Statistical relationship between large-scale upward field-aligned currents and electron precipitation

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Abstract  Simultaneous observations of Birkeland currents by the constellation of Iridium satellites and N₂ Lyman-Birge-Hopfield (LBH) auroral emissions measured by the Global Ultraviolet Imager (GUVI) onboard the Thermosphere, Ionosphere, and Mesosphere Energetics and Dynamics (TIMED) satellite are used to establish relationships between large-scale upward field-aligned currents and electron precipitation during stable current configurations. The electron precipitation was inferred from GUVI data using a statistical relationship between LBH intensity and electron energy flux. LBH emissions with >5% contribution from protons, identified by Lyman-alpha intensity, were excluded from the analysis. The Birkeland currents were derived with a spatial resolution of 3° in latitude and 2 h in local time. For southward interplanetary magnetic field (IMF), the electron precipitation occurred primarily within and near large-scale upward currents. The correspondence was less evident for northward IMF, presumably because the spatial variability is large compared to the areas of interest so that the number of events identified is smaller and the derived statistical distributions are less reliable. At dusk, the correlation between upward current and precipitation was especially high, where a larger fraction of the electron precipitation is accelerated downward by a field-aligned potential difference. Unaccelerated electron precipitation dominated in the morning sector, presumably induced by scattering of eastward-drifting energetic electrons into the loss cone through interaction with whistler-mode waves (diffuse precipitation) rather than by field-aligned acceleration. In the upward Region 1 on the dayside, where the electron precipitation is almost exclusively due to field-aligned acceleration, a quadratic relationship between current density and electron energy flux was observed, implying a linear current-voltage relationship in this region. Current density and electron energy flux in the regions of the large-scale upward currents from pre-midnight through dawn to noon are essentially uncorrelated, consistent with diffuse electron precipitation dominating the incident energy flux.

1. Introduction

The Earth's magnetosphere and ionosphere are coupled electromagnetically by field-aligned or Birkeland currents [Birkeland, 1908], whose large-scale statistical configuration was first established by Iijima and Potemra [1978]. Statistical distributions of the Birkeland currents have been determined as functions of the direction of the interplanetary magnetic field (IMF) from observations from single satellites [Weimer, 2001; Papitashvili et al., 2002; He et al., 2012] and the constellation of ~70 Iridium satellites [Anderson et al., 2008]. While the distribution of the currents is determined primarily by the IMF orientation, their intensity is modulated by ionospheric conductance and the solar wind electric field and ram pressure [Korth et al., 2010]. For southward IMF, the Birkeland currents occur statistically in two concentric rings at northern middle to high latitudes. The poleward and equatorward rings are termed Region 1 (R1) and Region 2 (R2), respectively. The R1 currents are directed downward at dawn and upward at dusk. The polarity of R2 is opposite that of R1 at the same local time.

Field-aligned currents can be carried by either electrons or ions, but magnetospheric (ionospheric) electrons are the dominant carriers of field-aligned currents flowing into (out of) the ionosphere. The contribution to the field-aligned current from precipitating electrons exceeds that of upward flowing ionospheric ions typically by an order of magnitude [Cattell et al., 1979]. Precipitating electrons carrying upward field-aligned currents can be accelerated by electric fields aligned parallel to the geomagnetic field [e.g., Evans, 1974; Mozer et al., 1980] or by dispersive Alfvén waves [e.g., Ergun et al., 1998; Chaston et al., 2003], and discrete auroral emissions may be produced in the process. However, electrons do not need to be accelerated to precipitate, and electrons having their bounce mirror point at or below the atmosphere are subject to diffuse
precipitation. Diffuse precipitation and associated auroral emissions are caused primarily by scattering of plasma sheet electrons into the loss cone by interaction with whistler-mode waves [Ni et al., 2011a, 2011b], which predominantly occurs in the dawnside magnetosphere [Meredith et al., 2003; Li et al., 2009]. Several statistical studies have been conducted using locations of precipitation boundaries to characterize the source regions and carriers of field-aligned currents. Wing et al. [2010] examined source regions of field-aligned currents on the dayside based on their location relative to precipitation boundaries observed by the Defense Meteorological Satellite Project (DMSP) and found that the current sheets typically originate from multiple source regions in the magnetosphere. Ohtani et al. [2010] compared the locations of nightside precipitation boundaries with those of the field-aligned currents and showed that in the dusk-to-midnight sector, the observations of accelerated electrons are often confined to the upward R1, indicating that monoenergetic electrons carry the currents there. These authors also showed that the relationship between the electron precipitation and the upward R2 currents is not straightforward. The equatorward boundary of the monoenergetic electron events in the midnight-to-dawn sector is located mostly within R2. In addition, while the poleward boundary of these events peaks on average near the poleward edge of R2, the location of this precipitation boundary can deviate substantially from that of the R2 currents. Ohtani et al. [2010] considered nightside local times and did not examine the relationship between current density and precipitation energy fluux.

