on night-time FACs is not significant. This is consistent with the result of Ohtani et al. (2005) that the dayside FACs were more intense when the ionospheric footprint was sunlit, and dependence of the night-time FACs density on the solar illumination was less clear. They revealed that the FAC in 1600–2200 MLT was more likely to be strong when the ionospheric footprint was dark. This is because auroral precipitation enhances the conductance more effectively in darkness than in sunlight (Newell et al., 1996). Ohtani et al. (2009) showed that the ionospheric conductance in the premidnight sector was higher in the dark hemisphere than in the sunlit hemisphere due to more intense auroral precipitation in the darkness.

Considering the intrinsic relationship auroral electrojets have with adjacent FACs, sunlight is expected to have a similar effect on the auroral electrojet. In other words, the solar illumination induced ionospheric conductivity is expected to be proportional to the current intensity during daytime, while having a weak

relationship with the night-time current. Recently, Ohtani et al. (2019) studied in detail the effect of the solar zenith angle (SZA) on the auroral electrojet using ground-based magnetic field observations. Interestingly, they found that the solar radiation on the dayside was proportional to the current intensity. At night, however, solar radiation had a different influence on the eastward and westward electrojet. More specifically, the solar illumination was proportional to the night-time eastward current, but the influence of solar radiation on the westward electrojet exhibited hemispheric and longitudinal differences. In some geomagnetic stations, the current was stronger for larger SZA, whereas in other geomagnetic stations, the current reached the maximum value at intermediate values of SZA. Furthermore, they showed that on including the effect of the Earth's dipole tilt angle (DTA), the hemispheric and longitudinal differences almost disappeared. More notably, the night-time westward electrojet was, in general, stronger for a smaller DTA and SZA. Therefore, they believed that at night, DTA and ionospheric conductivity contributed equally to the current intensity. Previous studies have shown that a smaller DTA can increase the reconnection efficiency in the subsolar magnetopause, enabling the solar wind energy to enter the magnetosphere and ionosphere more efficiently (Cnossen et al., 2012). Ohtani et al. (2019) provided us with an in-depth understanding of the formation of the auroral electrojet. However, Guo et al. (2014) showed that the IMAGE IU index, the eastward current index, in the 1300–2230 magnetic local time (MLT) and the IL index, the westward current index, in the 2300–0630 MLT exhibited a good correlation with the AU and AL indices. In other MLT sectors, the correlation was not good because the IMAGE magnetometer stations in northern Europe could not accurately determine the center position and peak intensity of the auroral electrojet. Therefore, it is necessary to use magnetic field data from low-Earth orbit satellites such as CHAMP because it can detect the full latitudinal profile of the auroral current. In fact, the position and peak density of the current can be more accurately determined by the satellite than from single geomagnetic station. CHAMP also provides global coverage that allows the simultaneous hemispheric study of the currents. In this study, we show new results indicating that the integrated conductance in the conjugate hemispheres has an important effect on the night-time westward electrojet, as revealed from the CHAMP observations.

