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Dayside Birkeland currents during substorms: An AMIE test of a substorm model

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Abstract. The assimilative mapping of ionospheric electrodynamics (AMIE) technique applied to three substorms shows no evidence to support a dayside current-shunting hypothesis for the substorm expansion phase onset.

Background to the Test

At the 1995 Bermuda Conference on Multiscale Phenomena in Space Plasmas, one of the authors suggested that the substorm expansion phase might start when the dayside region 1 currents, responding to a sudden drop in dayside merging at the magnetopause, partially shunt from the dayside to the nightside to become the substorm current wedge [*Siscoe*, 1996]. The hypothesis, formulated at a heuristic level, attempts to explain within the framework of the Kiruna conjecture (that substorm onset is closely coupled to events in the transition region between the magnetosphere and the magnetotail [*Kennel*, 1992]) why sudden changes in the interplanetary magnetic field (IMF) that reduce the rate of dayside merging frequently trigger substorm expansions [e.g., *Rostoker*, 1983], which Lyons [*1996*] has stressed is possibly one of their most salient phenomenological properties. The current-shunting hypothesis shares the basic motivation of the New Substorm Model of *Lyons* [1995], that is, to provide a explanation based on macroscopic physics of external triggering within the framework of the Kiruna conjecture. However, it goes beyond the Lyons model by providing a reservoir of energy to drive expansion before reconnection in the tail turns on.

In brief, the hypothesis is this: A sudden drop in the dayside merging rate drops the potential across the polar cap in the ionosphere, which drives region 1 currents. On the basis of a lumped circuit analog, the LR decay time for the region 1 currents is about 20 min [e.g., *Sanchez et al.*, 1991], whereas the drop in merging rate can be established across the dayside magnetopause in a solar wind flow time, about 4 min. Thus, for more than 10 min, the region 1 current system is carrying more current than the merging rate would drive in steady state. The excess current could simply decay in place, but there is a more interesting conceptual option. As *Stern* [1983] has illustrated, the magnetospheric end of region 1 currents can be directly connected to the substorm current wedge (see his Figure 6). Thus the suggested option is that the excess region 1 currents change their course; instead of closing across the dayside ionosphere, where they were needed before the IMF changed, now that they are not needed, they can close by shunting down the substorm current wedge channel, on the nightside. There they can dissipate their energy quickly by inductively energizing plasma sheet particles. In terms of substorm phenomenology, the shunting corresponds to dipolarization and the energization to injection.

From the perspective of the Bermuda Conference on Multiscale Phenomena in Space Plasmas, the current-shunting hypothesis explicitly connects the local process of substorm onset with the global process of convection. It solves a problem that arises in Kiruna-conjecture onset scenarios based on microscale processes: given the enormous volume of parameter space available to trigger microinstabilities throughout the tail, why does the instability tend to occur just where the tail and magnetosphere join? This is a macroscale property. Why, instead, does substorm expansion not occur at, say, 20 R_E or 30 R_E if it depends only on microinstabilities? (This, of course, is precisely the assumption of the near-Earth neutral line model, which has not the problem of reconciling a coincidence between the site of its local dissipation region and some macroscopically determined fiducial feature.) Thus a microinstability onset mechanism answering to the Kiruna conjecture has a problem in explaining why the instability, which by its nature depends only on local conditions, occurs at a place determined by macro-scale conditions. It might be that local conditions do not reach the threshold for the instability anywhere else except at that unique macroscale place, and this, indeed, is the position held by those wanting to hold on to both the Kiruna conjecture and a micro-instability onset mechanism. Still, the current-shunting hypothesis offers an alternative scenario that needs no special pleading. In this scenario, onset automatically occurs at the inner edge of the plasma sheet because only there can the energy transfer take place that makes the scenario work.

The current-shunting hypothesis has the at least virtue of making a relatively clean and testable prediction: the dayside region 1 currents should markedly weaken simultaneously with the growth of the current wedge. For the purpose of testing this prediction, the data analysis technique known as assimilative mapping of ionospheric electrodynamics (AMIE) is particularly well suited. It can be used to monitor the strengths of the dayside Birkeland currents and the current wedge through all phases of a substorm, in particular, through the transition from the growth phase to the expansion phase.