Global distributions of electron precipitation in the auroral oval have been derived as functions of geomagnetic activity from both particle [Spiro et al., 1982; Hardy et al., 1987; Newell et al., 1996, 2009; Sotirelis and Newell, 2000] and auroral imaging observations [Zhang and Paxton, 2008]. Using a multiyear database of particle observations by DMSP, Newell et al. [2009] developed a precipitation model based on solar wind driving conditions, which separately categorizes monoenergetic, broadband, and diffuse contributions to the aurora as inferred from the width and height of the peak in the energy spectrum of the precipitation. The spectral shape of the monoenergetic events resembles that of an “inverted V,” which is also associated with the discrete aurora, while the broadband aurora is caused by acceleration over a wider energy range. Precipitation not associated with either of the above categories was labeled as diffuse. The distribution of the diffuse auroral precipitation identified by Newell et al. [2009] is consistent with the equatorial distribution of whistler-mode chorus waves [Meredith et al., 2003; Li et al., 2009], which are primarily responsible for scattering electrons into the loss cone and causing the diffuse aura. This suggests that the Newell et al. [2009] classification of diffuse precipitation comprises a large fraction of precipitating electrons produced by mechanisms creating the diffuse aurora. The analysis by Newell et al. [2009] showed that energy flux associated with monoenergetic electron acceleration precipitates predominantly on the duskside [Newell et al., 1996], which suggests link to the statistical R1 system of Iijima and Potemra [1978]. The diffuse electron precipitation occurs at somewhat lower latitudes primarily from pre-midnight to post-dawn, consistent with the eastward drift of plasma sheet electrons.

Particle detectors observe precipitating particles directly, but auroral emissions can also be used to measure precipitation intensities and energies indirectly and have the advantage that they are acquired over an area rather than only at the satellite location. Inferring precipitation characteristics from auroral emissions requires either a transport model [Strickland et al., 1983; Germany et al., 1990] or empirical relationships [Sotirelis et al., 2013] to relate luminosity observations to incident particle characteristics. Both methods exploit the characteristics of N₂ Lyman-Birge-Hopfield (LBH) far-ultraviolet emissions in two wavelength ranges, LBH short (LBHS, 140–150 nm) and LBH long (LBHL, 165–180 nm). Both LBHS and LBHL emission intensities are proportional to the incident electron energy flux. The LBHS wavelength range lies within the O₂ Schumann-Runge absorption continuum, so that the LBHS intensity also depends on the electrons’ penetration depth into the atmosphere, which increases with particle energy. In the absence of significant proton precipitation, the electron energy flux and mean energy can be determined from the LBHL emission and the LBHS/LBHL ratio, respectively.

In this study, we compared electron energy flux distributions inferred from auroral emissions observed by the Global Ultraviolet Imager (GUVI) [Paxton et al., 1999] onboard the Thermosphere, Ionosphere, and Mesosphere Energetics and Dynamics (TIMED) satellite with distributions of the Birkeland currents observed by the Iridium satellite constellation [Anderson et al., 2000; Waters et al., 2001] during stable current configurations. Although numerous studies of the global electron precipitation distribution have been conducted [e.g., Hardy et al., 1985;
ψ = arctan(Bx, By), is shown in Figure 1. Following Anderson et al. [2008], we computed the statistical preliminary analysis are described in section 2. Example events are discussed in section 3. In section 4, the statistical distributions of the electron energy flux are compared with those of the Birkeland currents. The findings are discussed and summarized in sections 5 and 6, respectively.

2. Data Sets and Preliminary Analysis

In order to characterize relationships between field-aligned currents and electron precipitation, we identified reliable Birkeland current distributions inferred from magnetic perturbations measured by ~70 Iridium satellites with simultaneous observations of FUV auroral emissions by the GUVI instrument. The GUVI instrument was operational from February 2002 to December 2007. Iridium magnetic field observations for this period were processed into magnetic perturbations as described in Anderson et al. [2000], and the distributions of the Birkeland currents were computed by applying Ampere’s law to spherical harmonic fits of the magnetic perturbations [Waters et al., 2001]. The analysis technique allows the derivation of the Birkeland currents without assumptions of their geometry, e.g., infinite thin current sheet, and does not depend on statistical models or knowledge of ionospheric parameters, e.g., conductances. The temporal resolution of the Iridium magnetic field observations during this period was 1–2 orders of magnitude lower than it is today, capturing only one vector sample every ~200 s per satellite [Anderson et al., 2000]. To resolve the structure of the Birkeland currents to 3° in latitude, 1 h data accumulation from the entire constellation was required [Korth et al., 2004a, 2008a; Anderson et al., 2008]. Birkeland current distributions associated with consistent magnetospheric driving conditions were identified using the technique described by Anderson et al. [2008]. Briefly, regions of the large-scale field-aligned currents containing the peak upward and downward current densities were compared between consecutive 1 h distributions. Those sequential distributions for which the average overlap of the regions was at least 45%, consistent with visual inspection of the large-scale currents, were identified as stable. The stable current distributions identified in this manner were found to correspond to conditions that are more likely to be stable in the IMF direction [Anderson et al., 2008]. Similar to previous studies [Anderson et al., 2008; Korth et al., 2010], about 5% of the current distributions met the criterion for stability. For this study, a total of 1109 2 h intervals with simultaneous observations of the stable current distributions in the Northern Hemisphere by Iridium, FUV auroral emissions by GUVI, and IMF orientation by the Magnetometer [Smith et al., 1998] on ACE were retained for analysis. Simultaneous observations are defined here with the requirement that the center time of a 20 min. TIMED pass poleward of 50°N magnetic latitude (MLAT) lies within the 2 h window of a stable current interval. This implies that for a given pass, at a minimum, half of the GUVI observations are acquired during the Iridium events, although typically the containment is complete. The IMF was lagged from L1 to Earth using simple advection using solar wind plasma observations [McComas et al., 1998]. The histogram distribution of these events sorted into 45° wide bins of the IMF clock angle, ψ = arctan(Bx, By), is shown in Figure 1.
Birkeland current distributions in the Northern Hemisphere within each clock angle bin, which are shown in Figure 2 for current densities greater than two standard deviations (2σ) in a given bin.

