NEW PERSPECTIVES ON SUBSTORM INJECTIONS

Geoffrey D. Reeves
Los Alamos National Laboratory, Los Alamos, New Mexico, USA, 87545

Abstract. There has been significant progress in understanding substorm injections since the Third International Conference on Substorms in 1996. Progress has come from a combination of new theories, quantitative modeling, and observations – particularly multi-satellite observations. There is now mounting evidence that fast convective flows are the mechanism that directly couples substorm processes in the mid tail, where reconnection occurs, with substorm processes the inner magnetosphere where Pi2 pulsations, auroral breakups, and substorm injections occur. This paper presents evidence that those flows combined with an earthward-propagating compressional wave are responsible for substorm injections and discusses how that model can account for various substorm injection signatures.

1. Introduction

It has long been known that impulsive injections of plasma and energetic particles may be produced at geosynchronous orbit during substorms [e.g.. *Arnoldy and Chan*, 1969; *McIlwain*, 1974; *Belian et al.*, 1981]. The injection of energetic particles near the inner edge of the plasma sheet is one of the most common and reliable indicators of substorm onset. At geosynchronous orbit where a large number of well-equipped satellites have operated, substorm injections are observed in association with nearly every substorm identified using other traditional substorm indicators such as auroral breakups, magnetic bays, or Pi2 pulsations irrespective of the 'type' of substorm. They are most often studied in association with isolated substorms where the characteristic signatures and timings are clear. However multiple injections are also observed during so-called multiple-onset substorms; injections are frequently observed in association with "pseudobreakups"; and rather complex, nearly continuous injection activity is commonly observed during storm-time substorms. Therefore particle injections should be considered a *fundamental* characteristic of the substorm process – one which should be an intimate part of any successful substorm model.

The characteristic signature of a substorm injection is an increase in the fluxes of energetic particles (10s to 100s of keV) above their pre-substorm levels. When the fluxes at different energies increase simultaneously the injection is called "dispersionless". The region in which the substorm injection is observed to be dispersionless defines the "injection region". After they are injected the particles undergo energy-dependent gradient-curvature drifts and can therefore be observed as dispersed injection signatures at locations outside the injection region. If injected particles complete one full drift orbit they are referred to as "drift echoes". The observation of dispersed injection signatures (particularly by multiple satellites) is an unambiguous indication of a substorm injection. In the thin plasma sheet of the midnight region abrupt changes of particle fluxes are frequently caused by changes in the local magnetic field. Those effects are adiabatic, they are only observed in a localized region, and they do not produce a propagating injection signature.

This paper attempts to collect and synthesize some of the advances in the study of substorm injections that has occurred since the Third International Conference on Substorms (ICS-3) which was held in Versailles, France in 1996. Since that time there have been advances in theory, modeling, and in observations. Theory and modeling have produced quantitative and testable predictions that allow their validity and utility to be tested against competing theories. Observational advances have been made possible by an increasing fleet of satellites producing more global observations, the maturity and availability of historical data sets, and by new observational techniques such as Neutral Atom Imaging.

2. Reconnection, Fast Flows, & Substorm Injections

In the 1980's the established view of the substorm injection process and its relationship to the overall substorm was based on the "Near-Earth Neutral Line" model [*Hones et al.,* 1979] and the "Convection Surge" model [*Moore et al.,* 1981]. In this view reconnection in the plasma sheet produced a diversion of the cross-tail current into the ionosphere, precipitation of auroral particles, heating of the plasma sheet, and a dipolarization of the magnetic field that convected those hot particles into the geosynchronous region (Figure 1).