The auroral eastward current is directly affected by the convective electric field, and the westward current is controlled by both the convective electric field and the substorm process (Gjerloev et al., 2004). During a substorm, the westward electrojet on the nightside is provided by the closure of the substorm current wedge (SCW). It is common knowledge that the upward FACs in the pre-midnight and the downward FACs in the post-midnight form a closed loop through the westward electrojet. This remote closing is related to a Cowling channel (Boström, 1964; Cowling, 1932). The initial westward electric field drives a primary meridional Hall current within the high-conductivity channel. The Hall current can form a loop with magnetospheric FACs (flowing upward out of the ionosphere at the poleward and flowing downward into the ionosphere at the equatorward). If the current loop is blocked, positive charges will be built upon the poleward side, and negative charges will accumulate on the equatorward side to form a southward-polarizing electric field. The resulting southward Pedersen current forms a closed loop with the northward Hall current (Amm, 1995; Baumjohann et al., 1982). The southward polarization electric field conversely generates a westward Hall current, which is superimposed on the original westward Pedersen current to form an enhanced westward electrojet. This physical process is similar to the formation of the equatorial electrojet (Wang et al., 2019, 2020). Fujii et al. (2011) improved the model by proposing that the Cowling channel had a boundary not only in the north-south direction, but also in the east-west direction, to explain the energy supply from the magnetosphere to the ionospheric Cowling channel. Amm et al. (2011) calculated the ratio of the divergence of the Hall current and Pederson current by analyzing observations from the MIRACLE and the EISCAT radar. They approximately considered that the large value of the ratio indicated an increased Cowling efficiency. Their analysis showed an increase in the Cowling efficiency with increasing geomagnetic activity. There was a peak Cowling efficiency around 0245–0645 MLT, with the maximum possibility around 0500 MLT. Their results supported the assumption that the Cowling closure was efficient in the auroral bulge sector. However, due to the lack of observational data, they did not study the Cowling efficiency of 0745–1445 MLT and 1945–0045 MLT. Moreover, some studies argued that the upward FACs in the pre-midnight and the downward FACs in the post-midnight did not form a closed loop through the enhanced westward electrojet (i.e., Cowling remote closure). Instead, they believed the local closing, that is, the upward R1 FACs formed a closed loop through the northward Pedersen current with the downward R0 FACs located in the poleward (e.g., Gjerloev & Hoffman, 2002; Marklund et al., 2001).

To summarize, if the northward Hall current is completely closed by the magnetospheric FACs (note that FACs flow upward out of the ionosphere on the poleward and downward into the ionosphere on the equatorward side of the Hall current), there will be no Cowling channel. On the other hand, if the magnetospheric FACs are blocked or the polarity is opposite, the Hall current will be completely closed to the meridional Pedersen current. In that case, the westward electrojet is significantly enhanced. This provides us with a way in which we can verify the efficiency of the Cowling channel by comparing the polarity and intensity of the FACs on both sides of the westward electrojet. To our knowledge, there has been no statistical work that has studied FACs, auroral electrojets, and Pedersen currents simultaneously within the Cowling channel based on satellite observations, such as CHAMP, that detects the latitudinal profiles of these currents simultaneously.

In this study, we used the high-resolution magnetic field data of the CHAMP satellite from 2000 to 2009 to conduct a statistical study of auroral electrojets. More specifically, we focused on the influence of fluxtube-integrated ionospheric conductance and the substorm process on the westward electrojet. We investigate the temporal and spatial distribution and evolution of the westward electrojet during substorm periods and evaluate the efficiency of the Cowling channel. The procession method of satellite data is described in Section 2. The statistical results are presented in Section 3. Section 4 compares the obtained results with previous reporting. Finally, our findings are summarized in Section 5.

2. Method

CHAMP was launched into a near-polar orbit on July 15, 2000 (87.3° inclination). The orbital period was 93 min (Reigber et al., 2002). The auroral electrojets were derived from the scalar magnetic field data. It was assumed that the auroral electrojet is a set of infinite line currents in the E layer of the Earth's ionosphere (~115 km), 1° apart from each other. Olsen (1996) developed a method to retrieve the current intensity from the total magnetic field. This method was later applied to Ørsted data (Moretto et al., 2002) and Swarm data (Aakjar et al., 2016). The effectiveness of this method has since been confirmed by comparing the results of CHAMP and ground stations (Ritter et al., 2004). Various papers have utilized these data to study the relevant variations in the auroral electrojets as per the season, IMF, and magnetic storms (Huang et al., 2017a, 2017b; Wang et al., 2008).

For each auroral crossing of CHAMP between July 26, 2000, and September 4, 2010, we selected the peak of the auroral electrojet (positive or negative) and recorded its corresponding temporal and spatial (MLT, magnetic latitude, MLat) information. In total, there are 95,072 events in the Northern Hemisphere and 82,481 events in the Southern Hemisphere. The results are organized in the frame of quasi-dipole coordinates, as defined in Richmond (1995). Furthermore, the ionospheric Hall conductance, due to solar irradiation, as well as the fluxtube-integrated Hall conductance in the conjugate locations in the two hemispheres for the peak current are calculated. More importantly, the ionospheric Hall conductivity due to solar illumination was calculated based on the study of Moen and Brekke (1993): $\Sigma_H = F_{107}^{0.53} (0.81 \cos(SZA) + 0.54 \cos^{0.5}(SZA))$, where F107 is the solar flux index and SZA is the SZA. In the subsequent sections, the ionospheric conductance refers to the conductance induced by solar illumination.

