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Key Points:
- Dayside currents, both Regions 1 and 2, form promptly with solar wind forcing
- The onset of nightside currents, Regions 1 and 2, coincides with substorm onset
- Most of the current system develops from the nightside after onset

Supporting Information:
- Readme
- Figures S1
- Figures S2

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Abstract The Active Magnetosphere and Planetary Electrodynamics Response Experiment uses magnetic field data from the Iridium constellation to derive the global Birkeland current distribution every 10 min. We examine cases in which the interplanetary magnetic field (IMF) rotated from northward to southward resulting in onsets of the Birkeland currents. Dayside Region 1/2 currents, totaling ~25% of the final current, appear within 20 min of the IMF southward turning and remain steady. Onset of nightside currents occurs 40 to 70 min after the dayside currents appear. Thereafter, the currents intensify at dawn, dusk, and on the dayside, yielding a fully formed Region 1/2 system ~30 min after the nightside onset. The results imply that the dayside Birkeland currents are driven by magnetopause reconnection, and the remainder of the system forms as magnetospheric return flows start and progress sunward, ultimately closing the Dungey convection cycle.

1. Introduction

One response of a planetary magnetosphere to the solar wind interaction is the magnetic convection cycle [Dungey, 1961] that results from magnetic reconnection on the dayside and closes via merging of open magnetic flux in the magnetotail and subsequent sunward flows returning flux to the dayside. At Earth, this cycle drives the large-scale Birkeland currents, commonly denoted Region 1 (R1) and Region 2 (R2), and these currents reflect the intensity and configuration of the convection and the state of the coupled magnetosphere-ionosphere system [Cowley, 2000; Korth et al., 2010]. Statistical analyses have identified where the different portions of the Birkeland currents map in the high-altitude magnetosphere [e.g., Wing et al., 2011; Ohtani et al., 2012], and it is accepted that the R2 currents form as part of the magnetospheric response to convection driven by the solar wind [e.g., Brandt et al., 2004; Zheng et al., 2006]. Nonetheless, we still do not understand what fraction of the R1 current is directly driven and how much results from closure of the Dungey convection cycle in the magnetosphere. Indeed, the R1 current is often discussed as the driven current while R2 is the response [cf. Sisco et al., 2011]. This interpretation is at least implicitly adopted in ring current simulations that use the R1 currents or the corresponding fully formed polar cap convection electric field as the outer/poleward boundary to drive the inner magnetospheric response [Toffoletto et al., 2003; Zheng et al., 2006; Pembroke et al., 2012; Chen et al., 2012; Liemohn et al., 2013]. Earlier low-resolution MHD simulations principally yield R1 currents [Merkin et al., 2003, 2005], potentially contributing to the impression that R1 is independent of R2. More recently, high-resolution codes yield significant R2 currents that compare favorably with observations [cf. Merkin et al., 2013].

The average Birkeland current distribution during geomagnetically active conditions has been known for more than 35 years [Iijima and Potemra, 1976]. Figure 1 illustrates an instance of this system determined with 10 min of data acquired under the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE). Figure 1 (left) shows magnetic perturbation signals, dB, for the 10 min interval, 1920–1930 UT on 15 October 2010. Horizontal perturbations are shown in Altitude Adjusted Corrected Geomagnetic Coordinates (AAGCM) [Baker and Wing, 1989] as arrows originating at the measurement location. The length of each arrow indicates |dB| scaled as shown by the 500 nT reference arrow. Different colors denote data from different space vehicles (SVs). Data for each track consist of data from three to
four SVs, yielding a composite pass through the auroral zone. The data show the familiar eastward perturbation in the evening and westward perturbation in the morning, indicative in the Northern Hemisphere of the large-scale adjacent upward and downward current systems denoted R1 (poleward) and R2 (equatorward) by Iijima and Potemra [1976].

In this paper, we use observations of the Birkeland current system in response to isolated southward turnings of the interplanetary magnetic field (IMF) to characterize the time development of the system and better understand how the currents are related to magnetospheric convection. As a point of comparison, consider the expected sequence if the R1 system is driven by the solar wind dynamo independently of R2 such that the R2 system forms later as the shielding response of the inner magnetosphere develops. One would first expect the R1 currents to appear and only later, as the return convection and corresponding shielding develops, would the R2 currents appear.

