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Disruption of parallel current at substorm breakup

S. Perraut,¹ O. Le Contel,¹ A. Roux,¹ R. Pellat,² A. Korth,³ Ø. Holter,⁴ and A. Pedersen⁴

Abstract. We study the development of substorm breakups characterized by dispersionless injections of energetic particles at the geostationary orbit. The corresponding magnetic signature is a fast change from tail-like to dipole-like configuration with transient superimposed low frequency oscillations ($T \sim 1$ mn). We show that intense waves ($\delta B \approx 1$ nT) with shorter periods (1 s) systematically develop at breakup, and that their intensification is strongly related to the dipolarization and to the fast increase of energetic electrons. These “higher frequency” ($F \sim 1$ Hz) waves appear as short lasting bursts, strongly confined across the magnetic field. Hence they look like kinetic Alfvén waves and are likely to have finite parallel electric fields, thereby resonating with electrons. We compute the diffusion coefficient and show that electrons are heated along the parallel direction and can gain up to 5 keV in a few tens of seconds. This fast parallel diffusion of electrons leads to cancellation of the parallel current and therefore to a complete modification of the current system.

1. Introduction

During a magnetospheric substorm, a large fraction of the magnetic energy stored in the plasma sheet is transformed into kinetic energy. The most critical issue, for all substorm models, is the identification of a trigger. Roux *et al.* [1991b] gave evidence for the development of large amplitude ($\delta B \sim 10$ -20 nT), transient oscillations ($T \sim 1$ mn), just before, or during the dipolarization. They suggested that the Near Earth Plasma Sheet (NEPS) is ballooning unstable. This conclusion was challenged by Ohtani and Tamao [1993] who showed that the instability criterion for ballooning modes is marginally satisfied for conditions prevailing at breakup. More recently, Bhattacharjee *et al.* [1998] have developed two-dimensional simulations of the magnetotail, imposing line-tied boundary conditions at the ionosphere. They found that the compressible ballooning modes are excited with high wave number along the azimuthal direction. The MHD (or bi-fluid) approximation used to establish the instability criterion is, however, itself questionable; kinetic effects need to be taken into account. A kinetic theory of ballooning modes has been established by Hurricane *et al.* [1995], who concluded that the NEPS may well be ballooning unstable, but with a moderate growth rate. Observations presented in the present paper, show that the amplitude of ballooning modes increases very rapidly, often over less than one period of the ballooning modes. Such a fast increase cannot result from the linear

growth of ballooning modes driven unstable by pressure gradients; a faster process must be operating. In the present work we give evidence for intense waves, at much higher frequencies: $F \sim F_{H+}$, the proton gyrofrequency, that can lead to the disruption of the parallel current, at early breakup.

This study is based on measurements made on board the European geostationary spacecraft GEOS-2 close to the magnetic equator. We have selected dispersionless substorm events within the one minute resolution of the measurements of the differential intensities of electrons and ions. The corresponding magnetic signature gives evidence for a thinning of the plasma sheet, before substorm onset as described previously by many authors, including Korth *et al.* [1991], Roux *et al.* [1991a, b] and Perraut *et al.* [1995]. In addition to particle and fluxgate magnetometer measurements, we use wave measurements from the low frequency triaxial search coil magnetometer up to 10 Hz. Robert *et al.* [1984] and Perraut *et al.* [1993] have already pointed out that large amplitude electromagnetic fluctuations are observed at substorms. The correlation between ULF waves at $F \sim F_{H+}$ and breakup has been reported by Lui *et al.* [1990, 1992] and by Shinohara *et al.* [1998]. Lui *et al.* suggested that the waves they observed on AMPTE/CCE, result from a cross-field streaming instability. Shinohara *et al.* invoked a Lower Hybrid Drift Instability. The waves discussed here are electromagnetic; most of the energy is below F_{H+} but the frequency spectrum extends well above the proton gyrofrequency (typically 1 Hz at the geostationary orbit), $\delta E / \delta B \approx 1$ -5 times the Alfvén velocity, V_A . These waves appear as short lasting bursts, which suggests that they have a short spatial extension across the magnetic field. They are associated with field-aligned currents (FAC). In summary these “high frequency” waves ($\omega \sim \Omega_{H+}$, $\delta E / \delta B \sim V_A$, spatially localized) are very similar to kinetic Alfvén waves [Hasegawa, 1982; Goertz, 1986], but they are related with magnetic structures corresponding to parallel currents. In view of the above characteristics, we call them Current Driven Alfvén waves (CDA).

