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Alfvén modulation of the substorm magnetotail transport

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Abstract. This work explores the proposition that magnetic field resonances modulate the transport of particle and magnetic flux in the earth's magnetotail. Coordinated high- and low-altitude measurements during a substorm show periodic variations of magnetic field, plasma density and flow bursts in the magnetotail with frequencies that correlate well with those of magnetic field oscillations at geosynchronous altitude and pulsations measured by ground-based stations. The pulsations' frequency is in the Pc 5 range. The example presented here occurred during the substorm period of May 19-20, 1996, that was chosen as the first ISTP/GGS campaign for the ground-based and theory investigations. There appears to be a resonance between modes sustained by the near-Earth magnetic field and compressional and flapping pulsations that can be sustained by the magnetotail.

Introduction

Many models of substorm onset and evolution have been proposed since the first identification of the substorm process [Akasofu, 1964; Hones, 1979; Samson et al, 1992; Rostoker and Eastman, 1987; Goertz and Smith, 1989; Kan et al., 1988; Chao et al., 1977; Roux, 1985]. One group of models uses the MHD approach to simulate the magnetospheric configuration leading to the formation and evolution of a near-earth neutral line (NENL). Originally inferred from in-situ observations in the tail, it involves a growth phase during which magnetic flux is eroded from the dayside magnetosphere and transported to the tail where it increases the magnetic stress. The expansion or unloading phase then coincides with the formation of a magnetic neutral line close to the earth (between ≈ -10 R_e and ≈ -20 R_e) [Hones, 1979]. The subsequent reconnection dissipates magnetic energy through plasma acceleration in the central plasma sheet. Earthward flow is located earthward of the X-line; tailward flow constitutes a magnetically isolated structure that contains an O type neutral line commonly termed a plasmoid.

Another group of models envisions the substorm process as a consequence of wave resonances in the magnetosphere [Samson et al, 1992; Rostoker and Eastman, 1987; Goertz and Smith, 1989]. Field line resonances arise from the coupling of compressional energy in MHD waves to shear Alfvén waves. These resonances often have quantized frequencies with 1.3, 1.9, 2.6, and 3.4 mHz being very common. Samson et al., [1991] showed that these frequencies correspond to the first four harmonics of MHD cavity modes in regions between the magnetopause and turning points on dipolelike field lines outside the plasmasphere. The theory that describes resonances, wave guides, and cavity modes has reached a fairly sophisticated state [e.g., Southwood, 1974; Chen and Hasegawa, 1974a,b; Kivelson and Southwood, 1985, 1986; Zhu and Kivelson, 1988].

However, one of the crucial questions that has not been answered is whether the oscillations play any significant role in the onset and evolution of substorms. Observations place the location of the onset near the magnetic resonant shells [e.g., Samson et al., 1991, 1992] thus indicating that magnetic field resonances may play a role in triggering or producing substorm intensifications via, for example, mode conversion to kinetic Alfvén waves in the resonance and the nonlinear evolution of Kelvin-Helmholtz instabilities produced by the large velocity shears at the resonances [Samson et al, 1992; Rankin et al., 1993].

Identifying and quantifying how the different proposed mechanisms contribute to the plasma and magnetic field transport during substorms is an issue of fundamental importance for the International Solar Terrestrial Physics Program. In this paper we assess the possible role of magnetospheric resonances in the dynamics of the substorms of May 19-20, 1996, which was chosen as the first ISTP/GGS campaign for the ground-based and theory investigations.

