The macroscale evolution of the substorm injection

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Abstract: Particle injections occur during most, if not all, substorm expansive phases. Although it has yet to be worked out, there is clearly a relationship between the various macroscale expansive phase features which include not only the injection, but also the current disruption, fast flows, formation of the near-Earth neutral line, the dipolarization, auroral brightenings, Pi2s and PiBs, and more. In recent work, Spanswick et al. [13] have demonstrated that it is possible to identify a dispersionless injection using ground-based riometers, regardless of the fact that *in situ* identifications of these events are based on information from multiple particle flux energies. This work opens up the possibility, for the first time, of tracking the spatio-temporal evolution of the injection region (alternately the evolution of the injection boundary), at least as projected along magnetic field lines into the ionosphere. In this paper, we present initial results of a statistical survey of data from the CANOPUS (now NORSTAR) riometers. Based on these initial results, we argue that the dispersionless injection begins as a radially localized, azimuthally extended region that is, on average, beyond 8 Re in radial distance from the Earth. Once begun, the injection region as inferred from the riometer data expands both poleward (tailward) and equatorward (Earthward), although the equatorward expansion of the process appears to be limited to roughly 2° degrees latitude. Further, we carry out a superposed epoch analysis on a subset of our dispersionless injection events and fast flows as observed by Geotail when it is in the Central Plasma Sheet (CPS). Our results indicate that when a field line is engulfed by dispersionless injection (ie., by either moving across the injection boundary or as a consequence of the field line threading the initial injection region), instruments on a satellite on that field line in the CPS would detect fast flow starting at that same time. These initial results, though preliminary, point towards the expansive phase onset being on field lines that thread the inner CPS. Finally, we discuss the implications of this work for the upcoming NASA Time History of Events and Macroscale Interactions in Substorms MIDEX mission.

1. Introduction

The dramatic changes in the magnetospheric magnetic field, convection, and particle populations that occur during the substorm expansive phase give us significant clues about the macro- and micro-scale processes that are at work. These changes start with expansive phase onset, and include the dipolarization, formation of the substorm current wedge, injection, electron and proton auroral brightening, current disruption, fast flows, Pi2s and PiBs, and formation of the near-Earth neutral line. Although it is obvious that there interrelationships between these phenomena, attempts to elucidate a complete picture of these dynamics, including an understanding of cause and effect, have been frustrated by limitations in observation. It is widely held that sorting out these interrelationships would answer the long-standing question of what macroscale instability causes (or is) substorm expansive phase onset. Over the years, this has driven a multitude of event studies using extensive combinations of satellites and ground-based instrumentation. It is also the primary scientific objective of the upcoming NASA Time History of Events and Macroscale Interactions in Substorms (THEMIS) mission.

The desire to understand the macroscale substorm dynamics has been a motivation not only for event studies, but also for work aimed at developing observational tools for better characterizing the ionospheric and magnetospheric substorm dynamics. Work that would fall under this category includes the development of methods to infer the open-closed field line boundary from auroral redline emissions and the magnetic field stretching in the inner Central Plasma Sheet (CPS) from *in situ* ion precipitation measurements [3, 11]. These two studies in particular led to techniques for tracking changes in the magnetosphere using ground-based instruments. Although information so obtained is always *compromised* in some way, at the very least because it is a projection of information along magnetic field lines into the ionosphere, it is tremendously valuable because ut provides us with the possibility of tracking the substorm dynamics on a global scale. Recent work has shown that the injected electron population can be seen in riometers as an azimuthally drifting signature, and that the proton aurora is enhanced by injected protons [6, 4]. In recent work (see below), [13] have shown that riometers can be used to unambiguously identify dispersionless injections. This adds the injection to the growing list of magnetospheric processes that can be investigated using remote sensing of their ionospheric projection. In this paper, we discuss why riometers are an important tool for studying the injection, some specific new results, and how riometers will play an important role in the upcoming THEMIS mission.

Injections are dramatic increases in the fluxes of high energy electrons and protons in the CPS that occur during substorm expansive phase. These enhanced fluxes are a consequence of some combination of transport and energization. When the enhancements occur simultaneously (for practical purposes across several channels separated by at least tens of keV in less than two minutes) across a number energy channels, the injection is said to be *dispersionless* [2]. A dispersionless injection indicates that the satellite is in the region where the energization and/or transport is taking place. Significant dispersion indic-

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ates that the satellite is outside of that region (herein the "injection region"). The dispersion results from energy dependent primarily azimuthal drifts. Until recently, the injection has been exclusively studied by *in situ* observations, most often with the Synchronous Orbit Particle Analyzers (SOPA) on the Los Alamos National Laboratory (LANL) geosynchronous satellites.

