Correlation between Poynting flux and soft electron precipitation in the dayside polar cap boundary regions

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Abstract Observations have revealed large Poynting flux and soft electron precipitation around the cusp region, which have strong impacts on the polar ionosphere/thermosphere. Simulations also confirmed that Poynting flux and soft electron precipitation significantly change the neutral density and dynamics around the dayside polar cap boundary regions. However, no detailed study has been conducted to show if they should coincide with each other or not. Our analysis of Defense Meteorological Satellite Program (DMSP) satellite data reveals a complex correlation between them. Poynting flux and soft particle precipitation are coincident in some cases (match cases), but a clear displacement between them can also be identified in others (nonmatch cases). In the 29 cusp crossings from F13 we investigated, the ratio between nonmatch and match cases is close to 1:4. In nonmatch cases, the displacement between the Poynting flux enhancement and soft particle precipitation enhancement can be as large as 1° in geomagnetic latitude.

1. Introduction

The dayside polar cap boundary regions, including cusp and low-latitude boundary layer (LLBL), are special regions in the magnetosphere through which plasma, momentum, and energy from the solar wind can have direct access to the upper atmosphere. Typically, a significant amount of Poynting flux and soft particle precipitation is deposited in these regions. It creates such a unique window in the geospace environment for the solar wind-magnetosphere-ionosphere coupling and plays an important role to the precise specification of the upper atmosphere state during both quiet and active times. However, the size of these regions is small, for example, the cusp is typically 1–2° in geomagnetic latitude (MLAT), and the location is variable. It is very challenging to clearly identify them from the data and to precisely simulate it in the global models.

Using both satellite data and ground-based radar observations, the cusp can be identified in several different ways. Defense Meteorological Satellite Program (DMSP) satellites have polar Sun-synchronous orbits at about 840 km. Based on the particle observations on DMSP, Newell and Meng [1988], Newell et al. [1991], and Newell and Meng [1992] showed that in the cusp the characteristic energy of electrons and ions is smaller than 200 eV and 2700 eV, respectively. The total energy flux of electrons and ions is larger than 6 × 10⁷ keV/cm² s sr and 1 × 10⁷ keV/cm² s sr, respectively. The statistical average size is 2.5 h in local time and 1–2° in MLAT, which is centered near noon local time and 70–80° MLAT. Combining multispacecraft observations with ground-based observations, the cusp structures have been examined systematically and it was reported that lower energy ions arrive at higher latitudes since lowest energy particles reflect at the edges of the cusp and highest energies penetrate deepest due to the converging magnetic field [Trattner et al., 2003].

The dayside polar cap boundary is quite complex and includes different regions, such as the LLBL, the plasma mantle, and the cusp. Those regions are very close to each other, and sometimes, it becomes very tricky to distinguish one from another. While the cusp proper has been suggested as be a more limited region of the cleft (ionospheric signature of LLBL) localized near noon, the clear distinction between the two regions has been identified through the distribution and energy flux [Newell and Meng, 1988]. Note that this paper is not to discuss or alter the DMSP particle classification on the dayside, which has been well documented [Newell and
Meng, 1988; Newell et al., 1991; Newell and Meng, 1992]. The purpose of this work is to study the relationship between the particle precipitation and Poynting flux in those regions. The identification for different regions in Newell and Meng [1988] based on the DMSP particle data is adopted through using the Online Spectrogram Viewer developed by the Johns Hopkins University Applied Physics Laboratory (JHU/APL).

Due to the geomagnetic energy inputs, the neutral density in the thermosphere shows a substantial enhancement in the dayside polar cap boundary, which has been observed by the CHAMP satellite [Lühr et al., 2004; Rentz and Lühr, 2008; Rentz, 2009; Lühr and Marker, 2013]. Typical enhancements at 400 km altitude are 20% above background with a width of a few hundred kilometers, but in extreme cases more than 50% has also been observed. To figure out the mechanism for the large neutral density enhancement in such a small region, simulations have been conducted using different models [Schlegel et al., 2005; Demars and Schunk, 2007; Zhang et al., 2012; Deng et al., 2013; Sheng et al., 2014]. The theoretical study conducted in Deng et al. [2013] with the Global Ionosphere-Thermosphere Model (GITM) illustrated that Poynting flux and soft particle precipitation have comparable influences on the neutral density in the dayside polar cap boundary regions. The combined influence of Poynting flux and soft particle precipitation causes a more than 50% increase in the neutral density at 400 km, which is consistent with CHAMP observations in extreme cases.