Synoptic Substorm Measurements of the May 19-20, 1996, Substorm

Relationship of Ground-Based Measurements to POLAR Images

Two main onsets were detected by the various ground magnetometers in the nine hour local time sector spanning Kiruna, Leirvogur, Greenland, and the CANOPUS eastern

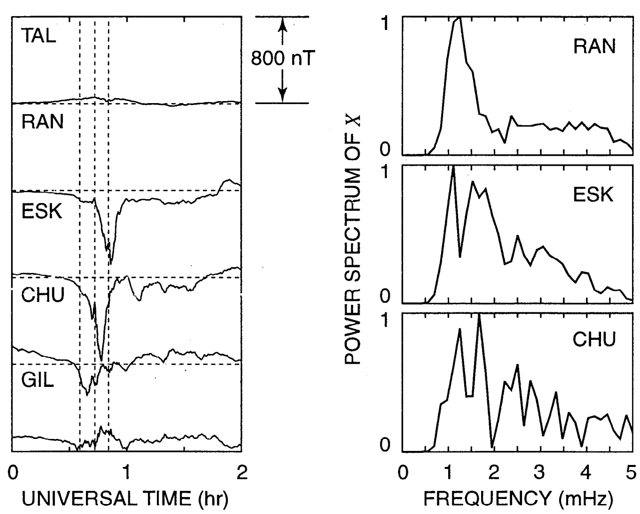

Figure 1. Left. X-component of the magnetic variations measured by the CANOPUS stations during the substorm of May 20, 1996. Vertical lines mark the times of discrete westward electrojet intensifications. Right. Power spectrum of the X component measured at Rankin Inlet, Eskimo Point, and Churchill between 00 and 02 UT.

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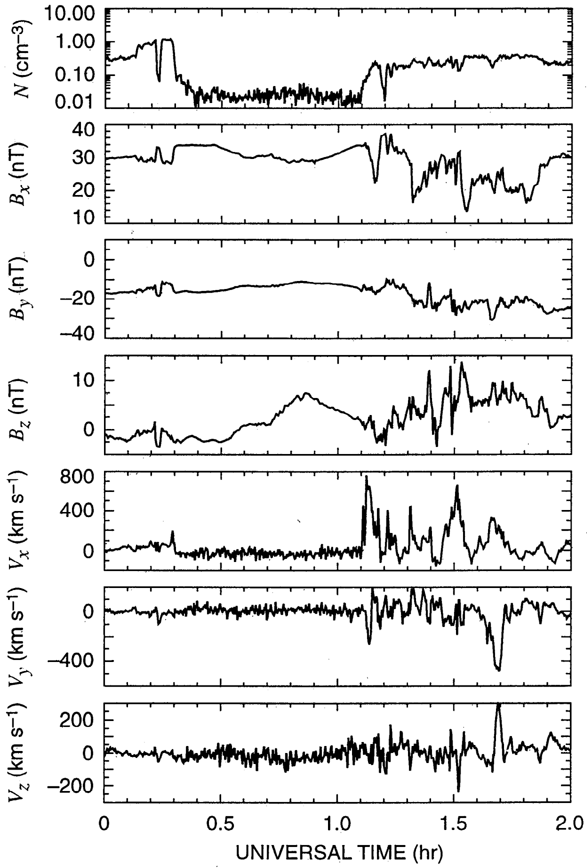

Figure 2. Geotail LEP and magnetic field measurements between 00 and 02 UT on May 20. Bulk velocity and magentic field components are given in GSM coordinates.

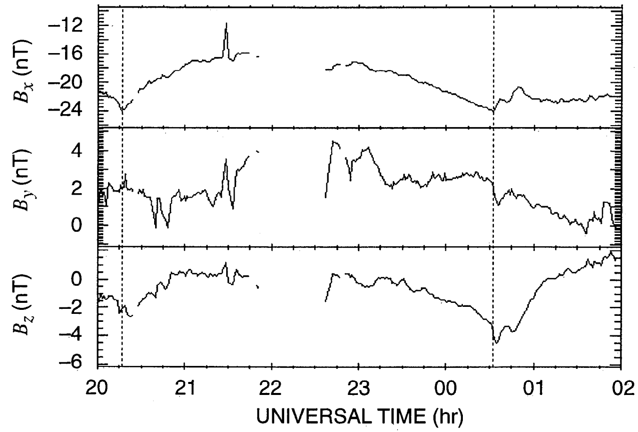

Figure 3. IMP 8 (GSM) magnetic field measurements of the southern lobe between 20 UT on May 19 and 02 UT on May20. Vetical lines mark the times when unloading starts.

meridional chain. The first onset was detected on May 19 at 2020 UT by Kiruna (64.7° MLAT, 2300 MLT) and at 2025 by Scoresbysund (72.1°, 2025). Both stations were south of the center of the westward electrojet. No other station measured an onset, although a westward electrojet enhancement was seen at Leirvogur (65.6°, 2041) and at western Greenland stations (MLT ~ 1839) at invariant latitudes higher than 70°.