Based on statistical studies using the SOPA data, it is now understood that dispersionless injections occur most often within a region centred about midnight but with ion injections displaced a half hour in local time to the west and electron injections displaced the same amount to the east [14]. [7] traced both ions and electrons observed in a dispersed injection with energies characteristic of relevant energy channels back to the point at which they would have been dispersionless to establish the azimuthal extent of the dispersionless injection on the drift paths that pass through the LANL satellites. Given that the LANL satellites are at geosynchronous orbit, the particle drift paths did not allow for exploration of the radial evolution of the injection region. For example, if the injection region formed outside of geosynchronous then the *Reeves et al.* analysis of the SOPA data provides a picture of the injection front as it passes through the geosynchronous region. [5] used Combined Release and Radiation Effects Satellite (CRRES) Medium Energy B (MEB) electron data to explore the distribution in radial distance of dispersionless injection (CRRES sampled a much broader range of L-shells than do the geosynchronous satellites). Their results indicated that the injection region forms at a range of L-shells, and in some events they managed to demonstrate an outer limit to the initial injection region. In another study, [10] used data from the LANL SOPA and CRRES MEB detectors, when the satellites were relatively close in space, to explore the radial motion and location of the injection region as it formed. Although their study was limited to the relatively few events where CRRES was near to a LANL satellite when both detected a dispersionless injection, they were able to infer that the injection region typically moves earthward inside of geosynchronous and forms within a few Re of geosynchronous orbit. The picture that has evolved from this and other work is that the injection forms in the pre-midnight sector, and is often, if not always, initially radially localized.

In a recent study, [13] have demonstrated that it is possible to use riometer data to identify a dispersionless injection in the magnetically conjugate CPS. Their work was motivated by an earlier study by [1] who showed that riometer absorption is very correlated with the integrated high energy electron flux measured at a satellite magnetically conjugate to that riometer, provided the conditions in the magnetosphere support strong pitch angle scattering of the electrons in that energy range. [13] reasoned that if one could develop a criterion for identifying a dispersionless injection from the integrated electron flux as measured at the satellite, then subject to the pitch angle scattering criterion being met, we should be able to accomplish the same thing using riometer data. If this is possible, then networks of riometers could be used to track the spatio-temporal evolution of the injection region with even one second time resolution. Of course, the results would be subject to the normal constraints on mapping that apply to all ionospheric observations that serve as a proxy for magnetospheric processes and boundaries; however, the riometer data can be placed in an appropriate context by comparing it directly with the other ionospheric data. For example, we could investigate the relationship between dipolarization, current disruption, and injection by using ground-based magnetometer, photometer, and riometer data.

Spanswick et al. [13] did find that there was a simple criterion the could apply to integrated MEB electron flux that *unambiguously* identified dispersionless injections as determined from the energy resolved data. Their criterion was that the electron flux rose to its peak value in less than 3 minutes, stayed elevated for at least 15 minutes, and was associated temporally with a substorm onset as identified by other observations. While every event identified with this criterion was a dispersionless injection, the criterion does not allow us to identify every such event. That is, this criterion misses some dispersionless injections that are clearly evident in the energy resolved data. [13] went on to find 15 events where CRRES was magnetically conjugate to the Canadian Auroral Network for the OPEN Unified Study (CANOPUS) network of single beam riometers. In each of these cases, the riometer data satisfied the criterion that was used to identify the dispersionless injection in the MEB integrated electron flux. As well, [13] went on to present the results of an extensive survey of the CANOPUS Gillam (ostensibly at or near geosynchronous) riometer data, and demonstrated that events that have this signature identified in the riometer data have essentially the same MLT distribution as do dispersionless electron injections identified by LANL SOPA. Given these results, [13] asserted that they are able to identify the dispersionless electron injection using the riometers, thus openning the door for more extensive studies of the spatio-temporal evolution of the injection region.