Newell and Gjerloev (2011) made great strides in utilizing more than 100 worldwide magnetometers in the latitude range of 40°–80° (SuperMAG project) to compute the auroral electrojet indices (SMU, SML, SME, similar to AU, AL, and AE). The substorm onset was identified from the SML index. They compared the SML and AL indices with Polar UVI substorm onsets between 1997 and 1998 and found that the SML index identified about 50% more onsets and was 4 min earlier than the traditional AL index. In our study, we used the 16,447 substorm onsets recorded between 2001 and 2009. The substorm onsets during this period tended to peak around 2300 MLT and 66° MLat.

3. Statistical Results

3.1. Effect of the Ionospheric Conductance

We first examined the distribution of the auroral electrojet with respect to the MLT and the ionospheric Hall conductance induced by the solar illumination. We used the ionospheric Hall conductance to order the eastward electrojet because the eastward current is well correlated with the SZA (Ohtani et al., 2019).

Figure 1. MLT versus ionospheric Hall conductance (left column) and fluxtube-integrated Hall conductance (right column) diagrams of the number of events, the magnetic latitude of the peak current density, and the peak current density normalized by its average in each MLT bin. The left and right columns are for the eastward and westward electrojet in the Northern Hemisphere, respectively. MLT, magnetic local time.

For the westward electrojet, we preferred considering the total Hall conductance at the conjugate positions of the two hemispheres. From top to bottom, Figure 1 shows frames of MLT versus conductance that capture the distributions of the number of events, the current peak magnetic latitudes, and the normalized peak current density in the case of both the eastward and westward electrojets in the Northern Hemisphere. It can be seen that the maximum Hall conductance around noon can reach 20 S, whereas at midnight, it only reaches 10 S. In each local time sector, the conductance has a wide range of variations, which is related to the seasonal and diurnal variation of the SZA. The eastward current tends to occur in the afternoon, whereas the westward current tends to occur in the midnight-to-prenoon sector. For eastward (westward) currents, the average number of events in each bin was ~ 211 (294), and the maximum number of events was greater than 884 (2200).

The distribution of current density peaks in the magnetic latitude is presented in the central panel of Figure 1. The average magnetic latitude of the eastward (westward) electrojet is $\sim 74.6^\circ$ (74.4°), which exceeds the detection range of traditional AE geomagnetic stations (between 63 and 70° MLat). We calculate the mean

value of IMF By at noon (1000–1400 MLT) when the eastward or westward electrojet is detected. The results show that the average value of IMF By is about 1.6 nT for the eastward electrojet, and the average value of IMF By is about –2.0 nT for the westward electrojet. This suggests that the peak electrojet around noon is the Disturbance Polar Y (DPY) current, with its flow direction determined by the IMF By polarity (eastward current for positive IMF By and westward for negative IMF By). The DPY current flows between the midday R0 and R1 FACs and tends to appear at higher latitudes (as shown in the middle panel of Figure 1).

At dawn, the eastward current is far less frequently observed than the westward current, whereas at dusk, the westward current is less frequently detected than the eastward current (as shown in the top panel of Figure 1). In the following we term the less frequently detected current as the minority current, and the more frequently detected current as the majority current. As can be seen from the middle panel of Figure 1, the minority currents tend to locate at higher latitudes than the majority current jets, and their dependence on the ionospheric conductance is not obvious. The average IMF Bz (By) value is calculated to be 1.3 (2.0) nT for the minority current (i.e., eastward electrojet) in the 0300–0900 MLT, and it is calculated to be 1.7 (–1.9) nT for the minority current (i.e., westward electrojet) in the 1500–1800 MLT. These minority currents reflect a part of the polar cap return current. This is consistent with Huang, Lühr, and Wang (2017), who stated that that during local summer in the Northern Hemisphere there was a return current channel over the polar cap. The return eastward currents were concentrated in the dawn sector for positive IMF By and the return westward currents were concentrated in the dusk sector for negative IMF By.