In GITM simulations, Poynting flux and soft electron precipitation coincided with each other all the time. They have been added in the model at the same time and in the same location. However, more observational evidence is needed to confirm the methodology and the correlation between the two types of energy inputs.

A previous study reported that more than 80% of the Birkeland current boundaries do not correspond to particle precipitation boundaries [de La Beaujardiere et al., 1993], which indicates that the electromagnetic energy inputs may not coincide with particle energy inputs in the polar region. Meanwhile, Watermann et al. [2009] showed that the current cusp, associated with intense small-scale magnetic field variations, may cover both the particle cusp and the LLBL.

Both Poynting flux and soft electron precipitation have been observed commonly in the dayside polar cap boundary regions. But the relative position of them has not been studied well. Certainly, different positions including totally overlapping, partially overlapping, and totally displaced can result in quite different consequences in the thermosphere and ionosphere. In order to improve our understanding of the neutral density enhancement around the cusp region, the relative position of Poynting flux and soft particles is very important. In this study, through analyzing both particle data and deduced Poynting flux data from DMSP satellite observations, the relationship between Poynting flux and soft particle precipitation in the dayside polar cap boundary regions has been examined closely. The results unveil that a complex correlation and a systematic study of the geospace environment are needed to fully understand these phenomena.

2. Methodology

DMSP observations of both particle precipitation and Poynting flux during several storm periods in 2004 and 2005 have been studied. The soft particle energy flux was calculated from the Special Sensor Precipitating Plasma Monitor (SSJ) on the DMSP spacecrafts. The SSJ dataset provided by the Air Force Research Laboratory consists of 1 s cadence electron and ion particle fluxes between 30 eV and 30 keV. The Poynting flux is obtained from the vector cross product of the electric field and perturbation magnetic field measured by the DMSP satellites ($\mathbf{S} = \mathbf{E} \times \mathbf{B}$, e.g., Kelley et al., 1991; Gary et al., 1994, 1995). An example of Poynting flux calculated from the DMSP F15 measurements along the satellite trajectory has been shown in Knipp et al. [2011]. The DMSP spacecraft are in polar orbits and fixed in local times, sampling the ionospheric plasma at about 840 km. The electric field is deduced from the ion drift measurement by the Special Sensor Ionospheric Plasma Drift/Scintillation Meter (SSIES) monitor and the simultaneous magnetic field obtained from the 1 s fluxgate data of Special Sensor Magnetometer through the equation of $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$. The resolution is at 4 s, and the corresponding space resolution is close to 30 km.

The perturbation magnetic field is the difference between the measured and International Geomagnetic Reference Field (IGRF) values of magnetic fields at the spacecraft locations, $\Delta \mathbf{B} = \mathbf{B}_{\text{measure}} - \mathbf{B}_{\text{IGRF}}$ [Huang and Burke, 2004]. The ion drift meter (IDM) of the SSIES monitor measures horizontal cross-track and vertical components of plasma drifts in the spacecraft frame, and the retarding potential analyzer (RPA) measures ion temperatures and the ram component of plasma drift [Rich and Hairston, 1994]. The cross-track component has been further processed from the spacecraft frame to the corotating frame. The quality flags for both RPA and IDM data include “1” for good data, “2” for questionable data which should be used with caution.
Figure 1. (a) DMSP F13 cross-track ion drift in the Northern Hemisphere during 02:15–02:37 UT on 24 July 2004. The color represents the quality flag of the ion drift data. “S” and “E” denote the starting and ending times for the DMSP satellite crossing, which we look at closely in Figure 2. (b) The DMSP measurements along the satellite trajectory shown in Figure 1a. (first to third panel) The ion drift in the ram \( V_x \), cross-track \( V_y \) and positive for antisunward, and vertical \( V_z \) and positive for upward directions. (fourth panel) The number density of both H\(^+\) (blue) from RPA and total ions (black) from SM. (fifth panel) The reduced Poynting flux from both electric and magnetic fields measurements. Only good and undetermined ion drift data have been used for the Poynting flux calculation. The diamond shows the estimation when only the cross-track \( V_y \) and vertical \( V_z \) ion drifts are included.