In this paper we present some additional results from the CANOPUS riometer data. In section 2, we explore the radial location of the initial injection region as projected along magnetic field lines in the ionosphere. In section 3, we use GEOTAIL INSTRUMENT data to study the relationship between the dispersionless electron injection and expansive phase fast flow in the CPS. Finally, in section 4 we summarize our results and point towards the future, with a particular eye on an upcoming and significant enhancement of the Canadian riometer network, and what that means for the upcoming THEMIS satellite mission.

2. The Radial Extent and Location of the Injection Region as it Forms

As discussed above, [5] showed that the injection at least sometimes forms on L-shells probed by CRRES with a clear tailward boundary. This result is consistent with an initial disturbance in the inner plasma sheet; however more work needs to be done. Even if the injection forms in the inner CPS region typically associated with current disruption, that does not mean it was not caused by something that happened further downtail. As well, the [5] study did not find this radial localization in all events, just a subset of those examined. Clearly, more work needs to be done to explore the radial extent of the initial injection region and its relationship to other substorm macroscale phenomena.

In this section, we use data from the CANOPUS "Churchill-line" riometers, which is aligned roughly along a geomagnetic meridian, and spans latitudes ranging from L=4.3 (Pinawa) up to well inside the typical polar cap. In particular, we use data from Pinawa (L=4.3), Island Lake (L=5.5), Gillam (L=6.7), Fort Churchill (L=8.2), Eskimo Point (L=10.2), and Rankin Inlet (L=12.4). Gillam would map to very near geosynchronous in the absence of magnetotail stretching, and Rankin Inlet would typically be inside the polar cap at expansive phase onset. These data provide an opportunity to explore the radial extent and location of the injection region as it forms.

2.1. Radial Extent

We surveyed 2 years of data from the Churchill line and manually identified all dispersionless injections according to the criteria of [13]. We are unable to find a single event in which a dispersionless injection was seen simultaneously at two riometers separated in latitude. There is always an unambiguous “start” of the injection at one station, flowed by an expansion on the timescale of 10’s of seconds which can engulf as many as 4-5 riometers along the Churchill line. The spacing between the stations combined with a $\sim 60^{\circ}$ beam width gives a separation between the instruments of approximately 1-2Re in the equatorial plane (obviously dependant on the magnetic configuration). This requires that the initial injection region form in a radially thin region such that the absorption would never be seen in two beams simultaneously. That puts an upper bound on the width of the injection region (when it forms) of about 1 Earth Radii.

2.2. Radial Location

From the same survey of the Churchill line we are able to compile statistics of the onset location (in latitude) and radial propagation characteristics. The majority of injection “onsets” along the Churchill line occur at Gillam (L=6.7) while the bulk of the injections are seen at Churchill (L=8.2). This is an artifact of propagation seen on the ground. We tend to see poleward motion of the injection region for most substorm injections, but equatorward motion is not guaranteed. For example, the vast majority of injection onsets observed at Gillam will also propagate poleward to Churchill. Those onsets that occur at Churchill will not necessarily propagate equatorward to Gillam. This preferential poleward motion for the ground-based mapping of the injection region skews the occurrence statistics, placing more injections at Churchill while the onset typically happens at Gillam. This implies that the radial location for the formation of the injection region is outside of geosychronous, probably at distances of 8-10 Earth Radii down tail (again, depending on the magnetic configuration). This also implies that a fair number of injection will likely not reach geosynchronous orbit. They occur at higher latitudes and are not able to reach L=6.6.

3. The Relationship Between Fast Flows and Dispersionless Injections

Fast flows in the CPS are commonly observed during substorm expansive phase. They are related to the expansive phase change from stretched to dipolar, however the cause and effect issues have not been resolved. In other words, these flows can be either launched from a forming neutral line in the mid-tail or represent material being drawn in by a collapsing current sheet in the inner CPS. This problem plagues our field, and will be a central issue in the upcoming THEMIS mission. Furthermore, the fast flow is crucial mode of transport between the current disruption and near Earth neutral line regions, and so sorting out the relationship between, for example, the fast flow and the dispersionless electron injection can be expected to be an important contribution to the overall resolution key substorm questions.

