Near-Earth Breakup in Substorms: Empirical and Model Constraints

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Abstract. We present experimental evidence supporting a near-Earth breakup with constraints that can be outlined as follows. Breakup is an instability of the inner plasma sheet. It consists of an arc intensification in the form of a linear instability, followed by nonlinear vortex formation and spatial expansion. The latter corresponds to the explosive onset of short period (Pi1-Pi2) pulsations on the ground and at geosynchronous orbit, and formation of a current wedge confined within the breakup region. Stability analysis, both analytical and numerical, of the region where the magnetic field topology changes from dipolar to stretched revealed that this region can become linearly and nonlinearly unstable with respect to the low-$\beta$ ballooning type of modes. We demonstrate a model example when the instability starts with a relatively slow linear stage, that is a combination of the exponential growth and oscillatory mode, and is followed by a nonlinear (or explosive) stage. The resulting dynamics are consistent with the observed explosive onset of short period pulsations at breakup that follows a period of relatively slow breakup arc intensification.

1. Introduction

Following Akasofu [1977], it is well accepted that auroral breakup is the first indication of the substorm expansive phase. Comparing the short time scale of auroral breakup to other phases of substorm suggests that breakup is an optical signature of a magnetospheric plasma instability that may initiate the substorm expansive phase. The fact that expansive phase onset is typically associated with auroral breakups has led to ongoing debates over what mechanism triggers breakups and at what distances from the Earth the breakup process initiates. Here we revisit the breakup process itself using high resolution data to identify different stages of the breakup and their signatures. For this purpose, pseudo-breakups and breakups of small substorms provide more valuable information than full substorms due to their localized nature and relatively unperturbed background conditions.
We define pseudo-breakups as vortices that develop from an arc embedded in the proton aurora region, expand poleward but which do not perturb the poleward boundary of the electron precipitation region and, quite often, do not affect most arcs poleward of the breakup vortex. Pseudo-breakups are not associated with full substorm onset, though some lead to a localized electrojet at the breakup region. We refer to these disturbances as small or local substorms. Full substorm onset, on the other hand, have a large surge that reaches the poleward boundary of the plasma sheet as indicated by the 630 nm emission region and are followed by a rapid, on a time scale of minutes or less, propagation of the substorm electrojet to longitudes much beyond the initial breakup region. We illustrate the difference between these types of auroral breakups in Figure 1 which shows examples of a pseudo-breakup, a local substorm, and a full substorm onset as seen by the Gillam All Sky Imager (ASI).

Figure 1. Examples of 577.7-nm ASI images for a small growth phase pseudo-breakup (a), local substorm (b), and full onset surge following the equatorward breakup (c). White bars in (a) and (b) indicate latitudinal extent of the proton aurora band.

There are several essential features of auroral breakups, that have been reported. The breakup starts from the arc that lies equatorward of all other arcs and intensifies on a time scale of minutes [Akasofu, 1977] near the poleward edge of the proton aurora region [Samson et al., 1992; Voronkov et al., 2000a]. For several cases, Lyons et al. [2002] found that this equatorward “breakup” arc is a new arc that appears and intensifies a few minutes before breakup and is distinct from growth-phase arcs which may remain unperturbed until the breakup vortex reaches their latitude. In the near-Earth plasma sheet, these auroral breakups are associated with the start of short period (Pi1 and Pi2) pulsations [Roux et al., 1991] and the beginning of dipolarization that may follow a cross tail current enhancement in the near-Earth plasma sheet [Ohtani et al., 1992]. For several event studies, Lui et al. [1992] showed that the first pulse of short period pulsations can be interpreted as a signature of current sheet disruption in the near-Earth plasma sheet. However, other mechanisms, such as a sudden reduction in the strength of convection [Lyons et al., 1997], strong field line resonances [Samson et al., 1998], and ballooning or interchange types of instabilities [e.g., Hurricane et al., 1997, 1998; Bhattacharjee et al., 1998; Cheng and Lui, 1998] may play a crucial role in the region. Considering that every model of expansion phase onset provides a distinct temporal sequence of processes, theories can be tested via higher resolution observations of corresponding signatures. However, the relative timing of processes observed on the ground and in the near-Earth plasma sheet remains uncertain. Addressing this issue is one of objectives of this study.