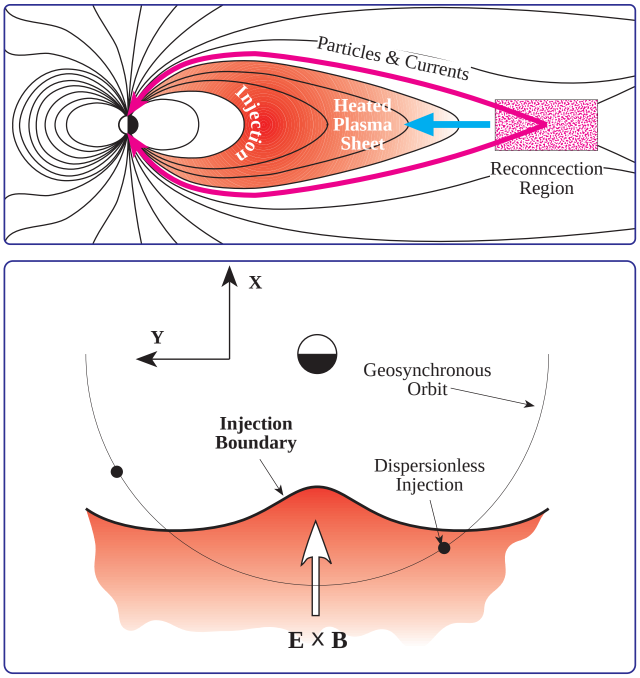

Figure 1. Schematic of the injection process based on the neutral line (top) and convection surge (bottom) models. The processes shown in this figure are described in the text.

However, several problems with this picture began to emerge in the early and mid 1990's. Studies of the location of the reconnection region have shown that it seldom forms inside of approximately 20 R_E [*Baumjohann et al.*, 1990; *Nagai et al.*, 1998]. In contrast the magnetic field lines on which the auroral breakup typically occurs appear to map to the region just outside geosynchronous orbit 6.6-10 R_E – which is also the region where substorm injections, Pi2 pulsations, and the substorm current wedge are observed [e.g. *Elphinstone et al.*, 1991; *Kennell*, 1992; *Reeves et al.*, 1996*a*; *Samson et al.*, 1992]. Therefore, at the time of ICS-3, much of the debate in substorm physics centered on whether reconnection and plasmoid formation were a cause or a consequence of inner magnetospheric processes [e.g. *Lui et al.*, 1990; *Lopez et al.*, 1990; *Reeves et al.*, 1992].

While the debate about the precise onset mechanism responsible for substorms continues, recent observations and modeling efforts allow us to construct a new framework in which to interpret substorm injections and their relationship to other substorm processes. Figure 2 is a schematic diagram that tries to represent a growing consensus on this framework. We will first try to explain what it represents and then present evidence for it – concentrating on how it helps organize the observations of substorm injections.

Figure 2 shows the equatorial plane with the Sun on the left. As in the near-Earth neutral line model reconnection begins in the tail, at the center of a very thin current sheet, and begins to form a plasmoid tailward of the neutral line. Unlike the near-Earth neutral line model this reconnection does not necessarily lead directly to any substorm signatures that are observable on the ground. Instead it produces strong convective flows that jet earthward and tailward from the reconnection region. (The color-coding represents the electric field strength based on a simulation by *Birn et al.* [1998].) When the flows approach the more dipole-like inner magnetosphere they are forced to slow and divert around the Earth. This slowing and diversion produces both strong inductive electric fields and vortical flows that in turn produce the field-aligned currents of the substorm current wedge [*Hesse and Birn*, 1992; *Birn and Hesse, 1998*]. While the fast flows do produce energization and transport [*Birn et al.*, 1997, 1998, Birn and Hesse, 1998] they do not appear to propagate into 6.6 R_E. Rather the braking of the flows appears to produce a compressional pulse that can further energize particles and transport them deep into the inner magnetosphere [*Li et al.*, 1998].