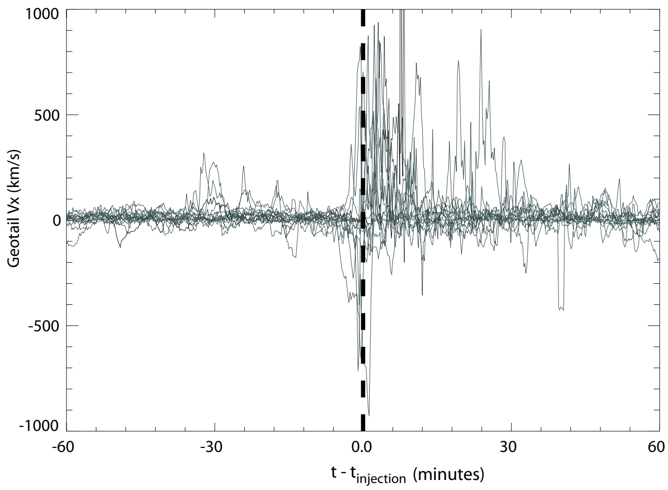

Fig. 1. Geotail flow (V_x) for the 14 events used in this study. $t_{injection}$ corresponds to onset of a dispersionless injection seen in the riometer closest to the footpoint of Geotail.

In this section we use data from the CANOPUS riometer network and the Geotail Low Energy Particle experiment (LEP) to investigate the relationship between fast flows in the CPS and the dispersionless electron injection. There are 14 events in the CANOPUS riometer data set for which: (1) Geotail is in the near Earth plasma sheet, (2) Geotail maps to the Canadian sector, (3) there is a dispersionless injection as identified by the CANOPUS riometers, and (4) Geotail does not enter the lobe during the growth phase. These events offer the best chance of simultaneously observing plasma sheet flows and the onset of the injection.

For all events, there was an associated plasma sheet flow and the time delay between the flow seen at Geotail and the injection was smallest for the riometer located the closest to the approximate footpoint of the Geotail satellite. The injection could be seen prior to the flow, but this always corresponds to a riometer not in the meridian of Geotail. In those cases, as the injection region expanded to the riometer closest to the footpoint, the flow would be seen at Geotail.

Figure 1 shows the timing between injection onset and earthward flow seen at Geotail. Again, this is for the riometer closest to the approximate footpoint of the Geotail satellite. The onset of the flow is within 1-2 minutes of the onset of injection seen in the riometers. The majority of the flow is earthward (positive) and occurs after the onset of injection. Within our set of events there are also 4 events over the Churchill line, where we have radial coverage with the riometers. For those events the onset of flow was still observed at the same time of injection onset and there was no evidence of activity in the riometers poleward of the onset station.

4. Discussion

We have used data from the CANOPUS riometer network to study the radial extent and location of the dispersionless electron injection. We found that with the resolution of riometers in the Churchill line (which maps to approximately 1-2Re resolution in the equatorial plane) we cannot simultaneously observe an injection in two stations separated in latitude. This puts an upper bound on the radial extent of the injection region as it forms. We also found that the injection region forms typically at latitudes of 67° invariant (Gillam), and then expands with a ground-based projection that is preferentially poleward.

In addition, we have used CANOPUS riometer and Geotail LEP data to study the relationship between the dispersionless electron injection and fast flows in the CPS during the expansive phase. We found 14 events for which Geotail maps to the Canadian sector, was the CPS, and a substorm associated dispersionless injection was observed in the CANOPUS riometers. For all of these events we found that the timing between earthward flow observed at Geotail and the injection seen on the ground was smallest ($\pm$ 1-2 minutes) for the riometer closest to the footpoint of Geotail. An injection can occur prior to the onset of high speed flow at Geotail, but as the injection region expanded to the riometer near the footpoint, earthward flow was observed. There are also 4 events for which the location of Geotail maps to the Churchill line. For those events there is no evidence of activity in the riometers poleward of the injection onset location prior to onset.

We summarize our results as follows. The dispersionless electron injection always forms as a radially localized region, stengthening the earlier results of [10]. The injection region typically forms on field lines that map to outside of geosynchronous, and that are most likely in the transition region between dipolar and tail-like fields in the CPS (ie., 8-10 Re). The injection expands both tailward and Earthward. The Earthward expansion usually but does not always reach stations that are ostensibly at or near being magnetically conjugate to the geosynchronous region. Whenever Geotail was in the CPS during the expansive phase, and its instruments first detected a fast flow, the riometer that is closest to being magnetically conjugate to the satellite detected the signature of a dispersionless injection. Moreover, the riometer and geotail results indicate that at least in our subset of 14 events, we saw no evidence of flow preceding observations of dispersionless injection. Given the radial location of the initial injection region, and the flow results, we assert that the fast flows are initiated by the same process that initiates dispersionless injection, and that they begin in the same region.