“3” for bad data, and “4” for data with undetermined quality. As shown in Figure 1, the quality flags for the \( V_x \) (ram drift or parallel velocity) ion flow measured by the RPA are mainly 2 or 3, which mean questionable or bad data. Meanwhile, DMSP F13 satellites are primarily in a dawn-dusk local time orientation, and the contribution of ram drift to the Poynting flux is relatively small. To be cautious, the Poynting flux in our results is calculated from \( V_y \) (horizontal cross track) and \( V_z \) (vertical cross track) ion flows measured by the IDM. Therefore, the quality of IDM data directly influences the quality of the Poynting flux.

Interestingly, the quality flag of the ion drift data around the cusp region has often been denoted as 4, undetermined. The reason is that around the cusp region the electric field is very variable and the standard deviation of the ion drift during the 4 s period can be larger than the average. When the satellite encounters the cusp region, the RPA processing algorithm cannot handle such a variable situation and no composition information can be deduced from the RPA. However, the SSIES thermal plasma instruments are designed to work in a predominately O\(^+\) plasma condition, and once the percentage of light ions (H\(^+\) and He\(^+\)) goes above 15%, the data are not reliable. Since there is no value for the fractional amount of O\(^+\) from RPA, we have no direct way to determine if the IDM data are good or bad, so these data are flagged as 4, undetermined. Nevertheless, undetermined IDM data are not necessarily bad data, and the ion drift may still produce reliable data. Figure 1 (right, fourth panel) shows the total plasma density from scintillation meter (SM) and H\(^+\) density from RPA along the satellite trajectory. While during the interval between S and E ("start" and "end" points of the segment of the satellite trajectory) the data become sparse, the average percentage of H\(^+\) is close to 2.2%, which indicates that the plasma is composed almost 98% of heavier O\(^+\) ions. Meanwhile, the convection pattern shown in Figure 1 (left) is antisunward flows at the high latitudes and sunward flows at lower latitudes, which is quite reasonable. Therefore, the IDM data with flag 4 (undetermined) around cusp are treated as useful data after a close examination of the composition and convection pattern. This diagnostic procedure has been conducted case by case before further data analysis.

3. Results and Discussion
3.1. Match Events
Figure 2a shows the Dst index and solar wind conditions during 21–26 July 2004, including interplanetary magnetic field (IMF), solar wind bulk speed in the Sun-Earth direction \( V_y \), and the bulk plasma density \( N \).
Figure 2. (a) $Dst$ index and solar wind conditions during 21–26 July 2004, including interplanetary magnetic field (IMF), solar wind speed in the Sun-Earth direction ($V_x$), and plasma density ($N$). The red vertical line marks the starting time for the segment of DMSP satellite trajectory shown in Figure 2b. The solar wind data are from OMNIWEB data set, in which all the original solar wind data have been time shifted to the bow shock nose (BSN). Only a 20 min delay has been enclosed in the solar wind conditions to take into account of the responding time of the electrodynamics in the Earth's polar region to the solar wind conditions at BSN. (b) DMSP F13 satellite trajectory around the dayside polar cap boundary regions in the Northern Hemisphere. $S$ and $E$ denote the starting and ending times for the DMSP satellite trajectory. (c) The DMSP measurements along the satellite trajectory shown in Figure 2b, including total energy flux (keV/cm$^2$ s sr) for both ions $JE_i$ (black) and electrons $JE_e$ (red), average energy of the particles AvgE, differential energy flux of electrons $E_e$ and ions $E_i$, and estimated Poynting flux $S$ (mW/m$^2$).

The minimum of the $Dst$ index was close to $-130$ nT, which indicates a moderate storm period. The red vertical line marks the starting time for the segment of the DMSP satellite trajectory shown in Figure 2b. Clearly, the period with cusp crossing we investigated happened between two storm periods. The solar wind data are from OMNIWEB data set, in which all the original solar wind data have been time shifted to the bow shock nose (BSN). An additional 20 min time shift has been enclosed in the solar wind conditions to take into account of the polar region electrodynamics responding time to the solar wind conditions at BSN. Figure 2b shows the DMSP F13 satellite trajectory around the the dayside polar cap boundary regions in the northern hemisphere. $S$ and $E$ denote the starting and ending times for the segment of the DMSP satellite trajectory. The location is very close to the typical location of the cusp, near noon time and close to 75° MLAT. Figure 2c illustrates the DMSP measurements along the satellite trajectory shown in Figure 2b, including total energy flux for both ions (black) and electrons (red), average energy of the particles, differential energy flux of electrons and ions, and estimated Poynting flux. As shown in Figure 2c (third and forth panels), both soft electron and soft ion particle precipitations have enhanced significantly in the LLBL and cusp. Figure 2c (first and second panels) shows that during that period the total energy flux and average energy of electrons and ions satisfy the criteria for the LLBL and cusp. The location is close to noon and 75° MLAT, the typical location of dayside polar cap boundary. The line in Figure 2c (fifth panel) shows the variation of Poynting flux along the satellite trajectory. Clearly, the Poynting flux also increased in the LLBL and cusp with the maximum of 10 mW/m$^2$. Since the temporal resolution of Poynting flux data set derived from DMSP observations is 4 s, which is equivalent to 30 km in distance, lots of small-scale structures can be identified in both particle data and Poynting flux. In general, the enhancements of soft particle precipitation and Poynting flux overlapped with each other in this particular case, so we name it as a match case.