2. AMPERE Data and Inversions

AMPERE provides global, continuous sampling of the magnetic field perturbations at low Earth orbit from the Iridium Communications constellation of 70 near-polar orbiting satellites [Anderson et al., 2000, 2002; Waters et al., 2001]. AMPERE was funded by the National Science Foundation to implement new flight software on the Iridium satellites to downlink magnetic field samples at 19.44 s (standard rate) or 2.16 s (high rate) intervals from every satellite in the communications network of 66 SVs and from on-orbit spare SVs. Test data were acquired starting in October 2009, and complete AMPERE data were collected from June 2010 through May 2013. The SVs are distributed over six orbit planes spaced equally in longitude, giving ~2 h local time spacing and a 9 min separation along track between adjacent SVs in each orbit plane. The AMPERE Science Data Center at the Johns Hopkins University Applied Physics Laboratory was developed to ingest, merge, and process magnetometer data and attitude estimates to yield detrended, intercalibrated perturbations reflecting signatures of Birkeland field-aligned currents flowing between the ionosphere and magnetosphere. Occasionally, data from an SV are not suitable for use in the analysis either because they are missing or because the attitude data are not sufficiently accurate to allow derivation of the $\delta B$. These data are replaced with data from the previous satellite that traversed the same region, i.e., 9 min earlier. Such replaced data are color-coded gray in the $\delta B$ displays. None of the data in Figure 1 are replaced. The present generation of preprocessing can yield disparities in the baselines for the $\delta B$ between satellites which are greatest during highly disturbed conditions [cf. Knipp et al., 2014]. The magnitude of the errors due to this artifact can be estimated by comparing the $\delta B$ near the Iridium orbit crossing points. For the events studied here the disparities in $\delta B$ at track intersections are ~100 nT or smaller (cf. supporting information).

The perturbation data are used in spherical harmonic inversions in a potential formalism [Waters et al., 2001; Green et al., 2006] tailored to the denser latitude sampling afforded by AMPERE. As discussed by Waters et al. [2001], the perturbations are represented as spherical coordinate spatial derivatives of a scalar potential.
expressed as a series expansion of cap harmonics. The potential and its gradient with respect to polar angle are set to 0 at the equatorward boundary, but the fit has no dependence on statistical models, indices, IMF/solar wind data, or ionospheric parameter assumptions, e.g., conductances. One advance, in addition to the higher sampling rate, over Anderson et al. [2000] and Waters et al. [2001], is that the AMPERE data allow use of the full horizontal perturbation vector in the inversion. This allows us to use the full least squares merit function [cf. Waters et al., 2001, equation (9)] without the restriction to the cross-track component of $\delta B$ [Waters et al., 2001, equation (10)] and more reliably reflects signals when the track is oblique relative to the currents, and at the edges of current regions or when currents are filamentary.

Results for the fitted magnetic perturbation, $\delta B_{\text{fit}}$, are shown in Figure 1 (middle). The fit used a longitude order of 5 and latitude order 20 from $\theta = 0^\circ$ to $60^\circ$, where $\theta$ is the colatitude or polar angle. This yields resolution in the currents of $3^\circ$ in colatitude and $2.4\ h$ in local time. The curl of $\delta B_{\text{fit}}$, derived from the basis functions’ recursion relations, yields the radial current density, $J_r$, in $\mu A/m^2$ as shown in Figure 1 (right). The basic AMPERE data products are the perturbations, $\delta B$, and the inversion results, $\delta B_{\text{fit}}$, and $J_r$ evaluated on a 1 h local time and by $1^\circ$ colatitude AACGM grid. The inversions were performed on 10 min data windows spaced every 2 min.

The global current distribution for this 10 min interval is consistent with previously reported statistical averages. The poleward R1 currents, upward in the evening and downward in the morning, are surrounded by the equatorward R2 currents, downward in the evening and upward in the morning. This basic pattern has been derived statistically from several data sets [Papitashvili et al., 2002; Weimer, 2005; Anderson et al., 2008; He et al., 2012]. The closure of these field-aligned currents constitutes the major fraction of the ionosphere dissipation, and the currents convey stress to the magnetosphere from the ionosphere [Cowley, 2000; Richmond and Thayer, 2000]. The derivation of these distributions every 10 min using AMPERE allows us to follow their temporal development globally for the first time.