For each Birkeland current distribution, auroral emissions associated with particle precipitation were observed simultaneously by the GUVI instrument. GUVI uses a scan mirror to observe the far-ultraviolet spectrum, and auroral emissions in the N₂ LBH short (140–150 nm) and long (165–180 nm) wavelength ranges and Lyman-alpha (Ly-α) emissions at 121.6 nm are integrated onboard and transmitted to ground. The instrument field of view extends from −67° to +60° of the nadir direction to yield an imaged swath along the satellite trajectory. For this study, only data obtained within ±60° of nadir were used in the analysis. The emission intensities were corrected for the slant path length through the optically thin auroral emission region by multiplying the emissions by the cosine of the look angle relative to nadir. The look angle-corrected LBH and Ly-α emissions were registered in magnetic latitude and local time on a grid with approximate cell dimensions 0.35° by 0.025 h, and LBH emission intensities, \( I_{LBHS} \) and \( I_{LBHL} \), converted to electron energy flux, \( J_{EE} \), and mean energy, \( E_e \), using the empirical relationships of Sotirelis et al. [2013]:

\[
J_{EE} \left[ \frac{\text{erg}}{\text{s cm}^2} \right] = 0.0025 \left[ \frac{\text{erg}}{\text{s cm}^2 \text{ R}^2} \right] I_{LBHL} |R|, \\
E_e [\text{keV}] = 19.6 [\text{keV}] \exp \left( -2.34 \frac{I_{LBHS} |R|}{I_{LBHL} |R|} \right).
\]

Figure 2. Statistical Birkeland current distributions in the Northern Hemisphere in 45° wide clock angle bins. The IMF direction is indicated by the arrows in the center of the panel. Red and blue colors correspond to upward and downward currents, respectively. Only currents above the 2σ confidence threshold are shown, and this level is marked by outlines.
These empirical relationships represent least-absolute-deviation fits of the electron precipitation measured by the SSJS particle detector [Hardy et al., 1984] and auroral emissions observed simultaneously along the same magnetic field line by the Special Sensor Ultraviolet Spectrographic Imager (SSUSI) [Paxton et al., 1992a, 1992b] on DMSP F16. The SSUSI and GUVI imagers share the same optical and detector designs, and both instruments’ wavelength bands, which are essentially identical, are calibrated against the same stellar spectra, so that the measured radiances are consistent. Thus, applying the derived relationships to GUVI data should yield reasonably reliable estimates of the average electron energy flux associated with the auroral emissions.

Figure 3. Model for Ly-α radiance per unit proton energy flux versus proton energy used to estimate proton energy flux.

Figure 4. Northern Hemisphere GUVI observations during orbit 20657 on 1 October 2005, 0919–0934 UT. The auroral emissions at (a) LHB long, (b) LBH short, and (c) Ly-α wavelengths. (d) The electron energy flux and (e) characteristic electron energy inferred from the LBH emissions, and (f) the proton energy flux estimated from the Ly-α emissions. Locations for which the proton energy flux exceeds 5% of the electron energy flux are shown in grey in Figure 4d.
The Sotirelis et al. [2013] relationships are only valid for electrons, and observations featuring significant contributions from precipitating protons, which also generate LBH emissions, have to be excluded from the analysis. The degree to which protons contribute to the energy flux estimates derived from the LBH emissions can be determined from the Ly-α emissions, which are induced solely by protons. The proton energy flux associated with the Ly-α emissions was approximated using the following procedure. First, the Ly-α radiance per unit energy flux of protons having mean energies in the range 0.5–300 keV was computed with the Boltzmann Three Constituent (B3C) auroral transport model [Daniell, 1993]. The model results, shown in Figure 3, illustrate that the Ly-α radiance decreases monotonically with increasing proton energy. Next, the appropriate conversion factor at the location of interest was interpolated given an estimate of the proton energy at that location from the Hardy et al. [1989] model for $K_p = 3$ and multiplied with the observed Ly-α radiance to yield the proton energy flux. The obtained proton energy flux was then compared with the energy flux inferred from the LBH emissions, and we retained only those observations for which the estimated proton energy flux contribution was less than 5% of the electron energy flux. This assessment was carried out on a per-bin basis, and data at the identified locations were removed from the analysis, so that they do not affect the statistical averages.