POLAR UVI images show a localized auroral intensification in the Kiruna local time sector that later expanded into a narrow latitudinal band at high latitude, in agreement with the position inferred from the ground-based measurements. The expansion that followed the first onset had a short duration (~ 30 min.) and a narrow longitudinal extent. There was a further intensification of the electrojet at Kiruna at 2350 UT but without any significant poleward expansion or aurora.

The second onset actually was a succession of stepwise electrojet intensifications that started almost four hours after the May 19 onset (Figure 1). UVI images and ground magnetograms show that the intensifications started near the CANOPUS longitude at 0035 UT and that a second intensification at 0044 UT was detected nearly simultaneously at that meridian (where the westward electrojet intensification produced a maximum intensity of 800 nT in the X component) and at the western Greenland chain (where the maximum H component intensity was 350 nT), despite being five hours apart. A third discrete electrojet intensification is seen at MARIA at 0051 UT The latitudinal center of the westward electrojet at onset was near Eskimo Point (72.1°, 1808) and Frederikshab (69.4°, 2249) and south of Leirvogur (65.6°, 0105). Pi 2 pulsations at 0035 UT were triggered only in the lower latitude stations -that is, Gillam (67.6° MLAT) and Churchill (69.9°). Eskimo Point (72.1°) measured a sudden onset enhancement of Pi 2's at 0044, and finally Rankin Inlet (73.9°) registered another sudden enhancement at 0052 UT. Therefore, the westward electrojet proceded poleward in a discrete fashion.

A Fourier analysis of the CANOPUS magnetograms shows that shortly after the 0035 UT onset Eskimo Point had the highest amplitude pulsations for frequencies above 1 mHz. Furthermore, these pulsations were linearly polarized at that site, whereas polarization was counterclockwise at Fort Churchill and clockwise at Rankin Inlet. Therefore, Eskimo Point must have been located near a resonant shell. The power spectrum of that station's data between 0000 and 0200 UT revealed spectral peaks at 1.1, 1.5, and 1.9 mHz, with secondary peaks at 2.6, 3.1, and 3.9 mHz (Figure 1.) All the data in this paper have been filtered with a 1 mHz to 10 mHz bandpass filter.

Geotail and IMP 8

During the interval comprising the May 20 expansions, Geotail was located in the evening tail, at X_{GSM} ~ -10 R_e, Y_{GSM} ~ 11 R_e, and Z_{GSM} ~ 4 R_e. IMP 8 was in the evening sector of the southern lobe (X_{GSM} ~ -26 R_e, Y_{GSM} ~ 6 R_e, Z_{GSM} ~ -12 R_e). A magnetic field mapping using the Tsyganenko 89 model places Geotail's footpoint at a longitude between the CANOPUS chain and Great Whale River and at an invariant latitude similar to Eskimo Point's. Although this mapping is not necessarily exact, it establishes that the spacecraft was located in the magnetotail region that correlates with the ionospheric local time sector that developed the onset and expansion.

LEP measurements indicate that Geotail's position was alternating between the plasma sheet and the plasma sheet boundary layer/lobe between 2140 UT on May 19 and 0020 on May 20, when it entered the lobe (Figure 2.) The excursion into the lobe happened during the tail loading that started at least at ~2300 UT (Figure 3) (a more accurate estimation of the transition between the end of one unloading and the beginning of the next is not possible due to a 40 min. data gap). Unloading started at 0033 UT. The monotonic decrease in $|B_x|$ simultaneous with the increase-then-decrease of $|B_z|$ is consistent with a tailward propagation of a current disruption or a neutral line [e.g., Jacquey et al., 1993] whose onset was