2. Observations

The position of the geostationary satellite GEOS-2 was slightly away from the nominal magnetic equator (3° magnetic latitude), except during short periods where, thanks to a longitudinal shift, the spacecraft was placed at the magnetic equator. Prior to breakup, during the growth phase, the Current Sheets (CS) that develop are so thin that GEOS was sometimes outside the CS. For the present study we have selected different substorm events: January 25, 1979 and January 26, 1979 while GEOS was away from the center of the CS and July 17, 1979 while GEOS was at the geomagnetic equator.

The three selected events correspond to dispersionless injections of energetic electrons and ions, as evidenced from differential fluxes, plotted here only for the first event. Hence the acceleration has to take place close to the spacecraft. Data

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from the first event: January 25, 1979 are displayed in Figure 1. This event (around 20:17 UT, i.e. \sim 23:00 LT) has already been studied by Roux *et al.* [1991a, b] and Perraut *et al.* [1993]. Figure 1, panel (a) displays data from all sky cameras, showing that a preexisting arc suddenly brightens close to the magnetic footprint of the satellite at 20:18 UT and later moves westward (a westward travelling surge). Prior to 20:18, during the growth phase a thin CS is formed, as evidenced by the decrease in the H component and the increase in V, until $V \approx H$, (see panel (b)). The dipolarization starts at 20:17 by a sudden decrease in V (about 30 nT in 1 minute), followed by an increase in H. Large amplitude (10 nT) transient oscillations ($T \sim 1$ minute, Pi2 range), identified by Roux *et al.* [1991] and Holter *et al.* [1995] as ballooning modes are superimposed. Notice that the amplitude of ballooning modes which was typically ≤ 1 nT before 20:17 suddenly increases at 20:17 and reaches ~ 10 nT in less than a minute. This burst of intense ballooning modes lasts about 5 minutes. Panels (c) and (d) show the differential intensities of electrons and ions

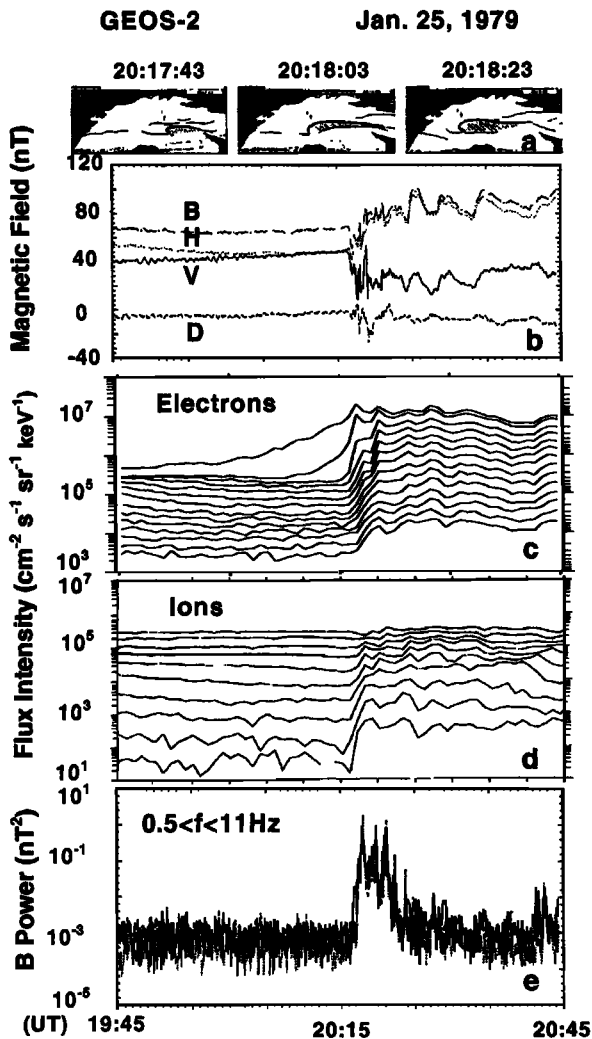


Figure 1. On the top, defolded allsky camera pictures showing the development and propagation of a westward traveling surge. Panel (b), V, D, H components and total DC magnetic field. Panels (c) and (d), differential flux intensity of ($\sim 90^\circ$ PA) energetic electrons and ions (~ 20 keV $< E < \sim 300$ keV). Panel (e), integrated power of δB components of waves around F_{H+} , between 0.5 and 11 Hz.