This note reports the application of the AMIE technique to test the current-shunting hypothesis. The result is that instead of weakening, the dayside Birkeland currents tend to strengthen during the expansion phase. Thus the test does not support the hypothesis, but tends to refute it.

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There is an interesting by-products of the test. The strengthening of the dayside Birkeland currents during the expansion phase has not previously been noted. Thus the result adds to the body of empirical information on substorm phenomenology.

The Test

The test is straightforward. We are looking for a shift in Birkeland currents from the dayside to the nightside at the onset of the substorm expansion phase. The current-shunting hypothesis calls for a major current shift, of the order of 1 MA. Such a shift should stand out in even a crude analysis. Therefore to look for the shift, it should be sufficient to partition the area of analysis (the polar region in the northern hemisphere north of 50° latitude) into local time quadrants: prenoon, postnoon, premidnight, and postmidnight. In each quadrant, we then compute the total up and down Birkeland currents of the region 1 sense and plots these as a function of time. Noting the behavior of the separate currents at times of substorm expansions as given by the AL index then shows whether the predicted current shift occurs.

Along with line plots of total region 1 sense currents in local time quadrants for the substorms discussed below, we have examined the corresponding contour plots of Birkeland currents at 5 min intervals covering the growth and expansion phases. The contour plots confirm the conclusions reached on the basis of the line plots.

The field-aligned currents used here are derived from the AMIE technique [*Richmond and Kamide*, 1988] for three substorms that occurred on March 29, 1992, July 20, 1992, and August 2, 1991. These are times for which northern hemisphere data coverage was particularly good and, therefore, for which the results of the AMIE technique are particularly reliable. The AMIE technique provides realistic ionospheric conductances by modifying statistical conductance models with various direct and indirect observations. The auroral contribution to the height-integrated Hall and Pedersen conductances are calculated by considering the total energy fluxes and average energies of the precipitating electrons [*Robinson et al.*, 1987] measured by the NOAA 12 satellite and the DMSP satellites that were operating during the events, four for the March 29 event and three for the other two events. In addition, magnetic perturbations as measured by ground magnetometers are used to modify the ionospheric conductivities [*Ahn et al.*, 1983] and provide an improved temporal and spatial resolution of the-high latitude ionospheric conductances. The detailed fitting procedure has been described by *Richmond and Kamide* [1988]. We believe that due to the good data coverage during the three selected periods (e.g., multiple satellites, more than 90 ground magnetometers, and several radars), the mapping of the electric field and ionospheric conductivity is sufficiently accurate to estimate the large-scale distribution of field-aligned current. (For a detailed description of the March 28-29 period, see *Lu et al.* [1996].)

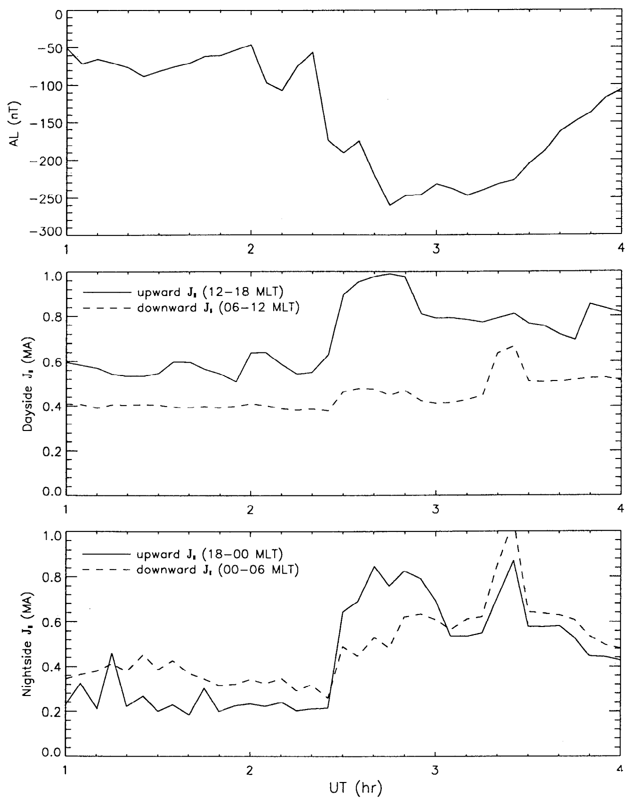

Figure 2. Same as Figure 1 for the April 1, 1986, substorm interval.