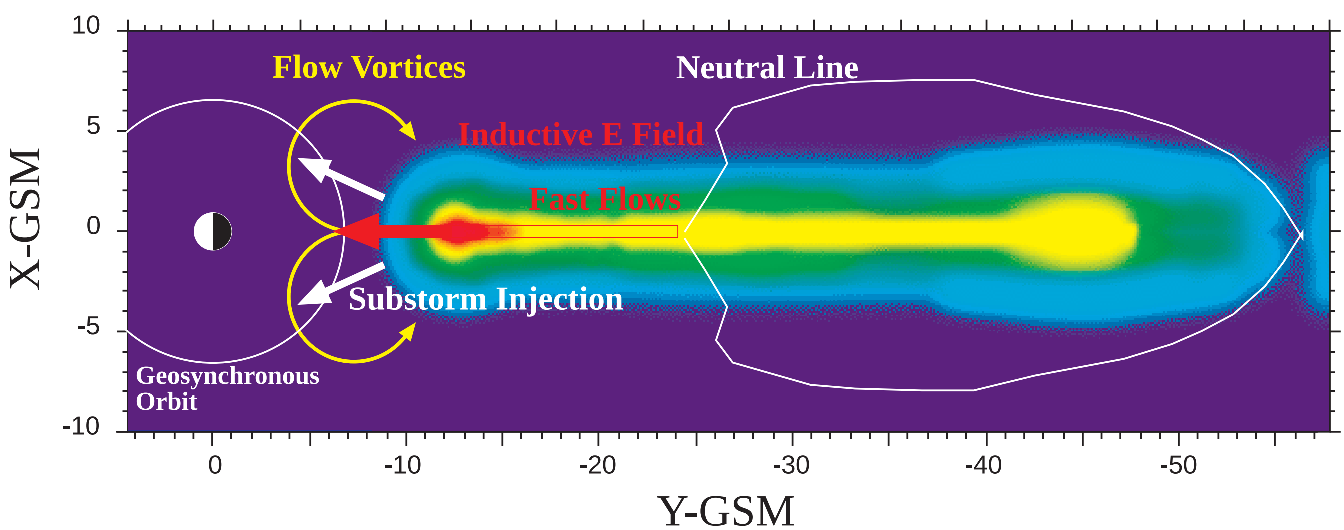

Figure 2. A schematic of the substorm injection. The color-coding represents electric field strength (based on a simulation by *Birn et al.* [1998].) In this model reconnection in the mid-tail initiates strong convective flows that jet earthward from the reconnection region. As the flows are slowed and diverted around the dipole-like inner magnetospheric field lines they launch a compressional wave which further energizes and injects energetic particles. The diversion of flow also produces vortices that drive field-aligned currents. While this model is similar in many respects to the neutral line and convection surge models, the fast flows play a central role in connecting mid-tail and near-tail substorm processes.

3. Evidence for Fast Flows and Near-Earth Braking

Perhaps the key feature of this picture of substorms is the central role that fast convective flows play in connecting the mid tail, where reconnection occurs, with the inner magnetospheric field lines where Pi2 pulsations, auroral breakups, and substorm injections occur. Evidence for the existence of fast flows inside of 20 R_E has been provided by *Baumjohann et al.* [1990] and *Angelopoulos et al.* [1992, 1994, 1996]. These flows were found to be earthward directed, convective, highly transient, and highly localized, but not always associated with traditional substorm signatures. More recently *Fairfield et al.* [1998*a*, 1998*b*] have shown examples of high speed flows measured by GEOTAIL that are clearly associated with substorms and, in fact, precede the observation of auroral breakups and substorm injections thus establishing that some subset of fast flows are substorm-associated.

The braking of fast convective flows as they reach the dipole-like inner magnetosphere has been studied by *Shiokawa et al.* [1998] They argue that while fast flows are only observed for a few minutes the braking of those flows causes pressure gradients that can perhaps drive the substorm current wedge continuously for 1-2 hours. They also showed that while flows in excess of several hundred km/s are relatively common, the occurrence frequency drops dramatically between -19 and 9 R_E where AMPTE-IRM made measurements. This is consistent with the study of *Reeves et al.* [1996*b*]. They studied dispersionless substorm injections using LANL geosynchronous and CRRES energetic particle measurements. They found that for the same substorm CRRES would consistently observe the dispersionless injection several minutes after the dispersionless injection was observed at geosynchronous orbit. A linear fit between delay time and radial separation gave an average propagation velocity of 24 km/s inside of 6.6 R_E.

4. Substorm Injection: Energization and Transport

The substorm model described in section 2 is only better for our purposes if it is more helpful in understanding the injection process than earlier models. In the neutral line/convection surge model transport was achieved through **E**×**B** drift and energization was achieved through betatron acceleration in the dipolarizing field [e.g. *Mauk*, 1986] and/or energization near the neutral line [e. g. *Baker et al.*, 1979]. However, transporting energetic particles from further than 20 R_E to less than 6 R_E without losing them to gradient-curvature drifts is problematic and attempts to quantitatively model injections due to betatron acceleration had not been successful, even when non-adiabatic effects are considered [e.g. *Delcourt et al.*, 1990]. The so-called "current disruption" model is not plagued with those problems because acceleration was postulated to be the result of an instability operating inside of 10 R_E such as ballooning [e.g. *Roux et al.*, 1991] or a current-driven instability [e.g. *Lui et al.*, 1993]. These models are newer and there have been few attempts to quantitatively model the injection process based on their hypotheses, but, as we will see they do not naturally account for the observed substorm signatures as well as the fast flow-based model.