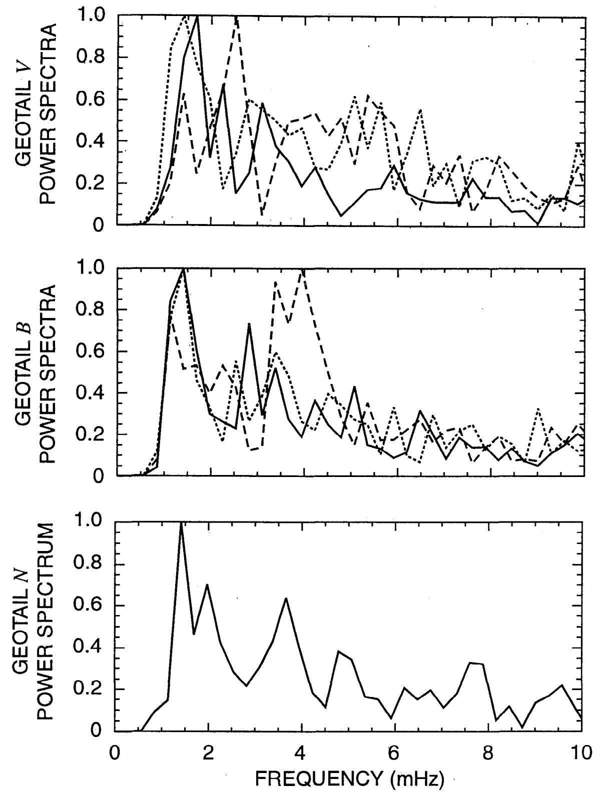

Figure 4. Normalized power spectra of (GSM) bulk velocity and magnetic field and ion density between 01 and 02 UT. Solid line corresponds to the X component, dotted to Y, dashed to Z.

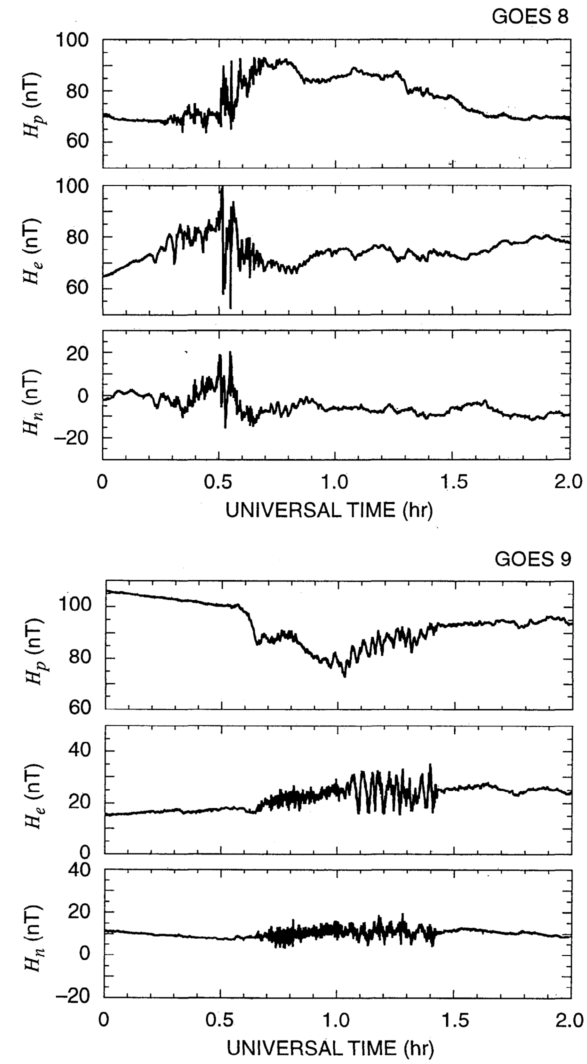

Figure 5. GOES 8 and 9 magnetic field measurements during the substorm of May 20, 1996. H_P is perpendicular to the satellite's orbital plane, H_e points earthward, and H_n is perpendicular to both H_P and H_e, pointing eastward.

earthward of IMP 8 and eventually passed directly underneath the satellite at 0036 UT. A partial recovery of the magnetic flux ensued between 0036 and 0042 UT, but it was followed by a further decrease of the magnetic flux. This stepwise progression suggests that the current disruption (or neutral line) interrupted its tailward propagation momentarily and then resumed it. The time lapse between magnetic flux changes was ~ 10 min. Therefore, the onset of the current disruption (or neutral line) as observed by IMP 8 occurred 4 min. after the first dipolarization and 13 min. after Geotail entered the lobe, during an interval of expanding surge.