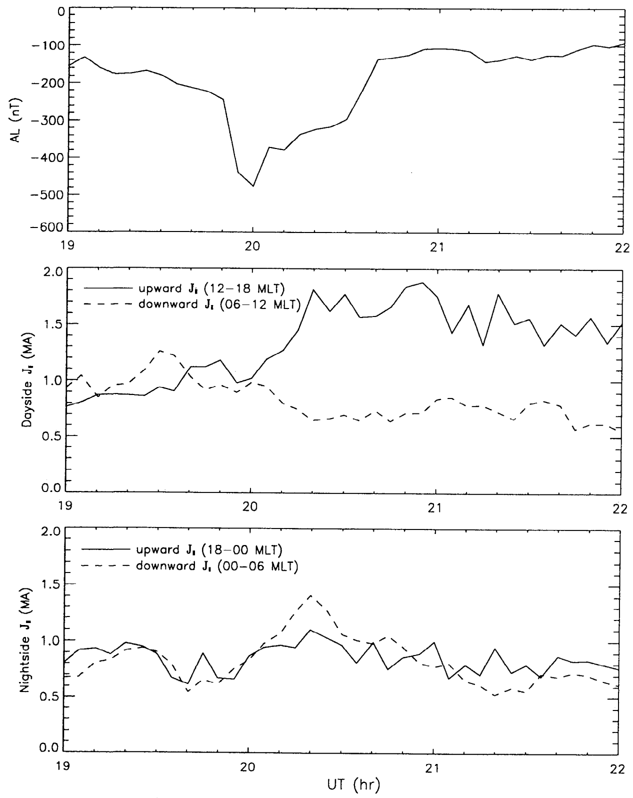

Figure 1. (top) The AL index, (middle) the strengths of the field aligned currents of the region 1 sense in the two dayside quadrants, and (bottom) the strengths of the field aligned currents of the region 1 sense in the two nightside quadrants for the March 29, 1992, substorm interval.

These dates of the three chosen events lie in seasons during which the dayside ionosphere in the northern hemisphere was in daylight, which means that the dayside conductivity was high enough to expect the dayside region 1 currents to have approached their full growth-phase strengths. This condition is a prerequisite for a good test of the current-shunting hypothesis. Winter hemisphere conditions would in general not satisfy this prerequisite.

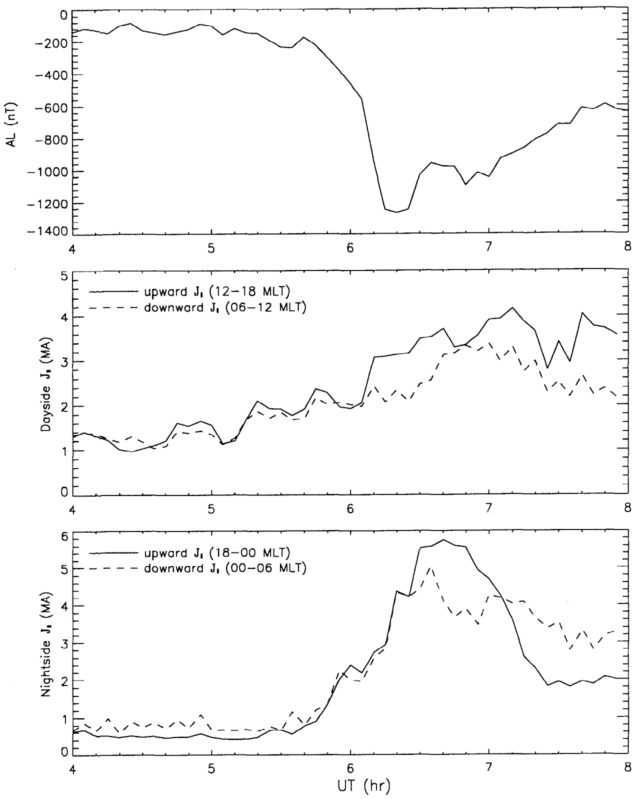

Figure 3. Same as Figure 1 for the July 20, 1992, substorm interval.

