THEMIS observations of the spatial extent and pressure-pulse excitation of field line resonances

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[1] We present a case study of Field Line Resonances (FLRs) in the dayside magnetosphere, observed in both electric and magnetic field components at multiple L-shells near the equator. The event measured by the five THEMIS probes and the nearby GOES and Geotail satellites provides a unique opportunity to differentiate between temporal and spatial characteristics of FLRs. Narrow-band FLRs were excited globally at different frequencies matching the local field line resonant frequency. In conjunction with a sharp increase in the upstream solar wind density, prompt intensification of the FLR power was observed at different L-shells, simultaneously at different frequencies and amplitudes. **Citation:** Sarris, T. E., W. Liu, X. Li, K. Kabin, E. R. Talaat, R. Rankin, V. Angelopoulos, J. Bonnell, and K.-H. Glassmeier (2010), THEMIS observations of the spatial extent and pressure-pulse excitation of field line resonances, *Geophys. Res. Lett.*, *37*, L15104, doi:10.1029/2010GL044125.

1. Introduction

[2] Geomagnetic pulsations of Ultra Low Frequency (ULF), roughly 1 mHz to 1 Hz (periods 1 to 1000 sec), are large-scale oscillations in the Earth's magnetic field and are often observed in space as well as on the Earth by ground-based magnetometers [e.g., *Glassmeier et al.*, 1999, and references therein]. Continuous ULF pulsations have traditionally been classified in 5 frequency ranges termed Pc1 to Pc5 [*Jacobs et al.*, 1964]. This classification does not necessarily indicate a different excitation mechanism or distinct physical characteristics of the pulsations; instead, it is based solely on their frequency. In fact, as shown in this paper, continuous pulsations that are excited by a common source mechanism can exhibit frequencies across different Pc ranges (Pc3 to Pc5 in the event described herein), depending on their location in the magnetosphere. This is consistent with *Engebretson et al.* [1986] who used AMPTE/CCE to show that the frequency of field line oscillations changes across L-shells, thus suggesting that the field lines oscillate at their individual frequencies.

[3] Generally, ULF wave sources are classified as either internal or external. Internal sources are primarily plasma instabilities, such as the drift mirror [*Hasegawa*, 1969] and bounce resonance instability [*Southwood et al.*, 1969]. These sources are expected to generate westward propagating poloidal ULF waves with high azimuthal wave numbers. External sources are solar wind driven and can produce ULF waves *via* the coupling of compressional magnetospheric pulsations to shear Alfvén waves [e.g., *Lee and Lysak*, 1989, and references therein]. These have mostly toroidal polarizations, low azimuthal wavenumbers and propagate anti-sunward. For example, the Kelvin-Helmholtz instability generates surface waves at the magnetopause and the fast magnetoacoustic mode in the magnetosphere [e.g., *Wright et al.*, 2000, and references therein]. The latter couple to Alfvén waves to produce Field Line Resonances (FLRs) where the local resonant conditions are met. The association between the KHI and FLRs has recently been studied using THEMIS observations [*Agapitov et al.*, 2009]. Another external source attributes FLRs to magnetospheric cavity/waveguide modes excited by the solar wind, especially when the magnetosphere can be described as a good global resonator [*Rickard and Wright*, 1994, and references therein]. Yet another possibility are perturbations in the solar wind which excite FLRs by compressional pulsations in the magnetosphere. These perturbations can be either coherent oscillations in the solar wind, or sudden pressure pulses: in the first case the geopulsations are expected to show frequency characteristics similar to those in the solar wind [*Sarafopoulos*, 1995]; in the second case the earthward compressional pulsations are usually characterized by a broad spectrum and often couple to narrowband FLRs, which develop with frequency characteristics that depend on the local cavity/waveguide frequencies [e.g., *Hudson et al.*, 2004]. Modeling studies have also described the process and characteristics of ULF wave excitation by pressure pulses [e.g., *Lee and Lysak*, 1989; *Southwood and Kivelson*, 1990]. Finally, it has been speculated that the ionosphere could constitute a source of magnetospheric pulsations, via fluctuating field aligned currents or perturbations in ionospheric conductances [*Engebretson et al.*, 1991].