Although the fast flow model is heavily based on the neutral line and convection surge models there are some fundamental differences. One of the most important results came from the simulations of *Birn et al.* [1997, 1998] which showed that the strongest electric fields in their MHD simulation were observed not near the neutral line but rather well earthward in the vicinity of the transition from tail-like to dipole-like magnetic field lines. Using test particle tracing in their MHD fields, *Birn et al.* were further able to show that this strong electric field region was the location of particle energization.

Li et al. [1998] have shown that the observed injection flux profiles can be reproduced using a relatively simple model in which an earthward propagating pulse of enhanced magnetic field strength (such as a compressional wave) is superimposed on the background magnetic field. As the particles surf this wave they are both energized and transported. In addition to showing remarkable quantitative agreement with observations this model helps explain how injections can propagate into the dipolar magnetic field regions inside 5 R_E [*Friedel et al.*, 1996; *Reeves et al.*, 1996*b*].

It is important to note that most of the results presented in this paper do not require reconnection or rule-out current disruption as the source of substorm onset. Any source that produces an earthward-propagating, convection-driven injection front can be expected to produce the same injection signatures. However, the model of *Li et al.* [1998] is in basic contradiction to the current disruption model. In the current disruption model the dipolarization is not associated with a compressional wave but rather with a rarefaction wave that propagates tailward [e.g. *Ohtani et al.* 1992] where it could possibly cause reconnection as a consequence. A rarefaction wave cannot produce particle acceleration through the process proposed by *Li et al.*

5. The Injection Region and Injection Boundary

Based on a statistical study of ATS data *Mauk and McIlwain* [1974] derived an expression for the ion injection boundary given as $R_b = (122 - 10\ Kp)/(LT - 7.3)$ where R_b is the radius of the boundary as a function of local time (LT) and magnetic activity (Kp). *Konradi et al.* [1975] extended the definition by assuming the boundary could be reflected about midnight to form a double spiral. As discussed above, the convection surge model of *Moore et al.* [1981] explained this boundary not as a time-stationary feature but rather as the earthward limit of a propagating "injection front".

Lopez et al. [1990] used AMPTE data to obtain the similar result $R_b = (140 - 17\ Kp)/(MLT - 10)$. However they interpreted the injection boundary quite differently. In their view the injection boundary was a limit of stability.

Behind that boundary the tail was assumed to be unstable and current disruption could produce a substorm injection. Earthward of that boundary the tail was assumed to be stable. Thus in their model the injection region had a true "boundary" in the traditional sense of delimiting two regions with quite different properties.

A refinement to the injection boundary picture was made by *Reeves et al.* [1991] who noted that the ion and electron injection regions could be slightly separated in local time such that a single satellite in the "injection periphery region" could observe a dispersionless electron injection with no ion injection or visa-versa. That result was greatly extended by *Birn et al.* [1997]. They found that in addition to an injection periphery region there were regions in which both electrons and ions showed dispersionless injections but that one was delayed with respect to the other and that the five regions (ion only, delayed electrons, simultaneous electrons and ions, delayed ions, and electron only) were well-ordered in local time. They explained this as the result of the earthward propagation of two azimuthally separated injection fronts for ions and electrons – a hypothesis that was well born out by their test particle simulations [*Birn et al.*, 1998].

In fact, it is well-known that electrons and ions have oppositely directed gradient-curvature drifts, so, if the earthward injection requires a finite time then separation of the two species is expected. This was one of the key factors that implied the source region for substorm injections was located outside – but not far outside – geosynchronous orbit. However, another important result of the simulation of *Li et al.* [1998] is that the propagating compressional wave locally reverses the magnetic field gradient and therefore can reduce or reverse the gradient drift (at least for 90° pitch angles). This process helps keep the ions and electrons together as they are injected earthward and allows particles to be transported (without significant azimuthal drift) to 6.6 R_E from tailward of 10 R_E where the simulations of *Birn et al.* [1997, 1998] and the observations of *Fairfield et al.* [1998*a*, 1998*b*] show that the effects of flow bursts are strongest.