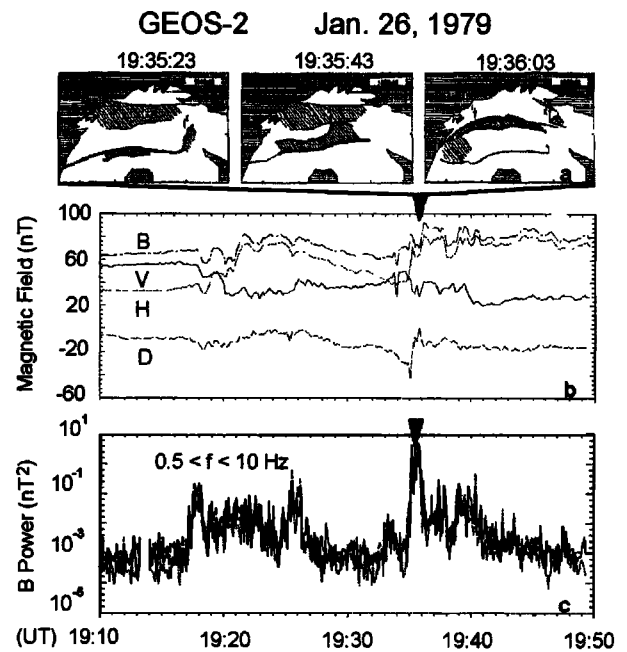


Figure 2. On the top, defolded allsky camera pictures showing the development and propagation of a westward traveling surge. Panel (b), V, D, H components and total DC magnetic field. Panel (c), integrated power of δB components of waves around F_{H+} , i.e. between 0.5 and 10 Hz.

($\sim 90^\circ$ PA); there is no dispersion for the most energetic populations ($E > 50$ keV) which are accelerated at substorm onset; the flux of medium energy electrons ($E \sim 25$ keV) increase before, as usually observed during the formation of the current sheet. Panel (e) displays the power of the magnetic fluctuations (CDA waves) integrated between 0.5 and 11 Hz, corresponding to Pi1. CDA waves grow very fast (few 10th of sec) and their amplitude reaches 1 nT. The growth of CDA waves and the enhancement in ballooning modes are simultaneous. Bursts of CDA coincide with enhanced fluctuations in the V and D components, which are interpreted as magnetic signatures of currents flowing along the H direction (fluctuations along H are weaker).

Figure 2 displays data from two successive substorms on January 26, 1979 as evidenced by the two dipolarizations (increase in H, decrease in V) observed in panel (b) around 19:20 and 19:35 UT (\sim 22:00 LT). Before the first event, the magnetic field line was strongly stretched ($V > H$) indicating that GEOS was inside the CS, ballooning modes have a long period ($T \sim 90$ s) and the intensity of the CDA waves (panel (c)) is around 0.1 nT^2 . After 19:26 UT, H decreases again and the ion flux ($E \sim 20$ keV) increases (not shown) and recovers to the same value as before the first substorm, indicating that GEOS is entering again the CS. The magnetic signature of the second event starts at 19:33 UT with large variations in V and D, which correspond to a FAC. The dipolarization occurs at $\sim 19:35$ UT while the power of CDA waves exceeds 1 nT^2 . Ballooning oscillations are superimposed on the 3 components of the fluxgate, but their period is very irregular. A discrete auroral form is observed on the ground around 19:22:30 UT (not shown) during the first large increase in H. The top panels show that a surge develops at 19:35:20 during the second substorm and passes over GEOS magnetic footprint at 19:35:40. At the same time the power in CDA waves is maximum ($> 1 \text{ nT}^2$) and a sharp increase in H (20 nT)

is observed. Notice that the peaks in the spectral density of waves, around 19:35 UT correspond to large fluctuations in the quasi-dc magnetic field, in particular in the D component.