The evolution of the auroral boundaries, tracked by the Sondrestrom incoherent-scatter radar elevation scans along the magnetic meridian, shows a poleward moving surge that reached past the Sondrestrom latitude at 0055 UT and soon afterward (during the 5 min. scan centered at 0103 UT) started to move equatorward. Therefore, Geotail's reentry into the plasma sheet at 0106 UT during the thickening of the plasma sheet occurred as the surge and polar cap boundaries were contracting.

Geotail reentered the plasma sheet at 0106 UT, during the plasma sheet recovery (see Figure 2.) Periodic bulk flow enhancements reaching up to 750 km/s were apparent during that period. The power spectra of the bulk velocity shows important frequency components at 1.3, 1.7, 2.2, and 3.1 mHz. (Figure 4.) The EPIC instrument also measured a sequence of anisotropies consistent with eartheard flows starting at 0110 UT and showing a periodicity of 9-10 min. (D. Williams, personal communication, 1996.) Magnetic field pulsations at 1.1, 1.3, 2.8, 3.4, and 3.9 mHz and periodic plasma density variations at 1.3, 1.9, and 3.7 mHz were also present during the same period.

Geosynchronous Satellites

On May 19-20 GOES 8 was situated at a geographic longitude of 74.8° W -that is, between the Churchill chain (at ~ 94° W) and the western Greenland chain (at ~ 50° W). GOES 9 was at 135.5° W, two and a half hours west of Churchill. GOES 8 measured a series of dipolarizations starting at 0029 UT (Figure 5) and separated from each other by about four minutes. Each dipolarization, lasting between one and two minutes, was followed by a partial recovery of the magnetic field toward the pre-dipolarization configuration and then by a further dipolarization. The power spectrum of GOES 8 magnetic field measurements show the main peaks at 1.3 and 1.9 mHz (Figure 6.) It also shows four other peaks at 3.0, 3.6, 4.2, and 4.8 mHz, bracketing the frequency of the periodic dipolarizations. The recovery of the plasma sheet occured simultaneously with the enhancement of Pc 5 pulsations in the GOES 9 time sector (Figure 5.) Pulsations consisted of a combination of compressional and toroidal modes (Figure 6), with the strongest frequency components at 1.1, 1.9, 3.1, 4.8, and 7.8 mHz.

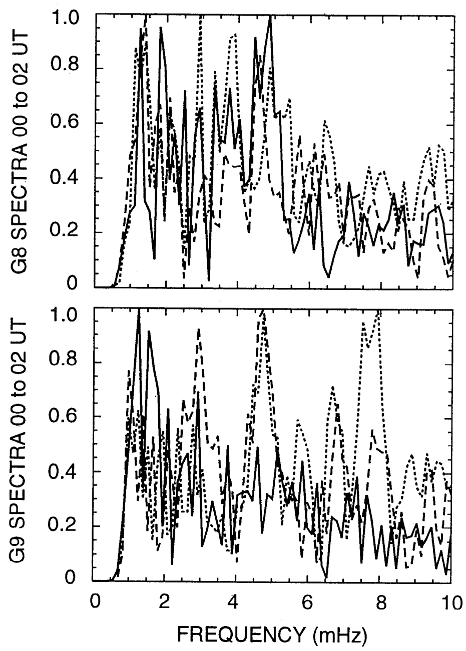

Figure 6. Normalized power spectra of the GOES 8 (top) and GOES 9 (bottom) magnetic field components between 00 and 02 UT. The solid line corresponds to H_p, dotted to H_e, dashed to H_n.

Are the Magnetosphere's Natural Resonances Coupling the Transport in Different Regions of the Tail?