Figure 1 (bottom) displays the distribution of the normalized current density. The current density in each cell is normalized by the average value of that MLT bin. The ionospheric conductance plays an important role in both the eastward and westward electrojets. Stronger eastward currents in both the daytime and night-time occur in the cases of higher conductivity. On the other hand, stronger westward currents during daytime tend to occur during higher conductivity periods, whereas those at night tend to occur in the lower conductivity regions.

Figure 2 shows the same three distributions in the Southern Hemisphere in the same format as Figure 1. We see that the eastward currents appear in the afternoon-to-pre-midnight sector, whereas the westward currents tend to occur in the midnight-to-prenoon sector. For the eastward (westward) current, the average number of events in each bin is ~150 (266), and the largest bin has more than 690 (1,880) entries. The eastward (westward) currents are located on average at -73.1° (-72.8°) MLat. The eastward currents and the daytime westward currents are proportional to the conductance, whereas the night-time westward currents exhibit the inverse relation.

3.2. Substorm Dynamic Effect

To obtain comprehensive information about the temporal and spatial variation of the auroral electrojet during a substorm, we sorted the CHAMP observations into six continuous MLT bins, extending from 1800 to 0600 MLT, in intervals of 2 h. The results of these six MLT subsets are named bin-2 (1800–2000 MLT), bin-1 (2000–2200 MLT), bin0 (2200–0000 MLT), bin1 (0000–0200 MLT), bin2 (0200–0400 MLT), and bin3 (0400–0600 MLT), respectively. The CHAMP observations were sorted into these MLT bins. For each substorm event, we considered four subsequent CHAMP orbits in each MLT bin (one before and three after substorm onset). In each MLT bin, the substorm onset time was taken as T_0 , and all the CHAMP passes of 70° MLat were considered within three time windows: orbit-1 was within $T_0 - 0.25$ h and $T_0 - 1.25$ h before substorm onset, orbit 0 within $T_0 + 0.25$ h and $T_0 + 1.25$ h, orbit 1 within $T_0 + 1.75$ h and $T_0 + 2.75$ h, and orbit 2 within $T_0 + 3.25$ h and $T_0 + 4.25$ h. We then performed superposed location averaging of the auroral electrojet and FAC profiles centered on the peak of the auroral electrojet, separately for each MLT bin and time window.

Figure 3 shows the magnetic latitudinal variation of the northern FACs and auroral electrojet. “0” Δ MLat is where the peak electrojet is located. Each subset has four curves in different colors. The black curve represents orbit-1 before the substorm onset, red represents orbit0 during the main phase of the substorm, and the blue and green curves represent the subsequent orbit1 and orbit2 during the recovery phase of the substorm. Before the occurrence of the substorm, except for the eastward current in the 1800–2000 MLT, the westward current prevails in the remaining night sector with the strongest current intensity within 0200–0400 MLT. At 1800–2000 MLT, there are obvious upward FACs located in the poleward and downward FACs

Figure 2. The same format as Figure 1, but in the Southern Hemisphere.

in the equatorward, which is typical of the dusk-side Region 1 (R1) and 2 (R2) FACs. At 2000–2200 MLT, only the upward FACs are observed poleward of the westward electrojet. At 2200–0000 MLT, the downward FACs are observed in the poleward, and the upward FACs are located equatorward, which is related to the Harang discontinuity. In the 0000–0006 MLT sector, typical dawnside R1 and R2 FACs can be observed.