3.2. Nonmatch Events

Figure 3 shows the geomagnetic and solar wind conditions and DMSP F13 measurements during 11–14 April 2005. The DMSP crossing happened at the beginning of the second active period, when IMF $B_z$ slightly turned to southward. The major difference between this event and the event shown in Figure 2 is the displacement
between Poynting flux enhancement and the soft particle precipitation enhancement. As shown in Figure 3c, both soft electrons and soft ions increased significantly between 69° and 73° MLAT, which is marked as LLBL and mantle. The Poynting flux also increased to 30 mW/m², but the location was between 73° and 74° MLAT, which is inside of boundary plasma sheet region. Actually, the Poynting flux enhancement was located at ∼1° higher latitude than the soft particle precipitation enhancement.

Large soft particle precipitation and large Poynting flux in the cusp have been observed, but complete knowledge of the relative location of different energy inputs in this region is still lacking. The behaviors and dynamics in other dayside polar cap boundary regions is even less understood. In this study 29 DMSP F13 cusp crossings have been identified and examined. The time and period of these crossings have been listed in Table 1. Poynting flux and soft particle precipitation enhancements match well in 23 crossings and have a clear displacement in 6 crossings. Interestingly, the DMSP measurements show both match and nonmatch cases, which opens some new questions about the correlation between the two different energy inputs in the polar cap boundary. For example, under what conditions the large particle precipitation is accompanied with or without a large Poynting flux in the dayside polar cap boundary regions? What are the possible physical mechanisms for these phenomena? Since the satellite measures the parameters along the satellite trajectory, the spacial and temporal variations cannot be separated from one single satellite measurements. Does the nonmatch case really represent a spatial displacement or a temporal delay between Poynting flux and soft particle precipitation? Why does the Poynting flux enhancement happen poleward of the soft particle precipitation enhancement in the nonmatch case? Certainly, more comprehensive study is needed before answering those questions. Meanwhile, it brings some additional challenge to the ionosphere/thermosphere models to simulate the ionosphere/thermosphere in the dayside polar cap boundary region precisely since it is not clear when these two energy inputs should be overlapped with each other and when they should not. Different relative distributions of energy inputs will result in significant difference in the ionosphere/thermosphere response.

The possible mechanisms for the displacement we propose include the variation of the IMF conditions and the energy transfer between the Poynting flux and the particle precipitation. For the first mechanism, the hypothesis is that when the IMF conditions especially the $B_y$ component change, the ion convection pattern and particle precipitation may change accordingly but under different paces, which results in the displacement between them. To examine this mechanism, the IMF conditions in 10 min interval centered on the starting time (marking as S in the satellite trajectory) of the satellite crossings for both match and nonmatch cases...
Table 1. F13 Cusp Crossing List