We also note that the separation of the ion and electron injection regions does not imply that two satellites separated in radius cannot both observe dispersionless injections. At any given radius a dispersionless injection will be observed when the injection front passes that radius, bringing energized particles with it. Any azimuthal drift behind the injection front will not cause any radial energy dispersion. [See *Reeves et al.*, 1996*b*.]

6. Substorm Injection Energy Cut-Offs

It has long been known that substorm injections tend to have an upper energy cut-off. *Baker et al.* [1979] showed that only 20% of substorm injections included an increase of electrons with energies greater than ≈300 keV. As we have noted, *Li et al.* have shown that the gradient drift can be essentially switched off by a compressional wave. However, that effect will apply to particles of all energies. Therefore there must, in general, be a lack of source for >300 keV particles in the near-Earth tail. This might be expected if fast flows are responsible for acceleration and transport from the mid- and distant-tail. Particles with sufficiently high energy would gradient-curvature drift out of the fast flow region before they could gain appreciable energy or be transported large distances. Quantitative modeling of the upper-energy cut-off remains an outstanding problem which could illuminate the connection between the *Birn et al.* and *Li et al.* simulations.

It is less well-appreciated that substorm injections (at least as seen at geosynchronous orbit) often have a lower-energy cut-off as well. Figure 3 shows electron fluxes and spectra from three instruments on LANL satellite 1989-046. Fluxes and composite spectra from three instruments are shown: MPA, in blue, covers ≈0-40 keV; SOPA, in green, covers 50-700 keV; and ESP, in red, covers ≈0.7-8.0 MeV. This interval was during the November 1993 magnetic storm and is therefore fairly active. Several dispersionless injections were observed after 1230 UT (LT≈UT-11 hrs.) We see that, while the spectra are continuous, the plasma population below 40 keV at times appears to behave independently of the population above 50 keV. In particular the substorm injections at ≈1320 and 1510 UT do not appear to extend below 50 keV.

This low-energy cut-off can also be understood as a result of a convective injection process. At geosynchronous orbit, under most conditions, a 50 keV electron is stably trapped. At some lower energy the effect of the cross-tail electric field is to transport the electron sunward where it can be lost to the magnetopause. (See, for example, figures 4.26 and 4.27 from *Lyons and Williams* [1984].) Night-side geosynchronous observations with the MPA instrument often show a population that looks like it has a plasma sheet source and is probably on open drift trajectories while SOPA observations on the same satellite show a trapped population.

During substorm injections the strong inductive electric field changes the trapping boundaries in a localized region near midnight and for time shorter than a drift period. As shown by the numerical simulations, this allows new energetic particles from the tail to have access to geosynchronous orbit. When the inductive electric field is removed those particles become trapped. Thus, at those energies the injection is really an input of "new" particles that previously had no access to geosynchronous orbit. At lower energies though, particles had access to geosynchronous orbit from the tail both before, during, and after the substorm onset. Therefore, while the inductive electric field might bring particles in from the tail faster, it brings them in by the same process.

The lower-energy cut-off is not always the same. That may be due to the pre-onset electric fields and location of the energy-dependent trapping boundaries. The lower-energy cut-off is also not typically the same for electrons and ions, which is also expected since the drift paths and trapping boundaries are different for electrons and ions.