After the substorm onset, the eastward electrojet and FACs were weakened (red curve) at 1800–2000 MLT. At 2000–2200 MLT, the westward current is significantly enhanced, and the latitude coverage becomes wider. The upward FACs are enhanced, with the center almost coinciding with the westward electrojet. At 2200–0600 MLT, the westward current is significantly enhanced, whereas the strength of both upward and downward FACs is slightly increased. The R1 FACs in the post-midnight sector increase more significantly than those in the pre-midnight sector. The upward FACs in the post-midnight sector are stronger than the downward FACs, indicating that there exists a net upward current. The downward FACs at post-midnight are stronger than the upward FACs, indicating that there is a net downward current. During the evolution of the substorm, one can see that the intensities of the auroral electrojet and FACs gradually decreased and returned to the pre-substorm level. In the Southern Hemisphere, signatures are not so clear (figures not

Figure 3. Superposed location analysis of the magnetic latitudinal distribution of auroral electrojet and FACs at six local time sectors during the substorm period. The reference location, 0° Δ MLat is where the electrojet peaks. Negative Δ MLat denotes equatorward of the peak electrojet, and positive Δ MLat denotes poleward of the peak electrojet. In each MLT bin, the substorm onset time was taken as T_0 , all the CHAMP passes of 70° MLat are considered in four local time windows. Orbit-1 is within $T_0 - 0.25$ h and $T_0 - 1.25$ h before substorm onset (black line), orbit0 is within $T_0 + 0.25$ h and $T_0 + 1.25$ h (red line), orbit1 is within $T_0 + 1.75$ h and $T_0 + 2.75$ h (blue line), orbit2 is within $T_0 + 3.25$ and 4.25 h (green line). The bars show the mean standard deviation of the averages.

shown), which is probably due to the poorer measurement geometry and hemispheric asymmetry of the substorm activity. Weygand et al. (2014) studied the relationship between the Southern Hemisphere AE (using eight geomagnetic stations in the Southern Hemisphere, mainly located in the eastern hemisphere, -60° to -70° MLat) and Northern Hemisphere AE (using conjugate geomagnetic stations in the Northern Hemisphere). They reported that the hemispheric difference was the largest at midnight and June solstice. According to Laundal et al. (2016), due to different solar illumination, asymmetrical magnetic field disturbances can be found in the conjugate regions.

4. Discussion

4.1. Ionospheric Conductance Effect

Based on nearly 10 years of CHAMP observations, it is shown that the eastward electrojet is correlated well with the ionospheric conductance over the whole day, whereas the night-time westward electrojet is inversely proportional to the total conductance. This feature is further demonstrated in Figure 4, which shows

Figure 4. Seasonal and local time variation of the absolute intensity of the eastward and westward electrojet (top panel) and ionospheric conductance and fluxtube-integrated conductance (bottom panel).

the seasonal and local time variations of the eastward and westward electrojets. The eastward electrojet shows a summer maximum and a winter minimum, peaking around 1200–1600 MLT in summer, which corresponds to the annual and local time variation of the ionospheric conductance, except for a small local time shift. The local time shift is due to the additional effect from the convection electric field in the northward direction that maximizes at about 1900–2000 MLT (Ahn et al., 1999). The peak westward electrojet occurs around midnight at equinoxes when the lowest total conductance occurs. Guo et al. (2014) investigated the dependence of the eastward electrojets in 1200–2200 MLT and the westward electrojet in 2200–0600 MLT on MLT and season within the IMAGE magnetometer longitude sector. They found that the maximum eastward electrojet was around 1600–1800 MLT in summer, and the maximum westward electrojet was ~0000–0400 MLT during the equinoctial months. Their seasonal variations are consistent with our results, whereas the local time differences are due to the narrower MLT sectors concentrated in their study.

Ohtani et al. (2019) found that in the daytime, both eastward and westward electrojets were more intense when the SZA was smaller, and in the midnight-to-dawn sector, the eastward electrojet was more intense for smaller SZA. These findings are consistent with our results. More interestingly, they reported that both the eastward and westward electrojets in the dusk-to-pre-midnight sector are more intense for larger SZA, and in the post-midnight-to-dawn sector, the larger westward electrojet preferred the intermediate SZA. These results are different from our results. We find that at night-time, the eastward electrojet is stronger for larger conductance, whereas the westward electrojet is larger for smaller conductance. These differences can be attributed to the difference in data sources. The ground station might not detect the strongest magnetic effects of the auroral electrojets under more solar illumination when the currents shift more poleward. The CHAMP satellite, in contrast, covers the entire latitudinal bands at a roughly constant MLT and transverses the current region rather quickly. Thus, it can detect the peak current center without bias.