[4] Identifying the source mechanism of local FLRs is difficult primarily due to limitations in measurements, which are usually single-point and are thus not able to distinguish spatial from temporal features. Furthermore, most spacecraft

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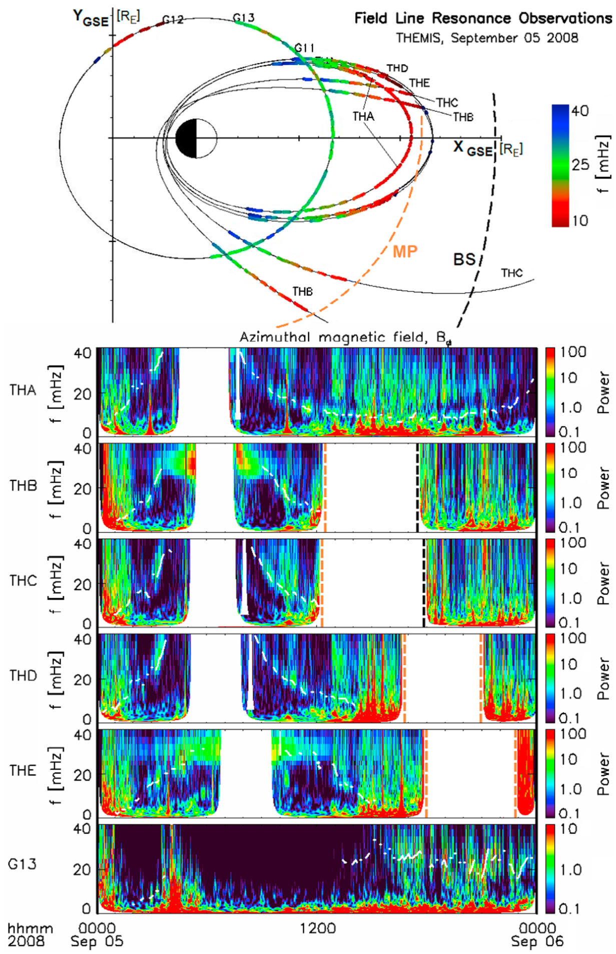

Figure 1. (bottom) Dynamic power spectra of the azimuthal component of the magnetic field, B_φ from the five THEMIS probes and GOES 13 on September 5 are plotted from 0 to 40 mHz. The white dashed lines correspond to the local peak in power, excluding power in 1–5 mHz and power in the higher harmonic. (top) The corresponding frequencies are plotted along the orbit (GSE coordinates) in a color scale, from 3 mHz (red) to 40 mHz (blue).

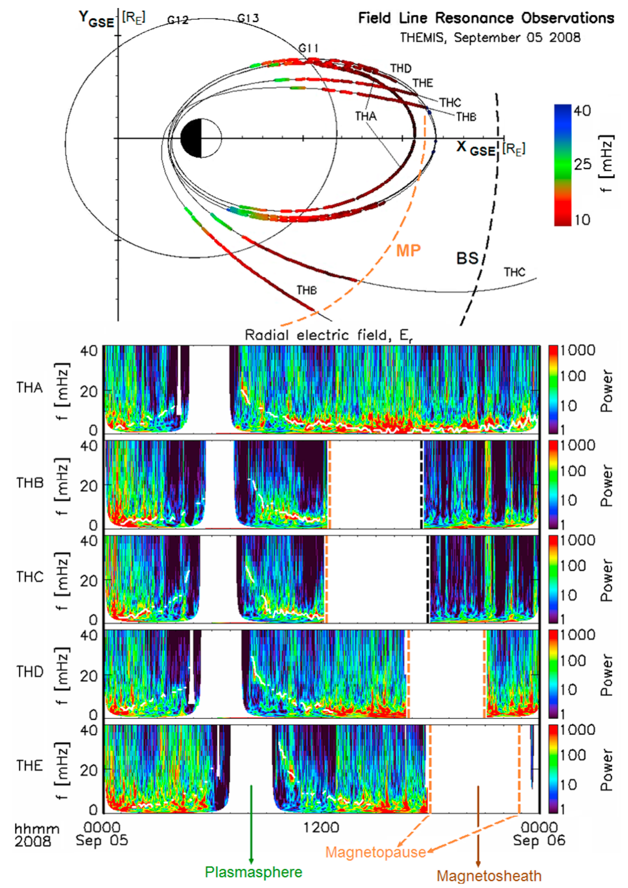

Figure 2. Similar to Figure 1 for the radial component of the electric field, E_r.

missions are limited in instrumentation or are in orbits that provide ambiguous measurements of ULF waves. On the other hand, chains of ground measurements are able to provide estimates of the radial and azimuthal propagation and, sometimes, the azimuthal mode number of magnetospheric pulsations. However, these measurements are strongly affected by the ionosphere, which is known to alter the polarization characteristics of magnetospheric waves [*Hughes*, 1974; *Rae et al.*, 2007].