3. Example Events

Example distributions of auroral emissions and inferred particle precipitation characteristics for two Northern Hemisphere TIMED passes are shown in Figures 4 and 5. Each event shows in Figures 4a–4c and 5a–5c the LBHS, LBHL, and Ly-α auroral emissions, and Figures 4d–4f and 5d–5f show the inferred electron energy flux.
electron mean energy, and proton energy flux in the same order. All observations are color coded according to the color bar below each panel. Duskside auroral emissions were observed by GUVI on 1 October 2005, 0919–0934 UT (Figure 4). The brightest LBH emissions (Figures 4a and 4b) were observed in a narrow, 1–2° wide latitude band near 70° MLAT, near the statistical peak in the R1 Birkeland currents during southward IMF orientation (cf. Figure 2). In addition, lower-intensity LBH emissions are evident just equatorward of this band. Comparison with the Ly-α emissions (Figure 4c) and inferred proton energy flux (Figure 4f) indicates that protons contribute a substantial fraction to the energy flux at the most equatorward latitudes. Proton precipitation, likely associated with diffuse proton aurora commonly observed in this region, is often the dominant contribution to the LBH aurora in this region, and observations with contributions to the energy flux above the 5% level, shown in grey in Figure 4d, were excluded from the estimates of electron energy flux and mean energy (Figures 4d and 4e) as described

Figure 6. Comparison of (b and d) the electron energy flux for the events depicted in Figures 4d and 5d with (a and c) the Birkeland current distributions. The Birkeland currents are presented in the same format as used in Figure 2, and their 2σ contours are overlaid on the electron energy flux distributions.
above. The second example shows dawnside observations by GUVI on 22 November 2005, 1520–1547 UT (Figure 5), where the peak LBH (Figures 5a and 5b) and Ly-α (Figure 5c) emissions are observed near 65° MLAT within the upward R2 during southward IMF and retreating to higher latitudes toward the dayside. The extent of the auroral emissions in latitude is somewhat larger than that observed on the duskside (see Figure 4), consistent with diffuse precipitation of plasma sheet electrons drifting eastward around the Earth. Although the proton energy flux registers in the same latitude range, its contribution to the LBH auroral emissions is small, yielding reliable estimates for electron energy flux (Figure 5d) and mean energy (Figure 5e) in this region.

The events shown in Figures 4 and 5 indicate good correlations between regions of electron precipitation and statistical, large-scale upward Birkeland currents. To explore the correlation between the electron precipitation and the upward Birkeland currents in more detail, we compare the Iridium and GUVI observations for these events in Figure 6. The Birkeland current distributions observed for 1 October 2005, 0900–1100 UT, and 22 November 2005, 1500–1700 UT, are shown in Figures 6a and 6c, respectively, using the same format as the panels in Figure 2. The IMF clock angles for these events were 124° ± 18° and 132° ± 13°, respectively, corresponding to southward and predominantly duskward IMF. Both events reflect prominent R1 and R2 current systems typically observed for southward and duskward IMF. The electron energy flux distributions inferred from the GUVI observations during these intervals are shown to the right of the currents overlaid with the 2σ confidence contours of the Birkeland currents, where red and blue contours outline regions of upward and downward currents, respectively (Figures 6b and 6d). The 2σ confidence level was computed from the residual magnetic perturbations of the spherical harmonic fit as described in Korth et al. (2004b) and amounts to ~0.15 μA/m². For 1 October, the electron energy flux observed within the GUVI swath is well confined within the afternoon-to-dusk sector of the upward R1 (Figure 6b). The upward currents in the pre-midnight sector lie outside the GUVI swath. The dawnside GUVI swath for the 22 November event was closely aligned the upward R2, and the electron precipitation is confined within this region on the nightside.

4. Statistical Analysis and Results

Similar agreement between large-scale upward currents and electron precipitation was found for most events. To quantify the comparison, we analyzed the correspondence in the location and intensity of the electron energy flux and Birkeland current density statistically. For this purpose, we sorted the events by IMF clock angle into 45° wide bins as was done for the Iridium current distributions in Figure 2. Within each IMF clock angle bin, the corresponding composite electron energy flux map was derived by evaluating the average electron flux at each 0.4° latitude by 0.07 h magnetic local time (MLT) grid point over all events with valid electron energy flux measurements at the grid point. The resulting statistical electron energy flux distributions sorted by IMF orientation are shown in Figure 7 in the same format as Figure 2. The 2σ contours of the upward (red) and downward (grey) current regions, from Figure 2, are overlaid on each distribution.