Figure 5. The seasonal and universal time variations of the night-time westward electrojet (absolute value) in the Northern Hemisphere (left frame) and the fluxtube-integrated ionospheric Hall conductance (right frame).

The seasonal and universal time (UT) variations of the night-time westward electrojet in the Northern Hemisphere are presented in Figure 5. In addition, the seasonal dependence shows significant changes in the UT variations. Strong currents mostly occur at equinoxes and in some UT sectors. Previous studies have shown that the equinoxes favor magnetic activity due to the coupling efficiency between the solar wind and magnetosphere (e.g., Temerin & Li, 2002) or due to the solar illumination (e.g., Lyatsky et al., 2001). Around December solstice and September equinox, the westward electrojets maximize between 1000 and 1900 UT. In contrast, the westward electrojets attain peaks within the time window of 2300–0600 UT during the June solstice and March equinox. As expected, the maximum conductance appears at different UTs during the summer and winter solstices. When comparing the total conductance and the current density, we can deduce that the current density is stronger when the conductance is lower. The same relationship is exhibited in the case of the Southern Hemisphere (figure not shown). This is in line with our earlier finding, that is, substorms prefer to start at times of low fluxtube-integrated conductivity (Wang & Lühr, 2007). With the substorm onset, high-energy particles are accelerated and precipitate into the ionosphere. Monoenergetic and broadband precipitation is most prevalent around pre-midnight during substorms, and the diffuse auroral precipitation is more intense in the pre-midnight-to-early-morning sector during substorms (Newell et al., 2010). This enhances the Hall conductivity at night-time. Based on substorm onsets in the two hemispheres as observed by the Far Ultraviolet Imager onboard the IMAGE spacecraft, Wang and Lühr (2007) conducted a statistical study on the seasonal and UT variation of the occurrence frequency of substorms. They found that the fluxtube-integrated ionospheric Pedersen conductances, induced by solar illumination, can explain the variation of the substorm occurrence with season and UT. The lower integrated conductivity was beneficial to the occurrence of substorms because it can lower the IMF threshold that triggers a substorm.

4.2. Substorm Effect

The substorm effect on the night-time electrojet can be more clearly seen from the superposed location analysis. Our work is the first to check the relative locations of FACs and electrojets during substorms by using a statistical approach based on CHAMP satellite observations. It shows that although the onset of the substorm mainly occurs in the pre-midnight sector, the substorm has an effect on the auroral electrojet over the whole nightside. The most significant enhancement of the westward electrojet occurs in the 2000–0400 MLT sector. This means that the most likely width of the SCW during the main phase is ~ 8 h of MLT. After the occurrence of the substorm, the eastward electrojet at dusk is weakened, whereas the westward electrojet is significantly enhanced. Interestingly, we observed that the position of the westward current coincides with that of the upward FAC in 2000–2200 MLT, which is basically consistent with the structure of a westward traveling surge (WTS; Erickson et al., 1991). Models and observations agreed that the intense upward FAC existed within the WTS (Kepko et al., 2015). Since there are no downward FACs located poleward, we might conclude that currents in this local time sector are mostly provided by a remote closure current. This

conclusion is in agreement with the results of Amm and Fujii (2008). By using electric and magnetic field observations as well as MIRACLE auroral images during a substorm onset, Amm and Fujii (2008) quantitatively separated two closures of current system (i.e., remote closure and local closure) near an aurora spiral under certain geometrical model assumptions. They found that in the western aurora, the remote closure made more than 80% contribution, due to the large gradient of conductance. In the eastern side of the aurora, they found that the local closure fed about 68% of the upward FAC.