To quantify the total Birkeland current, we integrated the $J_r$ distributions over specified colatitude and local time ranges. For a given colatitude range, $\theta_0$ to $\theta_1$, and local time range, $h_0$ to $h_1$, the net and total current were calculated from

$$I_{\text{Net}} = \pi R^2 \int_{\theta_0}^{\theta_1} \left( \frac{\partial}{\partial h} \right) J_r \sin(\theta) \, d\theta \, dh$$  

(1a)

$$I_{\text{Total}} = \frac{1}{2} R^2 \int_{h_0}^{h_1} \left( \frac{\partial}{\partial h} \right) \text{abs}(J_r) \sin(\theta) \, d\theta \, dh$$  

(1b)

where $R$ is the sphere radius corresponding to the 780 km altitude of the Iridium orbits, $h$ is in hours ($\pi/12$ converts from hours to radians), and the “$>$“ subscript indicates that only $J_r$ with absolute values greater than a specified background noise level were included in the integral. The standard deviation of $J_r$ was evaluated from 30 days of quiet intervals and was 0.053 $\mu A/m^2$. The value of $\sigma$ used in (1) was 3 times this value or 0.16 $\mu A/m^2$. Using this threshold restricts the integral to currents that are statistically significant. In 1a the signed current density is integrated, and $I_{\text{Net}}$ should be zero if the upward and downward currents are equal in magnitude. The standard deviation of $I_{\text{Net}}$ is a measure of the uncertainty in $I_{\text{Total}}$. The average $I_{\text{Net}}$ for a day is typically ~ 0.05 MA or lower, which we take to be a measure of the random error in the integrated currents. The $3^\circ$ latitude resolution in $\delta B_{\text{fit}}$ implies that gradients are smoothed and the maximum $|\delta B_{\text{fit}}|$ is lower than the observed maximum $|\delta B|$. The leading factor of $\frac{1}{2}$ in 1b converts the result to the total upward or downward current. We present results integrated from the pole to $\theta = 30^\circ$ and in AACGM local time for dayside, 06 MLT (magnetic local time) to 18 MLT, and nightside, 18 MLT to 06 MLT through midnight.

### 3. Birkeland Current Onset and Development

We show two examples of instances of the onset of Birkeland currents following a period of quiescence. For context we use the IMF measured by the ACE magnetometer [Smith et al., 1998] at the first Lagrangian point, L1, the $AE$ index, and the asym-$H$ index [cf. Mayaud, 1980].

#### 3.1. 24 February 2010

Data for the first event, 24 February 2010 from 1345 UT to 1700 UT, are plotted in Figure 2 showing the IMF, $AE$ and asym-$H$ indices, and total Birkeland currents. The IMF is time shifted using simple advection
from the L1 point to Earth using the solar wind speed measured at ACE [McComas et al., 1998], since our concern is the sequence of the currents’ development rather than precise timing between IMF features and the currents. Currents are plotted versus the end time of the 10 min windows of the AMPERE data, so that the appearances of currents are displayed no sooner than we can be sure that they were present. The $I_{\text{net}}$ average for the day was 0.058 MA in the north and 0.054 MA in the south. The dayside currents begin to increase within ~20 min of the first IMF southward turning. This is most evident in the Northern Hemisphere. Except for a few brief intervals, $|B_Y/IMF|/|B_Z/IMF| > 1$ with positive $B_Y/IMF$ after 1500 UT so that the dayside $R_1$ current pattern is somewhat distorted with the upward current extending to higher latitudes near noon, while the downward morning $R_1$ current extends toward noon at lower latitudes. After ~1515 UT, the total current is fairly stable and is mostly a dayside current until about 1600 UT. In the south, the dayside currents are underestimated since the Iridium orbit crossing point is near noon, and although perturbations were present (evident in AMPERE summary displays, cf. http://ampere.jhuapl.edu), the present preprocessing, fitting, and inversion procedures do not resolve the currents well for this geometry.