The composite maps of the electron precipitation show generally remarkable agreement with the distribution of the associated upward Birkeland current. The colocation is especially good for southward IMF. The correlation is less striking during northward IMF when both the current densities and the auroral emissions are typically weaker. Although differences in spatial scale sizes are evident in individual events, the averaging smoothes the spatial structure in the electron flux, so that the statistical distributions yield gradient scales comparable to those resolved in the average currents. As the IMF turns from dawnward/duskward to southward, the electron precipitation follows the equatorward expansion of the large-scale upward currents, and the magnitude of the peak electron energy flux increases as does the peak current density. The analysis is thus indicative of the important role of electrons as carriers of the upward field-aligned currents on a global scale. In this regard, we note that the correspondence between electron energy flux and upward current is stronger at dusk than at dawn. On the duskside, the averaged electron energy flux of magnitudes >1 erg/s/cm² is contained almost entirely within the upward R1 as indicated by the 2σ contours, whereas at dawn, the region of averaged electron precipitation appears to be shifted poleward with respect to the upward R2 by about 5°. The possible causes of this dawn-dusk difference are discussed below.
5. Discussion

We have determined distributions of electron energy flux incident at the ionosphere inferred from auroral emissions during stable Birkeland current conditions and compared their locations with those of the large-scale Birkeland currents as a function of IMF clock angle. To explain the variations in qualitative agreement between currents and precipitation, we consider both physical processes and limitations in the observations.

We first consider aspects of the analysis that influence the results. The determination of current and precipitation regions are subject to observational limitations in spatial resolution and sensitivity. First, while the periods depicted in Figure 6 show that the precipitation is, for the most part, confined within the upward current regions, the latitudinal extent of the electron energy flux is substantially smaller than that of the 2 h accumulated Birkeland currents at most local times. This is likely due to the spatial resolution afforded by the spherical harmonic analysis of the historical Iridium data, which cannot resolve current structures measuring less than 3° in latitude. Moreover, the necessity to accumulate data over 2 h intervals inevitably leads to latitude broadening of the magnetic signals as the actual latitudes of the currents varies on time scales of tens of minutes. Analysis of Iridium data with 10 min data accumulation obtained with the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) shows that the latitude extent of the currents is generally narrower than those obtained here and confirms that they are rarely stable in latitude for prolonged periods. While such variations were minimized...
by selection of stable current configurations, they cannot be entirely eliminated. One must therefore be mindful that the following interpretations are based on statistical data, the use of which broadens the actual current distribution in latitude.

Second, for northward IMF, the agreement between the current and precipitation regions is not as good as for southward IMF. The primary reason for the diminished spatial correspondence is that the field-aligned currents are much weaker under these conditions, and the magnitudes of the current densities are often below the 2α confidence threshold. The current distributions for northward IMF are thus not only confined to much smaller areas but are also substantially more variable than those obtained for southward IMF, so that the criterion for stability of the large-scale currents is fulfilled less often than for southward IMF, and the smearing associated with the 1 h accumulations is worse. Consequently, the number of identified stable events is substantially lower for northward IMF than it is for southward IMF when the current densities are typically higher and occupy larger areas (cf. Figure 2). LBH auroral emissions and upward currents can yield coherent distributions even under northward IMF conditions if the current density is sufficiently strong, >0.7 μA/m² [Korth et al., 2004a, 2005]. Here, however, the smaller number of events leads to larger statistical uncertainties in the distributions of both the Birkeland currents and the electron energy flux. Due to the reduced fidelity, the northward IMF distributions are not discussed any further.

Third, diffuse precipitation of auroral ions contributes substantially to the generation of LBH emissions at duskside low latitudes. While we have made an effort to eliminate such observations, the applied method is not perfect so that patchy regions of low to moderate energy flux are evident in some of the distributions. This is especially evident within the downward R2 current of the distribution for the 180° clock angle bin. Because these smaller-scale regions of energy deposition are not associated with electron precipitation, they are omitted from further discussion.

Upward field-aligned currents can be carried by precipitating electrons, and as noted in section 1, knowledge of the connection between field-aligned current and particle precipitation dates back several decades. However, global-scale correlations were never established, so that the results presented here are new. The consistent correspondence between currents and electron precipitation and the fact that the large-scale upward currents at dawn are located at latitudes equatorward of those at dusk imply that the electron auroral oval is offset toward dawn by a few degrees as is evident in previous studies of auroral electron precipitation [e.g., Sotirelis and Newell, 2000; Korth et al., 2008b]. The present findings indicate that the physical basis for this auroral asymmetry is indeed the relationship to upward currents, which are typically R1 at dusk and the equatorward R2 currents and dawn.

The colocation of current and precipitation boundaries is particularly good at dusk, and this finding can be understood in the context of previous work. Particle observations by DMSP [Newell et al., 2009] have shown that, except near midnight, duskside electron energy flux is primarily monoenergetic, indicating that it is caused by electrons accelerated in a field-aligned potential difference. The relative contribution of accelerated electrons to the energy flux incident at the ionosphere increases toward the dayside and is dominant in the afternoon sector. The relationship between the accelerated electron precipitation identified in these data and the large-scale field-aligned currents has been established by Ohtani et al. [2010] by locating the most equatorward and most poleward boundaries of electron acceleration relative to the R1/R2 currents. They found that the electron acceleration is very often confined within the upward R1 in the dusktomidnight sector. This is consistent with a direct causal relationship between the upward R1 currents and downward electron acceleration at dusk.