Figures 1, 2, and 3 show the relevant data fields for the three substorms. In each figure, the top panel gives the AL index as an indicator of substorm phase. The middle panel gives the strengths of the region 1 sense currents for the two dayside quadrants (downward for the dawnside quadrant and upward for the duskside quadrant). The bottom panel gives the strengths of the currents that have the sense of the substorm current wedge for the two nightside quadrants (also of the region 1 sense, as just described). Note that the AL index plotted in the top panel is based on ground magnetic perturbations measured by all stations that are located between 55 and 76 magnetic latitudes north and south (i.e., 63 stations for March 29 and 55 stations for the other two dates).

Before interpreting the figures in terms of the test of the current-shunting hypothesis, we note that for the March 29 and July 20 events, the dayside currents do not balance. The maps of current contours show, however, that the imbalance is taken up by the region 2 currents.

To appreciate the message in these plots, recall what one would expect according to the current-shunting hypothesis: at the onset of the expansion phase, as indicated by a sharp drop in AL, the dayside region 1 currents should weaken and simultaneously, by the same amount, the currents in the substorm current wedge should strengthen. Thus, in Figures 1-3, the signature of current-shunting is a drop of the trace in the top panel that lines up with a drop in both traces in the middle panel that, in turn, lines up with a rise by the same amount in both traces in the bottom panel.

Instead, we see that when the trace in the top panel drops, the traces in the middle panel remain virtually unchanged or rise along with the rise of the traces in the bottom panel, though not as much. The only exception occurs in the dayside-dawn quadrant for the March 29 event, where there is a drop in current around the time of the expansion phase. However, it fails to match the expectations of the current-shunting hypothesis in too many respects to be taken as support for the hypothesis. For instance, the drop starts after the expansion phase is well developed, and it is too small to be taken as the source of the current wedge current, which in any case begins rising earlier. The signature of current shunting is not present. The absence seen here of a distinct current-shunting signature at the onset of the substorm expansion phase holds also for all cases we examined, including AMIE analyses of southern hemisphere data.

Conclusion and Implications

Field-aligned currents of the region 1 sense (which include the substorm current wedge) do not exhibit a current-shunting behavior at the transition between the growth and expansion phases of a substorm. That is, by the evidence presented here, the onset of the expansion phase is not a consequence of some portion of the dayside region 1 currents shunting to the nightside to become the substorm current wedge. Instead, region 1 sense currents tend to increase in all quadrants beginning with the expansion phase. Contour plots of field-aligned currents suggest that this behavior is the result of the activation of convection type field-aligned currents (the so-called DP 2 current system) at the same time as the activation of the substorm current wedge (the so-called DP 1 current system). The close correspondence between these current systems has long been known [*Nishida et al.*, 1966, *Nishida*, 1968]. For examples of the simultaneous presence of both current systems, see *Kamide and Kokubun* [1996] and *Lu et al.* [1996]. The field-aligned currents associated with the DP 2 (convection) current system has the region 1 sense and extends over all four quadrants. We simply note that the activation of both current systems during the substorm expansion phase would account for the behavior of the region 1 sense currents as reported here.

The current-shunting hypothesis was proposed as an example of a global mechanism for initiating the substorm expansion phase within the framework of the Kiruna conjecture. The desirability of searching for global onset mechanisms was advocated because of a concern over a problem local onset mechanisms have in explaining the globally aware positioning of the site of onset (namely, near midnight at the threshold to the tail which is roughly the distance to the dayside magnetopause). A global mechanism has the possibility of automatically relating the local onset site to macroscale conditions with no additional assumptions. While this study gives evidence that the global current-shunting mechanism does not operate, it does not remove the desirability of seeking global onset mechanisms as a way to probe the viability of the Kiruna conjecture.

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