The upcoming THEMIS satellite mission will involve 5 satellites on equatorial orbits with periods of integer numbers of sidereal days (3, 1, and 1 satellites with 1, 2, and 4 sidereal day orbits, respectively). These satellites will be relatively phased on those orbits so that all 5 come together in apogee conjunctions every 4 days. As well, the conjunction meridian will be locked over central Canada throughout the mission. Of particular relevance to this study, and future work that will follow

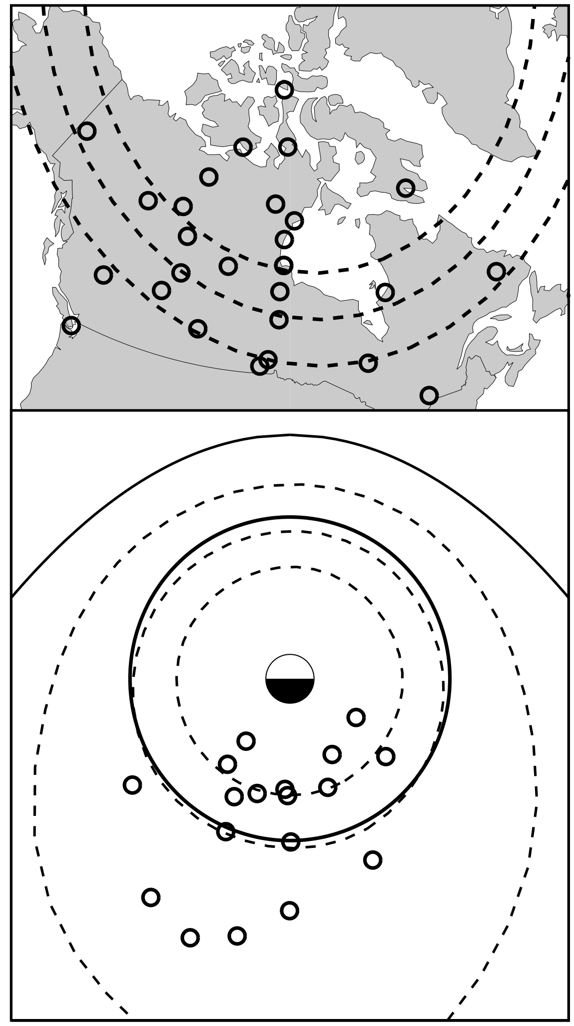

Fig. 2. The map at top shows the locations of the 13 existing NORSTAR riometers, as well as the riometers that Natural Resources Canada (NRCan) is planning to deploy in the summer of 2006. The three dashed contours on the map indicate 61°, 64° and 69° invariant magnetic latitude. The bottom plot shows the locations of the NORSTAR and planned NRCan riometers, as mapped to the equatorial plane using the T87 magnetic field model. The solid circle centered on the Earth indicates geosynchronous orbit.

from it, are the three THEMIS satellites that have one day orbits (and hence a mini conjunction every day), and that have apogees in the transition region between dipolar and tail like within which we think the injection starts. These satellites will provide observations of flows, dipolarizations, and injections in the region conjugate to the Canadian riometer network. This network will continue to operate during the THEMIS project as part of the Canadian GeoSpace Monitoring program (see http://cgsm.ca). In fact CGSM will boast a significantly enhanced riometer network during the THEMIS era (see Figure 2), operated by two separate CGSM program elements. NORSTAR (see http://cgsm.ca/norstar) will continue operation of the former CANOPUS riometers, and the Canadian Geological Survey will be deploying identical riometers at its

13 CANadian Magnetic Observatory System (CANMOS) sites and the four SuperDARN sites that are in Canada.

In summary, the work presented here provides important insights into the nature of the dispersionless electron injection, and the substorm expansive phase. Furthermore, it lays the foundation for an exciting future in our ability to track the substorm dispersionless electron injection. During the THEMIS era, our community will have at its fingertips data from three satellites in the region where the dispersionless injection typically forms. Furthermore, for all of those events, those satellites will be magnetically conjugate to a region within which 30 riometers will be operating. We will thus be able to follow the spatio-temporal evolution of the dispersionless injection from its very beginnings, with contemporaneous *in situ* observations of the dipolarization, fast flows, and the injection itself.

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