Figure 3 displays data from another substorm on July 17, 1979 at 22:30 UT, corresponding to 01:00 LT, while GEOS was located in the vicinity of the magnetic equator (V is very small). This event is described in *Perraut et al.* [1998], too. The H component and the total magnetic field B exhibit two consecutive increases. Around 21:50 UT, B increases and reaches 100 nT during a short time interval and then decreases down to the value before. One hour later the magnetic field B increases again but remains large, of the order of the dipolar magnetic field (120 nT). For those two magnetic field increases, the flux of energetic electrons behaves differently (not shown here): around 21:50 UT the flux increases only for the lower energies; there is no heating. Conversely one hour later, around 22:47 UT, the flux of electrons increases, especially at high energies, thus there is an heating. This, together with the different magnetic signatures, suggests that the first event is a pseudo breakup while the second one is a real breakup. Here again the low amplitude (few nT) ballooning modes ($T \approx 1$ mn) observed before breakup suddenly intensify to reach ~ 10 nT around 22:47, simultaneously higher frequency CDA waves ($F \sim F_{H+}$) suddenly grow (panel (b)). During the dipolarization, around 22:47 UT, the power of magnetic fluctuations exceeds 1 nT^2 , while it reaches only 0.1 nT^2 during the pseudo breakup. Unlike the two other events the signature in the V and D of FAC are weak. This lack of magnetic signature stems from the fact that during this last event GEOS is very close to magnetic equator, where the parallel current cancels.

The events presented in the three figures suggest that the large intensification of transient low frequency oscillations as well as the dipolarization occur when and only when CDA waves intensify. To confirm this suggestion, a statistical study has been made over 5 months of GEOS data. We have identified substorms where a dipolarization in the magnetic field and a sharp increase in the flux of energetic electrons and ions occur. 145 substorm events have been found during five months. For all these substorm events (no exception) CDA waves were observed during the dipolarization.

3. Electron diffusion by CDA waves

CDA waves are systematically observed during the early phase of substorms. Given their confinement across the

magnetic field, the CDA waves should have large $k_{\parallel} \rho_i$ and therefore finite parallel electric fields. Thus, while they propagate along the field lines, CDA waves undergo a Landau resonance with electrons, which leads to an heating of electrons along the parallel direction and to a dissipation of the parallel (magnetic field-aligned) current. The quasi-linear diffusion equation for electron distribution function due to the velocity space nonuniformity can be obtained from the formula (25) in *Hasegawa and Mima* [1978]. After some straightforward integration we get a diffusion time: $\tau_D = \langle (\Delta V_{\parallel})^2 \rangle / D$, where the quasi-linear diffusion coefficient D is defined as:

$$D = \frac{\pi}{2} \left(\frac{e}{m_e} \right)^2 \frac{E_{\parallel}^2 (k_{\parallel} = \omega / V_{\parallel})}{\Delta k |V_{\parallel} - V_g|}$$

where V_{\parallel} is the parallel velocity of the electrons and E_{\parallel} the parallel component of the wave amplitude. Δk is the spectral width and V_g the group velocity.

For small values of k_{\parallel} , $V_g \approx \omega / k_{\parallel}$, thus the diffusion coefficient is divergent. Yet it is possible to get rid of the divergences which occur if $V_{\parallel} \sim V_g$, by integrating the diffusion coefficient along the field line. To get an order of magnitude estimate of D , we have calculated a minimum value by neglecting V_g . Taking a frequency of the order of 1 Hz and a parallel electric field of 0.1 mV/m (2% of E_{\perp}), one obtains a diffusion coefficient $\sim 10^{14} \text{ m}^2 \text{ s}^{-1}$, corresponding to a diffusion time of ~ 2 s for an energy gain of 1 keV for electrons. After 10 s the electron temperature can increase by 5 keV, which corresponds to a strong heating.

The diffusion time is inversely proportional to the energy of CDA waves. Thus, for a given energy of electrons, the stronger the wave intensity, the shorter is the diffusion time. Furthermore, for a large wave energy, the diffusion time of low energy particles will be shorter than the electron bounce period, τ_B . Since parallel diffusion changes V_{\parallel} without changing V_{\perp} , the mirror point of particles, and hence the invariant J , is not conserved. Then, if electron diffusion occurs over a time scale shorter than the bounce period, the parallel invariant (or mirror point) is violated, thus the parallel current which is obtained by bounce averaging of the first moment is disrupted. Therefore the whole current system has to readjust. The closure of parallel currents being made via azimuthal currents, if the parallel currents decrease, the perpendicular currents have also to decrease to satisfy $\nabla \cdot J = 0$. For the first event shown in Figure 3 (the pseudo breakup) the energy of the CDA waves is smaller (by a factor > 10) than for the second (substorm). We suggest that $\tau_D > \tau_B$ for the first event and $\tau_D < \tau_B$ for the second one, which may explain why a magnetic reconfiguration occurs for the second and not for the first event.