| Event No. | Year | Month | Day | Start UT   | End UT   | Match or Not |
|-----------|------|-------|-----|------------|----------|--------------|
| 1         | 2004 | Jul   | 24  | 02:27:26   | 02:28:13 | Match        |
| 2         | 2004 | Aug   | 30  | 02:10:31   | 02:11:13 | Match        |
| 3         | 2005 | Feb   | 19  | 06:53:57   | 06:54:52 | Match        |
| 4         | 2005 | Apr   | 12  | 08:05:40   | 08:06:24 | Match        |
| 5         | 2005 | May   | 14  | 08:54:37   | 08:56:00 | Match        |
| 6         | 2005 | May   | 19  | 06:03:20   | 06:04:00 | Match        |
| 7         | 2005 | May   | 29  | 01:57:24   | 01:58:00 | Match        |
| 8         | 2005 | May   | 29  | 22:19:11   | 22:19:59 | Match        |
| 9         | 2005 | Jun   | 12  | 08:46:33   | 08:47:33 | Match        |
| 10        | 2005 | Jun   | 23  | 11:20:17   | 11:21:29 | Match        |
| 11        | 2005 | Jul   | 09  | 07:28:04   | 07:28:47 | Match        |
| 12        | 2005 | Jul   | 10  | 02:02:45   | 02:04:30 | Match        |
| 13        | 2005 | Jul   | 10  | 03:43:53   | 03:45:16 | Match        |
| 14        | 2005 | Aug   | 23  | 05:09:45   | 05:10:53 | Match        |
| 15        | 2005 | Aug   | 23  | 05:11:40   | 05:12:40 | Match        |
| 16        | 2005 | Aug   | 24  | 08:17:08   | 08:17:56 | Match        |
| 17        | 2005 | Aug   | 31  | 10:03:22   | 10:04:17 | Match        |
| 18        | 2005 | Aug   | 31  | 10:04:25   | 10:05:07 | Match        |
| 19        | 2005 | Sep   | 01  | 04:44:20   | 04:45:08 | Match        |
| 20        | 2005 | Sep   | 11  | 04:02:37   | 04:04:14 | Match        |
| 21        | 2005 | Oct   | 07  | 09:45:16   | 09:46:15 | Match        |
| 22        | 2005 | Oct   | 08  | 02:40:44   | 02:42:38 | Match        |
| 23        | 2005 | Oct   | 08  | 06:05:29   | 06:07:13 | Match        |
| 24        | 2004 | Nov   | 07  | 13:45:25   | 13:46:08 | Nonmatch     |
| 25        | 2005 | Feb   | 18  | 08:50:25   | 08:51:26 | Nonmatch     |
| 26        | 2005 | Apr   | 13  | 11:15:51   | 11:16:31 | Nonmatch     |
| 27        | 2005 | May   | 30  | 06:50:38   | 06:51:22 | Nonmatch     |
| 28        | 2005 | Aug   | 30  | 23:51:03   | 23:51:50 | Nonmatch     |
| 29        | 2005 | Oct   | 08  | 04:23:43   | 04:24:41 | Nonmatch     |

have been plotted out in Figure 4. Each case is represented by the same point style. If the points in the same style cluster together, it indicates that the IMF conditions are very stable. Otherwise, they vary with the time during the 10 min time window. The comparison between Figures 4a and Figure 4b shows no systematic difference of solar wind variation between match and nonmatch cases. The IMF conditions can be stable and quite variable for both cases. All nonmatch cases happened in the $B_z$ negative condition and more than half were in the $B_z$ positive condition, but more data are needed to confirm this feature and to approve the first
mechanism. Another possible mechanism is the energy conversion of Poynting flux to the particle kinetic energy flux when they are propagating along the magnetic field from magnetosphere into upper atmosphere, since the parallel electric fields generated by the Alfvén waves is a possible acceleration mechanism of auroral particles [Hasegawa, 1976; Thayer and Semeter, 2004]. Sounding rockets have observed similar displacement between these two energy inputs previously [Evans et al., 1977; Kletzing et al., 1996]. The confirmation needs the comparison of simultaneous measurements in the magnetosphere and upper atmosphere and kinetic simulations as well.

4. Conclusion

The dayside polar cap boundary is a special region including cusp and LLBL, through which a significant amount of Poynting flux and soft particle precipitation are deposited in the upper atmosphere. Commonly, the enhancement of Poynting flux and the enhancement of soft electron precipitation have been measured in these regions, but no detailed study has been conducted previously to examine the correlation between the two different energy inputs in the dayside polar cap boundary. The analysis of DMSP observational data revealed a complex relationship between them. While in some cases, Poynting flux and soft electron precipitation enhancements match very well, in others a clear displacement can be identified. In the 29 cusp crossings investigated, the ratio between nonmatch and match cases is close to 1:4. In nonmatch cases, Poynting flux enhancement can happen in a higher latitude than soft particle precipitation and the displacement can be as large as 1° in MLAT. The possible mechanisms for the displacement we propose include the variation of the IMF conditions and the energy transfer between the Poynting flux and the particle precipitation, but more data are needed to confirm them.

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