We present recent results of breakup studies utilizing ground-based and in situ observations. Our objective is to outline the background conditions from which the breakup starts and the sequence of breakup stages characterized by specific signatures. Within the context of the constraints provided by observations, we present theoretical and computational models of the nonlinear near-Earth plasma sheet instability that may potentially be relevant to the breakup process. Although these two models are based on different principals, they yield not only consistency to one another but also are in reasonable agreement with observations of breakups.
2. Location of the Near-Earth Breakup

The relative position of a breakup arc and the proton aurora band may provide essential information with respect to where the breakup location maps in the magnetosphere. The equatorward edge of the proton aurora region corresponds to a boundary between isotropic (more tailward) and anisotropic (more Earthward) proton populations in the magnetosphere and is referred to as the isotropy boundary IB [Newell et al., 1998; Donovan et al., 2002]. At the same time, proton precipitation requires sufficient scattering of particles into the loss cone. Perhaps, the most accepted mechanism for this scattering is nonadiabatic proton motion on stretched field lines [Sergeev et al., 1983; Zelenyi et al., 1990; Sergeev and Gvozdevsky, 1995; Wanliss et al., 2000]. In fact, Zelenyi et al. [1990] showed that scattering of energetic protons increases sharply when the curvature of magnetic field lines $R_c$ becomes comparable with the proton Larmor radius $R_L$. More specifically, Zelenyi et al. [1990] found that this nonadiabatic scattering into a loss cone is peaked when the ratio $\kappa = (R_c/R_L)^{0.5}$ to be roughly in the interval from 1 to 3. This implies that the poleward boundary of the proton aurora band roughly corresponds to the magnetospheric region where the magnetic field lines change from dipolar to stretched.

Combining these with the relative position of the breakup arc and proton aurora, the following latitudinal profile can be drawn (Figure 2). A breakup arc intensifies poleward of the peak in the proton aurora and maps to the region between the dipolar and stretched field lines poleward of the IB. In turn, field lines threading pre-existing growth phase arcs map further into the stretched magnetotail.

In order to test the spatial distribution suggested above, we attempted a preliminary statistical study of the position of the outer (tailward) boundary of the hot proton population using Geotail data. Using the database for 1995-1999 and selecting dates when Geotail crossed the midnight sector at 8-14 $R_E$, 17 crosses of the tailward boundary were identified with the following criteria: the satellite was definitely in the plasma sheet at distances less than 1.5 Re from the equatorial plane and within $\pm2$ hours from the midnight meridian, and the observed average proton energy inside the region reached at least 10 keV. The main observed features were as follows. An average position of the hot proton boundary was found at $10.3^{+0.6}_{-0.7} R_E$. An average maximum energy observed by Geotail Earthward of the boundary was $13^{+1}_{-1}$ keV. The ratio of the total magnetic field to the dipolar magnetic field at the point where the highest average proton energy was registered was $0.97^{+0.12}_{-0.06}$ becoming significantly reduced tailward of the boundary. Essentially, these results require more detailed in situ data analysis. However, we believe that these are consistent with the observations discussed above.

Overall, observational features discussed above suggest that breakup occurs in the near-Earth plasma sheet at equatorial radial distances of roughly $10 R_E$, in the region corresponding to the transition from a dipolar to a stretched magnetic field line topology.

3. Elements of the Breakup

As mentioned in the Introduction, a near-Earth breakup consists of a sequence of signatures observed from the ground and in the near-Earth magnetotail. In this section, we present the
sequence of main breakup stages as observed by the CANOPUS high-resolution photometer and ASI instruments and as seen from the geostationary GOES 8 spacecraft.

Figure 3 is a summary plot of the magnetic field at GOES 8, high-resolution Gillam photometer data, and Gillam all-sky images for an event study of a small local substorm. Figure 3 is a combination of Figures 5 and 6 in [Voronkov et al., 2002]. The first signature of the breakup was an arc intensification at the equatorward boundary of the electron precipitation region roughly corresponding to the poleward slope of the proton aurora band. The arc grew in intensity for $\sim 4$ minutes during the late growth phase. At geostationary orbit, this corresponded to the final stretching of the magnetic field lines. At $\sim 0353$ UT, the intensification of the breakup arc saturated and the breakup vortex started expanding poleward. This corresponded to the beginning of the rapid dipolarization at geostationary orbit. At this time, an explosive onset of short period pulsations was observed by GOES 8 ($\Pi_2$ at $\sim 18$ mHz and $\Pi_1$ at $\sim 46$ mHz), and by ground-based magnetometers ($\Pi_2$ at $\sim 18$ mHz) surrounding the breakup vortex region. Saturation of the vortex expansion by $\sim 0400$ UT corresponded to the decay of these short period pulsations.

Using the CANOPUS database of breakups for 1996 and 1997, and corresponding GOES 8 data, we attempted a statistical study of timing for these breakup elements. We illustrate the results in Figure 4 for 26 breakup events identified in the field of view of the Gillam ASI. All elements are related to the time of the optical breakup, namely to the time when a breakup vortex was first observed by the ASI. A precursor breakup arc intensifies roughly 4-5 minutes prior to the breakup. The optical breakup coincided (within $\sim 1-2$ min) with the start of dipolarization at geostationary orbit and with the onset of short period pulsations.

Summarizing this section, we suggest that breakup consists of two main stages. The first is a gradual breakup arc intensification in the late growth phase. The second stage starts as optical breakup vortex formation and poleward expansion coinciding with the beginning of dipolarization at geostationary orbit and on the ground.