In our work, we found that the downward FACs in the poleward and the upward FACs in the equatorward of the westward electrojets exist in the MLT sectors after 2200. The intensity of these FACs was not as strong as that of the westward auroral electrojets. The polarity distribution of FACs in these regions indicates that the Hall current flowing northward cannot form a closed loop with the magnetospheric FACs. Otherwise, the poleward side should be upward FACs, and the equatorward side should be downward FACs. Therefore, there is an accumulation of positive charges on the poleward of the aurora and negative charges on the equatorward of the aurora. The resulting polarization electric field in the southward direction can drive the southward Pedersen current and westward Hall current. The southward Pedersen current forms a closed loop with the northward Hall current. This indicates the effectiveness of the Cowling channel in these MLT sectors.

We utilized a method that is similar to Wang et al. (2005) to integrate the FACs in Figure 3 from the low latitude to high latitude along the satellite orbit, and obtain the latitudinal distribution of the integrated FACs, as shown in Figure 6. When the infinite current is aligned with the auroral oval, the intensity of the integrated FACs can be taken as the ionospheric closure current, that is Pedersen current, where negative values denote a poleward direction and positive values an equatorward direction. In the 1800–2000 MLT sector, the peak integrated FACs are positive, and in the 2000–0600 MLT sector, they are negative. This means that after the substorm, the meridional Pedersen current flows poleward in the 1800–2000 MLT and equatorward in the 2000–0600 MLT. The Pedersen current is enhanced in magnitude, but not as strong as the westward electrojet. We calculated the ratio of the peak intensity of the westward electrojet to that of the Pedersen current, α , which can approximately represent the variation of the ratio of the Cowling-enhanced zonal closure and meridional closure currents. It can be seen that the ratio α in the 2000–0400 MLT increases significantly after the occurrence of a substorm, which indicates that the efficiency of the Cowling channel in the 2200–0400 MLT sector has been greatly enhanced. The α value in the 2000–2200 MLT sector increase by about 250%, and the value in the 2200–0200 MLT increase by about 10%–20%. By using the MIRACLE and the EISCAT radar observations, Amm et al. (2011) found that the likelihood of the Cowling closure increased with the geomagnetic activity, which was most likely to occur in the early morning (0445–0545 MLT) sector. But their data were unavailable in the 1945–0045 MLT sectors. Thus, the difference between our work and theirs is that the data coverage is different, and our data cover the whole night-time.

Previous studies investigated individual characteristics of ionospheric conductance, FACs, and horizontal currents in the SCW model in a separate way (e.g., Fujii et al., 1994; Gjerloev & Hoffman, 2002). These works showed that the upward R1 currents were fed by R0 FACs located poleward of the aurora. For example, Fujii et al. (1994) revealed that downward FACs often occurred on the poleward side of the westward surge, which were fed by the southward current connected to the upward FACs at equatorward. Amm et al. (1999) used observations from the STARE radar, the Scandinavian Magnetometer network, and all-sky images and found that the upward FAC at the equatorward, and the downward FAC at the poleward of the aurora were connected by a southwestward electrojet. Marklund (2001) found that local current closure was more appropriate for explaining the satellite observation of an auroral bulge. Gjerloev and Hoffman (2002) found that upward and downward FACs existed at all local times. They mainly form a current loop through the meridional Pederson current. These studies emphasized that the local closing circuit is the main part of the SCW system, and the remote closing through a Cowling channel is not very effective. Our work is the first to compare the SCW model by combining the horizontal current with the FACs from CHAMP observations. The relative spatial distribution of the westward auroral electrojet and FACs demonstrates the coexistence of both the local closure and remote closure as derived from the CHAMP data. This finding is consistent with the newly developed SCW model (Kepko et al., 2015). The original SCW model consists of upward FACs localized in the pre-midnight sector and the downward FACs distributed on the post-midnight side, which are connected by a westward ionospheric electrojet. In the updated SCW model, it was suggested to

Figure 6. Superposed location analysis of the distribution of the integrated FACs and auroral electrojet over ΔMLat separately for six local time sectors during the substorm. The format is the same as in Figure 3. FACs, field-aligned currents.

include currents closing in the meridian plane (Kepko et al., 2015). Thus, the upward R1 FACs are provided by a local closure of the R0 current from the polar cap boundary, combined with a remote closure of the westward electrojet through the Cowling mechanism.