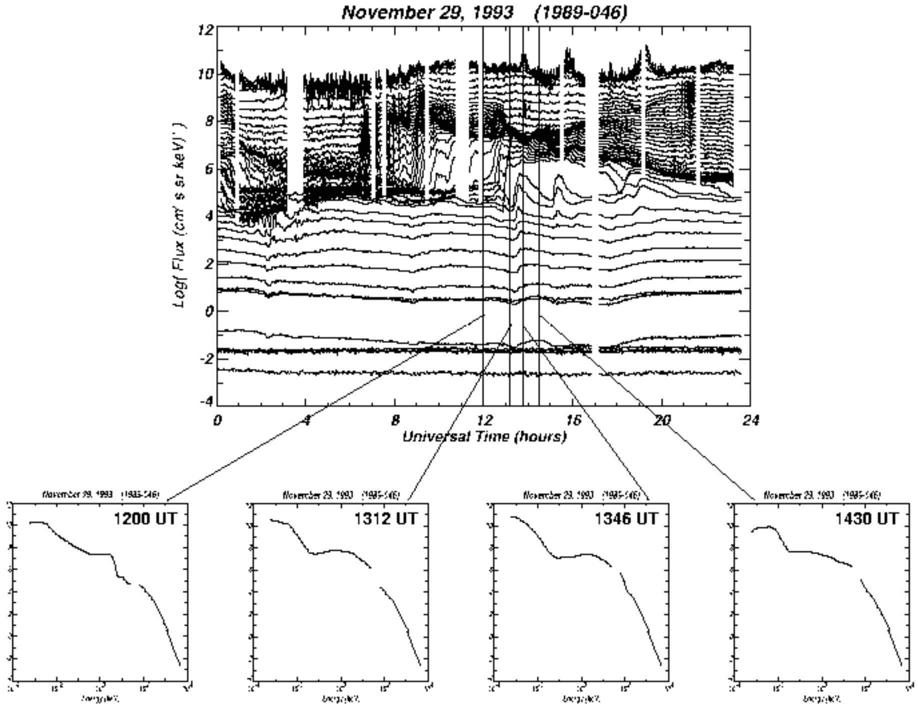

Figure 3. Data from three LANL particle detectors on geosynchronous satellite 1989-046. MPA, in blue, covers ≈0-40 keV; SOPA, in green, covers 50-700 keV; and ESP, in red, covers ≈0.7-8.0 MeV. Four spectra based on all three instruments are shown below. During substorm injections it is frequently seen that the electrons with energies of tens of keV show a large injection while lower energies remain essentially unchanged. This is attributed to the effect of energy- and species-dependent trapping boundaries.

This hypothesis may explain two other observations. Substorm injections seen outside geosynchronous orbit by AMPTE often look quite different from injections seen at geosynchronous orbit or inside geosynchronous orbit by CRRES. Dropouts and recoveries to pre-substorm flux levels are frequently observed. (See e.g. Figure 1 of *Lopez et al.* [1990].) Injections that increase the fluxes by several orders of magnitude are much less common in the AMPTE database but are much more common at geosynchronous orbit. This may be because AMPTE made most of its observations outside geosynchronous orbit. Likewise, during storm times, when the convection electric field is presumably large and the stable trapping boundaries move inward, individual substorm injections are sometimes difficult to identify in the geosynchronous database and even the energetic particle population begins to look like untrapped plasma sheet particles.

7. Conclusions

Since the Third International Conference on Substorms in 1996 there has been significant and substantive progress in our understanding of substorm injections and their relationship to other substorm processes. There is mounting evidence that fast convective flows are the mechanism that directly couple substorm processes in the mid-tail, where reconnection occurs, with substorm processes the inner magnetosphere where Pi2 pulsations, auroral breakups, and substorm injections occur. Simulations have shown that, when the flows are slowed and diverted around the obstacle formed by the dipole region, strong inductive electric fields form which both energize and transport particles. This naturally occurs at the transition between tail-like and dipole-like field lines. In the dipole region trapped energetic populations are enhanced by fresh energized particles from the tail. Strikingly different signatures can be seen as a function of radius, local time, energy, and species. Many of these features can now be modeled quantitatively by assuming an earthward-propagating injection front carried by a compressional wave.

A strong point of this model is that substorm injections are an integral part of the model just as they are an integral part of substorm observations. While many important and interesting questions about substorm injections remain, the field can undoubtedly be considered to be on more firm observational and theoretical ground than ever before.

References

Angelopoulos, V., F. V. Coroniti, C. F. Kennel, M. G. Kivelson, R. J. Walker, C. T. Russell, R. L. McPherron, E. Sanchez, C.-I. Meng, W. Baumjohann, G. D. Reeves, R. D. Belian, N. Sato, E. Friis-Christensen, P. R. Sutcliffe, K. Yumoto, and T. Harris, Multi-point analysis of bursty bulk flow events: 1. April 11, 1985, *J. Geophys. Res., 101*, 4967-4989, 1996.