This work reports observations of simultaneous periodicities in the electrojet enhancements, geosynchronous magnetic field, and magnetotail plasma and magnetic field. The periodic flow bursts detected in the evening plasma sheet at ~16 R_e during an expansion phase showed some frequency components that matched those at geosynchronous altitude and on the ground. Furthermore, plasma sheet magnetic field and plasma pulsations also showed matching frequency components.

Therefore, these observations suggest that plasma and magnetic field transport in mutually remote regions of the magnetotail can occur at preferred frequencies. There appears to be a resonance between modes sustained by the near-Earth magnetic field [Samson et al., 1992] and compressional and flapping pulsations that can be sustained by the magnetotail [Walker et al, 1993]. Some of the frequency components observed at geosynchronous and Geotail altitudes match the fundamental cavity mode frequencies. This suggests that the latter modes may modulate the substorm response of the magnetotail. A detailed description of such mechanism is beyond the scope of the present paper and will be addressed elsewhere.

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References

Akasofu, S.-I., The development of the auroral substorm, *Planet. Space Sci., 12*, 273, 1964.

Chao, J. K., J. R. Kan, A. T. Y. Lui, and S.-I. Akasofu, A model for thinning of the plasma sheet, *Planet. Space Sci., 25*, 703, 1977.

Chen, L., and A. Hasegawa, A theory of long-period magnetic pulsations, 1: Steady-state excitation of field line resonance, *J. Geophys. Res., 79*, 1024, 1974a.

Chen, L., and A. Hasegawa, A theory of long-period magnetic pulsations, 2: Impulse excitation of surface eigenmode, *J. Geophys. Res., 79*, 1033, 1974b.

Goertz, C. K., and R. A. Smith, Thermal catastrophe model of substorms, *J. Geophys. Res., 94*, 6581, 1989.

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

Jacquey, C., J. A. Sauvaud, J. Dandouras, and A. Korth, Tailward propagating cross-tail current disruption and dynamics of near-Earth tail: a multi-point measurement analysis, *Geophys. Res. Lett., 20*, 983, 1993.

Kan, J. R., L. Zhu, and S.-I. Akasofu, A theory of substorms: Onset and subsidence, *J. Geophys. Res., 93*, 5624, 1988.

Kivelson, M. G., and D. J. Southwood, Resonant ULF waves: A new interpretation, *Geophys. Res. Lett., 12*, 49, 1985.

Kivelson, M. G., and D. J. Southwood, Coupling of global magnetospheric MHD eigenmodes to field line resonances, *J. Geophys. Res., 91*, 4345, 1986.

Rankin, R., B. G. Harrold, J. C. Samson, and P. Frycz, The nonlinear evolution of field line resonances in the earth's magnetosphere, *J. Geophys. Res., 98*, 5839, 1993.

Rostoker, G., and T. E. Eastman, A boundary layer model for magnetospheric substorms, *J. Geophys. Res., 92*, 12187, 1987.

Roux, A., Generation of field-aligned structures at substorm onsets, Proceedings of ESA Workshop on Future Missions in Solar, Heliospheric, and Space Plasma Physics, *Euro. Space Agency, Spec. Publ. ESA SP-235*, p. 151, 1985.

Samson, J. C., R. A. Greenwald, J. M. Ruohoniemi, T. J. Hughes, and D. D. Wallis, Magnetometer and radar observations of MHD cavity modes in the Earth's magnetosphere, *Can. J. Phys., 69*, 929, 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.

Southwood, D. J., Some features of field-line resonances in the magnetosphere, *Planet. Sp. Sci., 22*, 483, 1974.

Walker, A. D. M., J. M. Ruohoniemi, K. B. Baker, R. A. Greenwald, and J. C. Samson, Spectral properties of magnetotail oscillations as a source of Pc5 pulsations, in *Advances in Sp. Phys., 13*, 59, 1993.

Zhu, X. M., and M. G. Kivelson, Analytic formulation and quantitative solution of the coupled ULF wave problem, *J. Geophys. Res., 93*, 8602, 1988.

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