The relationship between occurrence of CDA waves and the parallel acceleration of electrons is also illustrated by the development of auroral arcs at the footprint, as shown in Figures 1 and 2. A more direct relation between the parallel heating of electrons and the power in CDA waves is illustrated by Figure 4 where we show that the flux of field-aligned electrons is enhanced when the CDA waves are the most intense.

4. Conclusion

For the three substorms discussed above as well as for other dispersionless injection events, low amplitude (≈ 1 nT)

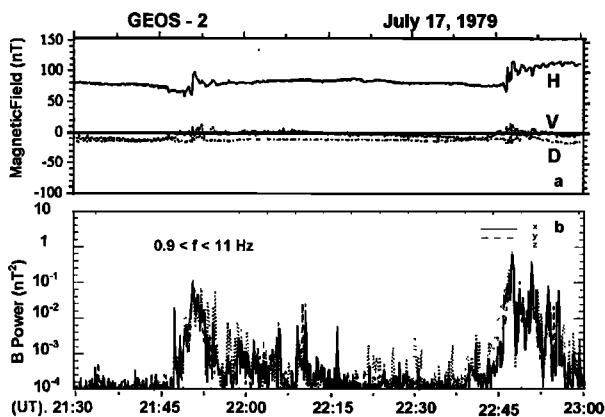


Figure 3. Panel (a), V, D and H components of the DC magnetic field. Panel (b), integrated integrated power of δB components of waves around F_{H+} .

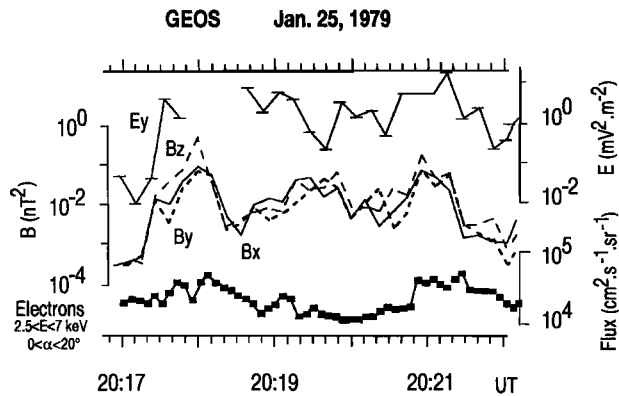


Figure 4. At the top, the integrated power between 1.2 Hz ($\sim F_{H+}$) and 11 Hz has been calculated for the electric component (highest curve) and for the 3 magnetic components Bx (solid line), By (heavy dashed line) and Bz (dashed line); Bz is aligned with B_0 . In the lowest panel, the electron flux with an energy ~ 5 keV and pitch angles $< 20^\circ$.

oscillations ($T \approx 1$ mn) observed during the growth phase suddenly intensify. These low frequency modes develop too fast to be due to a linear growth associated with an instability. Thus there are two options for explaining the short time scale of the substorm onset: either it is a nonlinear detonation, as suggested by *Hurricane et al.* [1999] or a process involving fast growing higher frequency waves. The observations presented here support the second interpretation. We have shown that the sudden intensification (over ~ 1 mn) of the low frequency mode coincides with an even faster growth of higher frequency waves ($T \sim 1$ sec) identified as Current Driven Alfvén waves (CDA). The first maximum in the intensity of CDA waves is observed just before or at dipolarization whatever the location of GEOS-2 with respect to the magnetic equator. This, together with the fact that CDA waves can grow very fast over a much smaller time scale, strongly suggests that CDA waves are directly involved in the magnetic field reconfiguration at breakup. We have shown that the CDA waves, which have a finite parallel electric field component, produce via Landau resonance, an efficient parallel heating of electrons that can gain up to 5 keV in 10 s.

For large amplitude CDA waves (≥ 1 nT) the diffusion time (~ 2 s for $\Delta E \sim 1$ keV) is less than the bounce period of the electrons, thus the second invariant is violated, the parallel motion of the electrons is strongly disturbed, and the parallel current is disrupted. Therefore the whole current system has to readjust; because the closure of parallel currents is made via azimuthal currents, if the parallel currents decrease, the perpendicular currents have also to decrease to satisfy $\nabla \cdot J = 0$.

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