Substorm onset is near 1600 UT, ~90 min after the first southward IMF turning, and ~45 min after the dayside currents in the north reach 0.5 MA. At this time, the nightside currents also increase and subsequently exceed the dayside currents in the north. As the substorm progresses, the nightside current continues to increase, more than doubling the total current, in both the Northern and Southern Hemispheres. A series of $\delta B$ and corresponding $J_e$ distributions in the Northern Hemisphere spanning substorm onset are shown in Figure 3. For this event, AMPERE returned data in its high-rate mode. The frames were chosen to show the first 10 min interval with evidence of nightside Birkeland current onset through full development of the currents. Plots of $\delta B$ and $J_e$ evaluated every 2 min for 1530 to 1700 UT, spanning the interval in Figure 3, are included in the supporting information. From 1515 UT to 1630 UT the dayside currents are relatively stable. Prior to onset near 1600 UT, $R_1$ and $R_2$ currents are present almost exclusively on the dayside. The first signature of onset appears in the 1542–1552 UT frame as narrow westward perturbations at ~68° magnetic latitude (MLAT), postmidnight near midnight, indicating that the corresponding currents formed sometime between 1542 and 1552 UT. Smaller perturbations first appear in adjacent tracks in the 1546–1556 UT frame (see supporting information), so we know that the currents started at these locations sometime between 1546 and 1556 UT. It takes until at least 1602 UT for the $\delta B$ on the adjacent tracks to become as large as they first appear at midnight as evidenced in the 1602–1612 UT frame. The $\delta B$ are predominantly east-west perturbations and reach ~500 nT corresponding to a net current per unit azimuth distance of ~400 A/km. This indicates the

![Figure 2. Birkeland currents, IMF, and magnetic indices for 24 February 2010 from 1345 to 1700 UT. (top to bottom) The IMF in GSM coordinates ($B_x$ in red, $B_y$ in green, and $B_z$ in blue); the AE and asym-H indices in black and red traces, respectively; and the time series of dayside (red), nightside (blue), and total (black) Birkeland currents for the Northern and Southern Hemispheres. The total currents were evaluated from integrated AMPERE current distributions as in equation 1b. The time used to plot the Birkeland current results is the end time of each 10 min data window. The horizontal gray lines in the bottom two panels are 3 times the standard deviations of $I_{\text{net}}$ for the north and south for the day.](image-url)
onset of pairs of upward (equatorward) and downward (poleward) currents as reflected in the $J_r$ distribution.

In the 1602–1612 UT frame, the track at ~2200 MLT near 70 MLAT exhibits westward $\delta B$ on the poleward edge of the currents but the $\delta B$ are eastward on the equatorward side, indicating the presence of three current sheets.

While the currents first appear near midnight, the dayside currents are largely unchanged and only later do the currents further from midnight increase. The tracks further toward dawn and dusk show no evidence of enhanced currents until 1550 UT near 2000 MLT and 1552 UT near 0400 MLT, when comparatively modest $\delta B$ are first detected on these tracks. The $\delta B$ at 2000 MLT and 0400 MLT continue to grow and by 1642 UT are as large as the first $\delta B$ observed at midnight an hour earlier. The $\delta B$ at dusk (1800 MLT) and just after dawn near 0700 MLT change very little until they increase somewhat by 1622 UT. From 1532 UT to 1622 UT, the total current increased from 0.45 MA to 1.2 MA, while the dayside currents changed relatively little (see also Figure 2).

### 3.2. 15 October 2010

Data for a second event, 15 October 2010 from 1730 to 2000 UT, are shown in Figure 4. For this day, the $I_{net}$ average was 0.026 MA in the north and 0.049 MA in the south. The IMF turned predominantly southward shortly after 1800 UT and increased abruptly in magnitude at ~1825 UT while remaining southward. Near 1835 UT, the Birkeland currents increased and the currents were generally strongest on the dayside although the nightside currents also increased. The geometry of the orbit tracks in the south was more favorable for measurement of the dayside currents for this event than the 24 February 2010 case, so the Southern Hemisphere dayside currents are more reliable. The geometry in the south was favorable for nightside currents in both cases. The Northern Hemisphere currents reached just over 1 MA by ~1900 UT, and from 1900 to 1920 UT the nightside currents increased to become comparable to the dayside currents. Substorm onset, as indicated in $AE$, occurred shortly before 1940 UT. Spanning onset, the nightside currents increased further leading to a doubling of the current from 1930 to 2000 UT.