There are other explanations for the SCW model. For example, Gjerloev and Hoffman (2014) proposed two SCW systems that were separated in latitude. According to their model, there is a SCW in the pre-midnight, where the morning FACs flow into the ionosphere and the midnight FACs flow out of the ionosphere. They formed a closed loop through the westward electrojet. There is also a second SCW in the pre-midnight. The FACs flowing down into the ionosphere near midnight form a closed loop with the FACs flowing up from the ionosphere after midnight. The SCW in the pre-midnight sector is located more equatorward than the SCW in the post-midnight sector. In our statistical study, we take the peak value of the auroral electrojet as the reference and derive the average distribution of the FACs on both sides. Thus, it is difficult to judge whether there is an overlap of two SCW near midnight. However, we conducted a statistical study on the most probable latitude of the night-time peak electrojet during different substorm periods. Figure 7 shows the number of events of the night-time peak auroral electrojet as a function of MLat, separately for four orbits during the substorm periods. It can be seen that the center of the westward electrojet in the post-mid-

Figure 7. The event number of the night-time peak auroral electrojet as a function of MLat for four subsequent orbits in six different MLT sections in the night-time. The average MLat in each MLT is shown in the subfigures. MLT, magnetic local time.

night is at a lower latitude than that in the pre-midnight during substorms. In this respect, our observations seem to support the results of Gjerloev and Hoffman (2014).

5. Conclusion

The effect of solar illumination and the substorm process on the auroral electrojet was investigated by using 10 years of high-resolution magnetic field data from the CHAMP satellite. The relative spatial distribution and evolution of westward electrojet and FACs during substorm periods were investigated for the first time. To summarize key highlights as follows:

- (1) The eastward electrojet is proportional to the ionospheric conductance induced by sunlight in both the daytime and night-time sectors. The maximum eastward electrojet occurs around 1200–1600 MLT in the local summer, and the minimum occurs in winter. This corresponds to the annual and local time variations of the ionospheric conductance
- (2) The westward electrojet peaks around midnight at the equinoxes. During the December solstice and September equinox, we found stronger westward electrojets between 1000 and 1900 UT. On the contrary, around the June solstice and March equinox, the westward electrojets maximize within 2300–0600 UT. There is a clear correlation between the stronger current density at times of lower conductance. This is consistent with the fact that substorms prefer to start at times of low fluxtube-integrated conductance

- (3) The position of the westward electrojet coincides with that of the upward FAC in 2000–2200 MLT, which is consistent with the structure of a westward traveling surge. Since there is no downward FAC located poleward, the upward current in this local time sector is mostly supplied through a remote closure current
- (4) The downward FACs on the poleward and upward FACs on the equatorward side of the westward electrojets exist in the MLT sectors after 2200. The polarity distribution of FACs in these regions indicates that the Hall current in the northward direction caused by the westward electric field cannot form a closed loop through the magnetospheric FACs. The enhancement of these FACs was not as strong as that of the westward electrojets. This indicates the formation of a Cowling channel related to the substorm electrojet in this MLT sector
- (5) The ratio of the peak intensity of the westward electrojet to that of the meridional Pedersen current in the 2000–2200 MLT sector increases by about 250%, and the ratio in the 2200–0200 MLT increases only by about 10%–20%. These results indicate the increased efficiency of the Cowling channel in the nighttime during substorm periods
- (6) The center of the westward electrojet in the post-midnight sector is at a lower latitude than that at pre-midnight during substorms, which is consistent with the results of Gjerloev and Hoffman (2014)

Data Availability Statement

The solar wind and interplanetary magnetic field, as well as F107 and magnetic activity indices can be downloaded from OMNIWeb (<https://omniweb.gsfc.nasa.gov>). HW's work is sponsored by the National Nature Science Foundation of China (41974182 and 41674153).

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