Angelopoulos, V., C. F. Kennel, F. V. Coroniti, R. Pellat, M. G. Kivelson, R. J. Walker, C. T. Russell, W. Baumjohann, W. C. Feldman, and J. T. Gosling, Statistical characteristics of bursty bulk flow events, *J. Geophys. Res., 99*, 21,257, 1994.

Angelopoulos, V., W. Baumjohann, C. F. Kennel, F. V. Coroniti, M. G. Kivelson, R. Pellat, R. J. Walker, H. Lühr, and G. Paschmann, Bursty bulk flows in the inner central plasma sheet, *J. Geophys. Res., 97*, 4027, 1992.

Arnoldy, R. L., and K. W. Chan, Particle substorms observed at the geostationary orbit, *J. Geophys. Res., 74*, 5019, 1969.

Baker, D. N., R. D. Belian, P. R. Higbie, and E. W. Hones, Jr., High-energy magnetospheric protons and their dependence on geomagnetic and interplanetary conditions, J. *Geophys. Res., 84*, 7138, 1979.

Baumjohann, W., G. Paschmann, and H. Lühr, Characteristics of high-speed ion flows in the plasma sheet, *J. Geophys. Res., 95*, 3801-3809, 1990.

Belian, R. D., D. N. Baker, E. W. Hones, Jr., P. R. Higbie, S. J. Bame, and J. R. Asbridge, Timing of energetic proton enhancements relative to magnetospheric substorm activity and its implication for substorm theories, *J. Geophys. Res., 86*, 1415-1421, 1981.

Birn, J., and M. Hesse, Substorm effects in MHD and test particle simulations of magnetotail dynamics, (*this volume*).

Birn, J., M. F. Thomsen, J. E. Borovsky, G. D. Reeves, D. J. McComas, R. D. Belian, and M. Hesse, Substorm electron injections: Geosynchronous observations and test particle simulations, *J. Geophys. Res., 103*, 9235, 1998.

Birn, J., M. F. Thomsen, J. E. Borovsky, G. D. Reeves, D. J. McComas, and R. D. Belian, Characteristic plasma properties during dispersionless substorm injection at geosynchronous orbit, *J. Geophys. Res., 102*, 2309-2324, 1997.

Delcourt, D. C., J. A. Sauvaud, and A. Pedersen, Dynamics of single-particle orbits during substorm expansion phase, *J. Geophys. Res., 95*, 20,853, 1990.

Elphinstone, R. D., D. Hearn, J. S. Murphree, and L. L. Cogger, Mapping using the Tsyganenko long magnetospheric model and its relationship to viking auroral images, *J. Geophys. Res., 96*, 1467, 1991.

Kennel, C. F., The Kiruna conjecture: The strong version, in *Proceedings of the First International Conference on Substorms*, ESA SP-335, p. 599, ESA, 1992.

Fairfield, D. H., T. Mukai, A. T. Y. Lui, C. A. Cattell, G. D. Reeves, T. Nagai, G. Rostoker, H. J. Singer, L. M. Kaiser, S. Kokubun, A. J. Lazarus, R. P. Lepping, M. Nakamura, J. T. Steinburg, K. Tsuruda, D. J. Williams, and T. Yamamoto, Geotail observations of substorm onset in the inner magnetotail, *J. Geophys. Res., 103*, 103, 1998*a*.

Fairfield, D. H., T. Mukai, T. Yamamoto, M. Brittnacher, G. K. Parks, G. D. Reeves, S. Kokubun, K. Hashimoto, H. Matsumoto, and D. A. Gurnett, Earthward flow bursts in the inner magnetotail and their relation to auroral brightenings, AKR intensifications, geosynchronous particle injections and magnetic activity, *J. Geophys. Res., submitted*, 1998*b*.

Friedel, R. H. W., A. Korth, and G. Kremser, Substorm Onsets observed by CRRES: Determination of energetic particle source regions, *J. Geophys. Res., 101*, 13,137, 1996.

Hesse, M., and J. Birn, Relative timing of substorm features in MHD simulations, in *Proceedings of the First International Conference on Substorms*, ESA SP-335, p. 553, ESA, 1992.

Hones, E. W., Transient phenomena in the magnetotail and their relation to substorms, *Space Sci. Rev., 23*, 393, 1979.