4. Model of the Two Stage Explosive
Near-Earth Breakup

In this section we present a relatively new model of the two stage breakup near the inner edge of the plasma sheet. The model is based
on the MHD Lagrangian approach. Results of this analysis were tested via nonlinear three-dimensional MHD simulations.

The mathematical method used in the model is a combination of the Lagrangian approach [Pfirsch and Sudan, 1993] and differential geometrical formalism [Dobias and Samson, 2002 and Dobias et al., 2002]. This method was used to analyze dynamics of potential energy in the magnetized low-β plasma system with stretched (out of dipolar) magnetic field lines [Dobias et al., 2002]. In order to initialize the problem, we employed some characteristics of the plasma and magnetic field outlined in Section 2. We assume that the plasma is isotropic and that the breakup vortical structure is large enough to use the MHD approach. In the region of interest at 10\(R_E\), magnetic field lines are set up to be stretched so that they cross equatorial plane at \(L+1R_E\), where \(L\) is the distance where these field lines would cross the equatorial plane were they dipolar. This system is initially unstable with respect to the linear ballooning (or interchange) instability, and our goal is to show that eventually this instability transfers into a nonlinear explosive stage.

Using the Lagrangian approach, Dobias et al. [2002] analysed the growth of the second and third order terms of the potential energy. In their expansion, the first order corresponds to the equilibrium state, the second order is a linear term that combines the exponential growth and oscillator, and the third term is nonlinear.

Dynamics of linear and nonlinear terms is shown in Figure 5a. Initially, the linear term dominates predicting the exponential growth of the instability. Eventually, this growth saturates (in fact, due to the compression of magnetic field lines) and the system may proceed into an oscillatory regime. However at this stage, the nonlinear term rapidly grows. When this term becomes dominant in the system, we can expect the onset of the explosive instability.

Following predictions of the Lagrangian approach, we have undertaken nonlinear MHD simulations of the perturbation growth in a system similar to the one described above. The computer model we use is described in more details in [Voronkov et. al., 2000b]. We illustrate dynamics of the system in Figure 5b.
which shows evolution of the maximum field aligned component of vorticity \((\nabla \times \mathbf{V})_\parallel\) in the equatorial plane.

The similarity of dynamics predicted by two models is evident. Initially the perturbation grows exponentially which corresponds to the linear stage of the instability. This growth saturates and the system attempts to transfer into oscillatory behavior. However at this time, growth of nonlinear potential energy brings the system into an explosive stage.

In order to complete this section, we would like to note the similarity of the above model results to the experimental evidence in Figure 3 for a two stage, linear and nonlinear, instability at the breakup. The first stage is relatively slow arc intensification that eventually tends to saturate. This arc saturation stage, however, corresponds to fast vortex expansion and explosive onset of short period pulsations both on the ground in the region of the vortex expansion and at geostationary orbit.

5. Summary

In this paper, we have revisited the near-Earth breakup problem using recent high-resolution observations of breakups in order to picture where breakup starts and how it develops. We have also utilized these observations to model the breakup region topology and to test the stability of the region. The observed temporal dynamics of breakup were compared with results of two independent models, Lagrangian approach and nonlinear MHD simulations, of the low-\(\beta\) ballooning instability. The relative consistency of models to one another and to the observed evolution allows us to suggest the following constraint for the near-Earth breakup.

Breakup starts in the region of the Earthward pressure gradient tailward of the isotropy boundary. This region corresponds to the transition from dipolar to stretched topology of the magnetic field lines. A preliminary analysis of Geotail data imply that this region is roughly at 10 \(R_E\) in the equatorial plane. Stability analysis of the magnetic field topology reveals that this region can be unstable to the low-\(\beta\) ballooning instability that develops on stretched field lines.

The breakup consists of two stages. The first corresponds to the relatively slow arc intensification poleward of the peak of the proton aurora region. According to our model results, this relates to the linear part of the instability that includes the exponential growth and oscillatory mode. The second stage, namely auroral breakup, is a poleward vortex expansion seen simultaneously with dipolarization at geostationary orbit. However more importantly, the start of this stage coincides with the explosive onset of short period pulsations seen on the ground in the vicinity of the optical breakup and at geostationary orbit. With the model approach, we suggest that this can be interpreted as the start of the nonlinear part of the instability bringing the system into an explosive stage.

However we point out that even though the general consistency between the model and observational constraints is reached, there are many aspects that are not clear. The threshold of the nonlinear instability has not yet been found. This problem is directly connected to the problem of the equilibrium and stability of the inner edge of the plasma sheet, and also to the question of what role the convection may play in this problem. Further, requirements for the trigger of the instability, or of an initial perturbation, have not been yet revealed. In our opinion, the explosive character of the breakup is evident, but the question of its importance in larger scale substorm dynamics has not been addressed.

Overall, we conclude that the near-Earth breakup is a self-consistent nonlinear instability of the inner plasma sheet that brings the region into explosive stage, but the relation to the other elements of the substorm activity remains an open issue.

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