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**Figure 3.** Sequence of Northern Hemisphere AMPERE magnetic field perturbation data, $\delta B$, and Birkeland current distributions, $J_r$, for the isolated substorm of 1530–1700 UT, 24 February 2010 using the same formats as Figure 1 but here with the $\delta B$ overlaid on the $J_r$ distributions. The terminator at 105 km altitude is shown in gray dashed lines. The first four panels are spaced by 10 min and the last three by 20 min. The display threshold for $J_r$ is 0.15 $\mu$A/m², and saturation is set to 1.0 $\mu$A/m².
The temporal sequence is similar to the first case, although the dayside/nightside distinction is not quite as prominent: the southward turning initially led to an increase in the dayside currents followed by an increase and subsequent growth in the nightside currents. The increase in the nightside currents occurred close in time to the AE signature of substorm onset approximately 10 to 15 min after the time when the nightside currents exceed the dayside currents (1925 to 1935 UT). As in the first example, the current increases on both the dayside and nightside during substorm expansion, yielding more than double the total current, in both the Northern and Southern Hemispheres.

A sequence of $\delta B$ and $J_r$ patterns for this event is shown in Figure 5, and corresponding frames every 2 min are included in the supporting information. For this event, AMPERE returned standard-rate data. The initial dayside
currents extend over a broader local time range for this event than for the 24 February case. There appear to be some R1 currents extending into the nightside, although their intensities are lower than they are later. The duskward $\delta B$ near noon is indicative of positive $B_{Y-IMF}$ and by this time $|B_{Y-IMF}/B_{Z-IMF}| \sim 1$. The first suggestion of an onset is in the second panel, 1902–1912 UT, near 67° MLAT and 0100 MLT where there is one westward $\delta B$ vector above the noise. In the third panel, 1912–1922 UT, the premidnight track displays a rotational $\delta B$ signature at the same latitude while the $\delta B$ on the tracks at 0400 MLT and at 2000 MLT are little changed. In the 1922–1932 UT interval, the $\delta B$ at 2000 MLT shows an enhancement that is stronger than that observed earlier and which we associate with substorm onset. Corresponding increases at other local times occur later and are evident by 1942–1952 UT. The $\delta B$ and currents continue to intensify as evidenced in the final frame, 2002–2012 UT, which also exhibits stronger $\delta B$ near 0700 MLT. As with the previous case, the data indicate that the onset occurred on the nightside, in this case with an initial onset near midnight and a subsequent onset near 2000 MLT, before intensifying over a broader range of local times and extending to the preexisting dayside currents. The increase in total current was approximately a factor of 2.5.