Konradi, A., C. L. Semar, and T. A. Fritz, Substorm-injected protons and electrons and the injection boundary model, J. Geophys. Res., 80, 543, 1975.

Li, X., D. N. Baker, M. Temerin, and G. D. Reeves, Simulation of dispersionless injections and subsequent drift echoes of energetic electrons associated with substorms, *Geophys. Res. Lett., submitted*, 1998.

Lopez, R. E., D. G. Sibeck, R. W. McEntire, and S. M. Krimigis, The energetic ion substorm injection boundary, *J. Geophys. Res., 95*, 109-117, 1990.

Lui, A. T. Y., P. H. Yoon, and C.-L. Chang, Quasi-linear analysis of ion Weibel instability, *J. Geophys. Res., 98*, 153-163, 1993.

Lui, A. T. Y., A. Mankofsky, C.-L. Chang, K. Papadopoulos, and C. S. Wu, A current disruption mechanism in the neutral sheet for triggering substorm expansions, *Geophys. Res. Lett., 6*, 745, 1990.

Lyons, L. R., and D. J. Williams, *Quantitative Aspects of Magnetospheric Physics*, D. Reidel Publishing Co., Boston, MA, 1984

Mauk, B. H., Quantitative modeling of the "convection surge" mechanism of ion acceleration, *J. Geophys. Res., 91*, 13423-13431, 1986.

Mauk, B. H., and C. E. McIlwain, Correlation of Kp with the substorm-injected plasma boundary, *J. Geophys. Res., 79*, 3193, 1974.

McIlwain, C. E., Substorm injection boundaries, in *Magnetospheric Physics*, edited by B. M. McCormac, p. 143, D. Reidel, Hingham, Mass, 1974.

Moore, T. E., R. L. Arnoldy, J. Feynman, and D. A. Hardy, Propagating substorm injection fronts, *J. Geophys. Res., 86*, 6713-6726, 1981.

Nagai, T., M. Fujimoto, Y. Saito, S. Machida, T. Terasawa, R. Nakamura, T. Yamamoto, T. Mukia, A. Nishida, and S. Kokubun, Structure and dynamics of magnetic reconnection for substorm onsets with Geotail observations, *J. Geophys. Res., 103*, 4419, 1998.

Ohtani, S., S. Kokubun, and C. T. Russell, Radial expansion of the tail current disruption during substorms: a new apporach to the substorm onset region, *J. Geophys. Res., 97*, 3129-3136, 1992.

Reeves, G. D., L. A. Weiss, M. F. Thomsen, and D. J. McComas, Quantitative Experimental Verification of the Magnetic Conjugacy of Geosynchronous Orbit and the Auroral Zone, in *Substorms 3*, ESA SP-339, 187, 1996a.

Reeves, G. D., R. W. H. Friedel, M. G. Henderson, A. Korth, P. S. McLachlan, and R. D. Belian, Radial propagation of substorm injections, in *Substorms 3*, ESA SP-339, 579-584, 1996b.

Reeves, G. D., G. Kettmann, T. A. Fritz, and R. D. Belian, Further investigation of the CDAW 7 substorm using geosynchronous particle data: Multiple injections and their implications, *J. Geophys. Res., 97*, 6417, 1992.

Reeves, G. D., R. D. Belian, and T. A. Fritz, Numerical tracing of energetic particle drifts in a model magnetosphere, *J. Geophys. Res., 96*, 13,997, 1991.

Roux, A., S. Perraut, A. Morane, P. Robert, A. Korth, G. Kremser, A. Pederson, R. Pellinen, and Z. Y. Pu, Role of the near earth plasmasheet at substorms, in *Magnetospheric Substorms*, Geophys. Mono. 64, American Geophysical Union, 201, 1991.

Samson, J. C., D. D. Wallis, T. J. Hughes, F. Creutzberg, J. M. Ruohoniemi, and R. A. Greenwald, Substorm intensifications and field line resonances in the nightside magnetosphere, *J. Geophys. Res., 97*, 8495, 1992.

Shiokawa, K., G. Haerendel, and W. Baumjohann, Braking of high-speed flow and azimuthal pressure gradient as driving forces of substorm currents, (*this volume*).

Correspondence to: G. D. Reeves (+1-505-665-3877, Fax: +1-505-665-4414, E-mail: reeves@lanl.gov)