It remains to consider possible reasons for lower correspondence between the electron precipitation and duskside R2 upward currents. To examine this, we present in Figure 8 the current density, \(j_H\) (black), and electron energy flux, \(\varepsilon\) (light red), averaged within ±1 h MLT of the dawn-dusk meridian as functions of latitude from dusk to dawn for the 180° clock angle bin. Consistent with Figures 2 and 7, we find good agreement of the boundaries and peak in the electron precipitation with those of the upward R1 currents at dusk. As noted above, the low-level energy flux over the duskside R2 is likely caused by a small fraction of precipitating protons and diffuse electrons, which passed the criterion for removal of these data. In contrast, on the dawnside, the low-latitude onset of precipitation is located about 5° poleward of the equatorward boundary of the upward R2 current, maximizes within R2 but somewhat poleward of the currents, and extends with decreasing magnitude throughout much of the downward R1. To test the sensitivity of the
energy flux and the minimum latitudes at which these quantities were observed on the dawnside. For each event, the above characteristic latitudes were identified in the precipitation within 0.5 h wide MLT intervals between 3 and 9 MLT, and the average values, $\bar{\lambda}$, were computed over all MLT intervals for which there were data. Next, the corresponding latitudes in the current distributions, $\bar{\lambda}_{j\parallel}$, were determined for the same MLT intervals, and the latitude differences, $\Delta \lambda = \lambda_{j\parallel} - \lambda$, were evaluated. Consistent with the statistical analysis, the 2SD confidence level, 0.15 $\mu$A/m$^2$, and the minimum detection level, 0.1 erg/s/cm$^2$, were used as thresholds for $j_{||}$ and $\varepsilon$, respectively. Figure 9 shows the histogram distributions for $\Delta \lambda$ of the peak latitudes at (a) dusk and (b) dawn and (c) of the minimum latitudes on the dawnside. The distributions in Figures 9a and 9b show the peak latitudes of $j_{||}$ and $\varepsilon$ closely aligned. Although the distribution at dusk (dawn) is skewed slightly toward positive (negative) $\Delta \lambda$ values, indicating that the peak in the current density is located somewhat poleward (equatorward) of the latitude showing the maximum precipitation intensity, the differences are within the 3° latitude resolution of the Birkeland currents so that they are not statistically significant. On the other hand, the histogram distribution in Figure 9c shows a clear skew toward negative values, where the equatorward boundary of the precipitation is located, on average, 4° further poleward of that of the currents. This difference exceeds the latitude resolution of the Birkeland currents, suggesting that the offset in the equatorward boundaries evidenced in the statistics (cf. Figure 7) is genuine. Note that the event shown in Figure 6d deviates from the statistical average and does not display the latitude offset. Understanding the circumstances leading to this deviation and the implications for the dynamics of the system are important future work.

Similar differences in the boundaries were identified by Ohtani et al. [2010] who found that the boundary of the most poleward electron precipitation is more widely distributed with respect to the dawnside R2 than it is to the duskside R1. To explain this, one must consider the particle dynamics in the magnetosphere. The guiding center drift velocity of a particle within the magnetosphere can be expressed as [Kivelson, 1995]:

$$\mathbf{v}_D = \frac{\mathbf{E} \times \mathbf{B}}{qB^2} + \frac{W_{\text{kin},||}(\mathbf{B} \times \mathbf{B})}{qB^2} + \frac{2W_{\text{kin},\perp} \mathbf{R} \times \mathbf{B}}{qR_c^2 B^2}$$

(2)

where $\mathbf{E}$ is the macroscopic electric field; $\mathbf{B}$ is the magnetic field; $W_{\text{kin},||}$ and $W_{\text{kin},\perp}$ are the particle’s kinetic energies parallel and perpendicular to $\mathbf{B}$, respectively; and $R_c$ is the local radius of curvature of the magnetic field line. The terms in equation (2) are referred to as $\mathbf{E} \times \mathbf{B}$, gradient, and curvature drifts, respectively. In response to the magnetospheric electric and magnetic fields, electrons are transported earthward in the magnetotail and directed eastward around the planet, so that electrons are predominantly encountered at dawn. As the electrons drift around the planet, they gyrate around the magnetic field lines.
and bounce between the Northern and Southern Hemisphere mirror points. The mirror altitude depends on the particle's equatorial pitch angle, $\alpha_{\text{eq}} = \alpha \sin \sqrt{B_{\text{eq}}/B_m}$, and moves along the field to lower altitudes as $\alpha_{\text{eq}}$ decreases. Particles with mirror points below the ionosphere will be lost due to atmospheric collisions and contribute to diffuse auroral precipitation. For particles with sufficient energy, this process will induce auroral emissions without acceleration by a field-aligned potential drop. As mentioned above, a prominent mechanism for such particle losses from the magnetosphere is the scattering of pitch angles by interaction of particles with whistler-mode waves. This process occurs predominantly in the dawnside magnetosphere [Meredith et al., 2003; Li et al., 2009] in a region consistent with precipitation of diffuse auroral electrons incident at 65°–75° latitude observed statistically by Newell et al. [2009], which dominates that of accelerated electrons over much of the dawnside ionosphere. The poleward edge of the dawnside particle precipitation in Newell et al. [2009] is consistent with that of our analysis (cf. Figure 7). We conclude that while field-aligned electron acceleration may occur on the dawnside, diffuse electrons have a larger contribution to the distribution of precipitating electrons in this region, leading to the observed dissimilarities in the poleward boundaries of the dawnside R2 and the electron precipitation.