4. Discussion

The sequence in these two cases is not entirely consistent with the hypothesis that the R1 currents form first followed by the R2 currents. More extensive documentation of the current system development is clearly warranted, but the examples demonstrate that, at least on occasion, the system behavior is at variance with the concept that R1 forms independently of R2. The actual sequence appears to be that R1 currents develop on the dayside, possibly accompanied by some R2 current, presumably in response to magnetopause reconnection on the dayside, while the nightside currents are not yet present. About 30 to 40 min after the onset of dayside currents, nightside currents appear suddenly in a localized region, intensify, and expand toward the dayside. Only thereafter is the Birkeland current system familiar from statistical analysis fully formed. A schematic of this scenario is shown in Figure 6. With the onset of dayside reconnection, antisunward convection starts near noon and transports flux into the polar cap from the closed to the open field line region. Dayside convection leads to a growing region of open flux in the polar cap, which expands progressively toward the nightside as illustrated in Figure 6a. The flux feeding this flow into the polar cap comes from inflows at lower latitudes toward noon. The return flows from the nightside to the dayside may be widely distributed in latitude and need not correspond to flows across the open-closed separatrix within the magnetosphere but rather to the expansion of the open flux in the polar cap. This phase of an expanding polar cap corresponds to the substorm growth phase [e.g., McPherron, 1970; McPherron, 1979]. There may be some R1 current at local times significantly away from noon, possibly dependent on the ratio $|B_{Y-IMF}/B_{Z-IMF}|$, but they are of lower intensity than occur later. The polar cap expansion and contraction associated with the substorm cycle is evident in the R1/2 currents [Claussen et al., 2012, 2013a, 2013b], but note that in these cases, because the R1/2 currents at other local times are relatively weak, this polar cap expansion is not evident in the currents. At some point, return flows start on the nightside across the separatrix between open and closed field lines as shown in Figure 6b. We suggest that this is associated with the localized onset of Birkeland currents on the nightside.
nightside, which are nearly coincident with substorm onset [cf. McPherron, 1979]. These currents consist of both R1 and R2 senses. In particular, the fully developed R1 currents do not precede the R2 currents, consistent with detailed studies of the substorm current wedge currents in the AMPERE data [cf. Murphy et al., 2012, 2013]. After the nightside return flows begin, the nightside Birkeland currents spread in local time and intensify possibly preexisting weaker currents near dawn and dusk. This eventually leads to the complete current system indicated in Figure 6c.

The response to onset of convection driven by southward IMF is such that poleward R1 currents develop first on the dayside, and then the R1 and R2 currents develop together starting near midnight. A modest R2 dayside current may also develop, reflecting flow of already closed flux to replace flux transported into the polar cap. Except near noon, the R1 currents are coupled to and perhaps limited by R2 current development. That is, dayside reconnection drives antisunward flows near noon and a modest R1 system develops in direct response to these flows. Only later, with the onset of magnetospheric return flows and plasma injection into the inner magnetosphere, do the primary R2 currents develop beginning near midnight, and this simultaneously promotes R1 currents paired with the new R2 currents. This paired set of currents presumably appears in concert with the return flows in the inner magnetosphere and expands to merge with the preexisting dayside current system. In this way, the magnetospheric return convection is responsible for much, if not most, of the active-time Birkeland current system.

The sequence in development of the Birkeland currents suggests an additional or alternative mechanism for penetration of high-latitude electric fields to middle and low latitudes. During the initial development phase, before the onset of nightside currents, the dayside currents correspond to an electric potential distribution with significant fringing fields originating from the local time gradients in the currents, nominally near dawn and dusk. These fringing field regions will contribute to electric fields at subauroral latitudes. In this sense, the penetration electric fields might, in at least some conditions, be understood as fringing fields of an incomplete R1/2 system present before magnetospheric return convection begins or is fully developed. This contribution to low-latitude and midlatitude electric fields should be strongest during the initial phase of convection prior to onset of the nightside return flow.

The results raise several questions. First, how prevalent is this behavior? An informal survey of the AMPERE data suggests that the sequence displayed in the examples is at least not uncommon, but extensive documentation of the current systems’ development is clearly warranted. Second, are the dayside polar cap antisunward flows unchanged by the nightside onset, or is there an intensification in the dayside reconnection flows as well? That is, does the inductive reactance of the tail act to resist subsolar reconnection until substorm onset? Third, can the development of Birkeland currents be used to distinguish IMF conditions that require magnetotail reconnection to close the convection cycle? For strongly northward IMF, reconnection-driven ionospheric convection occurs entirely on the dayside and is not subject to magnetotail reconnection. As the IMF rotates from north to south, there must be a transition between these convection modes, and it may be reflected in different sequences in the Birkeland currents. Finally, does magnetospheric preconditioning affect the feedback? If the inner magnetosphere were already populated with high-temperature plasmas, the R2 currents could develop more promptly in response to the onset of return flows and corresponding electric fields, since the plasma pressures required to carry the currents would already be in place. This would be evident in a stronger initial dayside R2 current and perhaps more rapid development of the R1/2 currents following nightside onset. Further analysis of the development of the Birkeland currents in concert with observations of convection, ionospheric currents, and magnetospheric plasma populations, whether inferred from low-altitude precipitation or in situ at high altitudes, should shed light on these issues.

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