A latitude mismatch between the current and precipitation boundaries is also observed at the equatorward edge of the upward R2 at dawn (cf. Figures 7 and 8). This particular feature is not present in the event shown in Figure 6d, which could simply result from the fact that individual events may deviate from the statistical picture or be indicative of the previously described challenges associated with deriving reliable field-aligned currents from the historical Iridium data on a global scale. The difference in the statistical boundaries may likewise be explained by particle dynamics. The drift equation (2) describes two classes of drift trajectories, one that is closed around the planet and one that is open to the tail, providing access of plasma sheet material to the near-Earth region. The boundary between these two types of trajectories is referred to as the Alfvén layer. Since both the gradient and curvature drifts depend on the energy of the particle, the Alfvén layers are energy dependent and effectively control particle access to
the inner magnetosphere. For time stationary electric and magnetic fields, particles with lower energies can penetrate deeper into the inner magnetosphere than higher-energy particles. Because equatorial magnetic field lines closer to the Earth are rooted in the planet at lower latitudes, the Alfvén layers also limit the latitude range over which precipitation can occur. We propose that the equatorward boundary of the observed electron precipitation in Figure 7 is the minimum latitude at which electrons having sufficient energy to induce LBH auroral emissions can precipitate. Equatorward of this boundary, lower-energy electrons can precipitate and carry the upward current, but their energy is insufficient to generate a measurable auroral emission signal.

Our hypothesis is consistent with theoretical calculations of Alfvén layers by Korth et al. [1999]. The electron energy of the Alfvén layer associated with the equatorward edge of the observed precipitation boundary can be estimated from minimum energy flux required to produce measurable LBH auroral emissions and the upward current density in the region of interest. The energy flux incident at the ionosphere can be written as the sum of two components [Lyons et al., 1979]:

\[ \varepsilon = \varepsilon_0 + |eV|_j, \]

where \( \varepsilon_0 \) is the energy flux prior to acceleration, \( e \) is the elementary charge, \( V \) is the field-aligned potential difference, and \( j \) is density of the upward current carried by the net flux of electrons from the magnetosphere to the ionosphere. The first term in equation (3) is the unaccelerated component of the electron flux, such as from diffuse electron precipitation, while the second term is the increment in energy flux due to acceleration. Assuming that the electron precipitation is solely due to acceleration and given the minimum electron energy flux producing measurable LBH auroral emission, \( \sim 0.1 \text{ erg/s/cm}^2 \), and the statistical upward current density in the region equatorward of the precipitation boundary, \( \sim 0.1 \mu \text{A/m}^2 \), equation (3) yields an acceleration potential of \( \sim 1 \text{ kV} \). During moderate geomagnetic activity, the geocentric distance of the 1 keV electron separatrix at dawn is \( L = 4-5 R_E \) [Korth et al., 1999], which maps to surface latitudes \( \lambda_E = 60^\circ-63^\circ \) in a dipole approximation where \( \cos^2 \lambda_E = L^{-1} \) [e.g., Baumjohann and Treumann, 1997]. Plasma sheet electrons precipitating equatorward of this boundary, which coincides with the equatorward limit of the statistical dawnside precipitation, do not carry sufficient energy flux to produce LBH auroral emissions. It is thus possible that the discrepancy of current and precipitation boundaries at the equatorward edge of the dawnside R2 results from the inability to infer the precipitating electron energy flux \( < 0.1 \text{ erg/s/cm}^2 \) from LBH auroral emissions.

The analyses above are qualitatively consistent with our knowledge of electron precipitation characteristics, motivating further quantitative analysis. From equation (3) it is evident that in regions where the precipitation is primarily diffuse, only a weak, if any, correlation between \( \varepsilon \) and \( j \) is anticipated. To test this, we use the statistical distributions from the 180° clock angle bin (cf. Figures 2 and 7) and extract those pairs of observations, which are contained within the 2σ contours of the large-scale upward R1 and R2. A scatterplot of these data, shown in Figure 10a, does not exhibit any significant relation between current density and energy flux. The observed lack of correlation is expected because unaccelerated precipitation, consistent with pitch angle-scattered diffuse auroral electrons, is coincident with upward currents at local times between pre-midnight and noon and contributes the majority, 84%, of the energy flux into the ionosphere [Newell et al., 2009]. According to Newell et al. [2009], the portion of the upward R1 sunward of the terminator is most suited to establish a quantitative relationship between \( \varepsilon \) and \( j \). A scatterplot of the fraction of data points in this region is shown in Figure 10b and displays a definite, non-linear relationship. Although a clear dependence between \( \varepsilon \) and \( j \) exists, there is a large spread in the distribution. The statistical spread could result either from weak dependence of the quantities or from random noise in the data, and it is important to distinguish these effects. Noisy data may result from the disparate spatial resolutions evident in the distributions of Figures 2 and 7. To assess the effect of spatial resolution on the derived dependency, we smoothed the electron energy flux to the spatial resolution of the Birkeland current (3° in latitude and 2 h in local time). The smoothed precipitation data, presented in Figure 10c, exhibit a much tighter distribution with respect to the current densities, indicating that the difference in spatial resolution is the likely cause for the weaker correlation in the original data set (Figure 10b). The strong relationship between \( \varepsilon \) and \( j \) may be interpreted as follows. Assuming that there is a linear relationship between field-aligned current density and potential difference, i.e., \( j = |eV|/k \) [Knight, 1973], equation (3) implies

\[ \varepsilon \approx |eV| j - j^2. \]
A quadratic fit of the data points in Figure 10c, represented by the red line, implies that the data are agreeable with equation (4) and thus supports a linear current-voltage relationship in upward current regions dominated by electron acceleration as proposed by Knight [1973]. Forty years after it was first proposed, the validity of the Knight [1973] relation is still a subject of active debate. While our results and other observations [e.g., Lyons et al., 1979; Weimer et al., 1985, 1987; Haerendel et al., 1994; Olsson et al., 1996; Lu et al., 1998; Korth et al., 2004a] have been interpreted as consistent with a linear current-voltage relation, several studies did not find a clear linear correlation between current density and auroral potential [Sakanoi et al., 1995; Olsson and Janhunen, 2000a, 2000b; Shiokawa et al., 2000]. Our results indicate that identifying precipitation characteristics relevant to the underlying theory is not simple and requires a careful distinction between discrete and diffuse precipitation. Moreover, the results show that in regions where discrete electron precipitation predominates, the Knight relation holds generally and indeed governs the precipitation flux. It is conceivable that those studies reporting deviating results included observations in regions with substantial diffuse auroral precipitation not suited for verifying the underlying theory. It is also possible that the diverging findings are due to a change in nature of the current-voltage relation with operating regime. A statistical analysis of inverted-V structures by Dombeck et al. [2013] suggests that the current-voltage relationship is complex for $|eV| < 1$ kV and becomes linear for larger field-aligned potential drops. This result is consistent with the linear current-voltage relation inferred here from LBH auroral emissions induced by electrons in the several keV energy range [Sotirelis et al., 2013] and may also be in agreement with studies that have deduced a more complex functional behavior.

6. Summary

We have compared statistical distributions of the large-scale Birkeland currents from the Iridium constellation with composite distribution of simultaneously obtained electron precipitation observed during stable current configurations. The electron precipitation was inferred from auroral imaging observations by the
GUFI instrument on the TIMED spacecraft using a statistical relationship to convert N₂ LBH intensities to electron energy flux. Proton contributions to the LBH emissions were identified by their Ly-α intensity and excluded from the analysis. The Birkeland currents were derived with a spatial resolution of 3° in latitude and 2 h in local time. For southward IMF, the electron precipitation occurred primarily within and near the large-scale upward current regions, while the correlation was less definite for northward IMF, presumably because the spatial variability is large compared to the areas of interest so that the number of events identified is smaller and the derived statistical distributions are less reliable. Good correspondence of upward field-aligned currents with FUV auroral emissions under northward IMF conditions has been demonstrated previously for selected events showing current densities >0.7 μA/m² [Korth et al., 2004a, 2005]. The correlation between currents and precipitation was better at dusk, where a larger fraction of incident electrons is accelerated downward by field-aligned potential difference in the upward R1, than at dawn, where diffuse precipitation of electron drifting eastward around the planet, which is not driven by field-aligned acceleration, dominates. In the upward R1 on the dayside, where the electron precipitation is almost exclusively due to field-aligned acceleration, a quadratic relationship between current density and electron energy flux was observed, implying a linear current-voltage relationship in this region. In contrast, current density and electron energy flux in the regions of the large-scale upward currents between premidnight to noon are essentially uncorrelated because the majority of the energy flux incident at the ionosphere is from diffuse electron precipitation, which does not require field-line acceleration and therefore does not reflect any current-voltage relation. Thus, the relationship between field-aligned currents and precipitation varies widely even within the large-scale upward current regions, and this variability may have impeded the validation of the current-voltage relation in the past.

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References
Baumjohann, W., and R. A. Treumann (1997), Basic Space Plasma Physics, 329 pp., Imperial College Press, London.

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An empirical model, KORTH ET AL.

Weimer, D. R. (2001), Maps of ionospheric


Paxton, L. J., et al. (1992b), SSUSI - Horizon-to-horizon and limb-viewing spectrographic imager for remote sensing of environmental

Strickland, D. J., J. R. Jasperse, and J. A. Whalen (1983), Dependence of auroral FUV emissions on the incident electron spectrum and neutral

Ohtani, S., S. Wing, P. T. Newell, and T. Higuchi (2010), Locations of night-side precipitation boundaries relative to R2 and R1 currents,