[5] The five micro-satellites of the THEMIS mission (hereafter termed "probes" A through E) provide unique opportunities to characterize ULF pulsations in the magnetosphere, because of their instrumentation (both electric and magnetic field measurements are available) and orbits (close to the equatorial plane and across different L-shells). The use of THEMIS electric and magnetic field measurements to characterize ULF waves was demonstrated for an outbound pass of the five THEMIS probes in a string-of-pearls (similar orbits) configuration by *Sarris et al.* [2009], who identified the waves as toroidal mode FLRs, showed the L-dependence of their resonant frequencies to be consistent with models, and estimated the mode number to be $m \sim 13$. In another recent study, *Liu et al.* [2009] presented a statistical analysis of a large number of FLR events and investigated their spatial extent and occurrence rates, differentiating between toroidal and poloidal waves. In this paper we present a case study of global measurements of FLRs in a different phase of the THEMIS mission, when the five probes are spread across different L-shells and local times, complemented by GOES geosynchronous measurements. For most of the day on September 5, 2008, FLRs are observed throughout the dayside magnetosphere, showing a persistent source, during a time when the earth magnetosphere was immersed in a high-speed solar wind stream. For one instance during this event we identify a distinct intensification of the FLR power simultaneously at different locations with different frequencies matching the local resonant conditions; this can unambiguously be associated with a concurrent solar wind pressure pulse measured by ACE, Geotail and GOES. Similar events associating the excitation of ULF waves with sudden variations in solar wind parameters have been reported in the past [e.g., *Baumjohann et al.*, 1984; *Agapitov and Cheremnykh*, 2008], however those observations could not clearly identify frequency characteristics across different L-shells. In this study we

present multi-spacecraft measurements of FLR excitation using the ideal separation of the THEMIS probes.

2. Observations

[6] During the fifth phase ("dayside science", 15/04/08-15/10/08) of the THEMIS mission [*Sibeck and Angelopoulos*, 2008], the apogee of all 5 orbits is in the dayside as follows: probe A is the inner-most of the five satellites, with apogee at ~10 R_E; probe B is the furthest away, at ~30 R_E; probe C is at ~20 R_E, and probes D and E at ~12 R_E. As shown in Figures 1 (top) and 2 (top), at each orbit all probes cross the plasmasphere and inner magnetosphere; probes B, C, D and E also cross the magnetopause (MP); probes B and C cross the bow shock (BS) as well.

[7] In Figures 1 (bottom) and 2 (bottom) spectral measurements from, respectively, the FluxGate Magnetometers [*Auster et al.*, 2008] and Electric Field Instruments [*Bonnell et al.*, 2008] onboard probes A through E are plotted, in the field-aligned coordinate system, from 0 to 40 mHz for the components with the most prominent FLRs: the azimuthal component of the magnetic field, B_φ, and the radial component of the electric field, E_r. In some cases waves in E_φ were also observed; however no strong oscillations where observed in B_r. We consider this as an indication of the appearance of mostly ULF waves of toroidal polarization. The transformations from GSE to the local field-aligned coordinate system are described by *Sarris et al.* [2009]. In Figure 1 (bottom) the spectrum of the azimuthal component of the magnetic field from GOES-13 is also plotted. The appearance of narrow-band peaks in power in particular ULF frequencies can be seen in all THEMIS spacecraft; their characteristics are similar to the ones examined by *Sarris et al.* [2009], where they were positively identified as FLRs. In that study, this identification was based on a 90^o phase difference between E and B, which is a strong indication of standing waves, and further supported by modeling using the approach of *Kabin et al.* [2007]. The uniqueness of the present study is that, on September 4, 2008, FLRs were observed simultaneously throughout the inner magnetosphere, enabling precise characterisation of their spatial extent and excitation mechanism, as discussed below.

[8] In Figures 1 and 2 the local peak in power is indicated with white dashed lines on top of the dynamic power spectra. The locations of observation of these power peaks are plotted in the upper panels along the orbits in a color scale marking the corresponding frequency, from 3 mHz (red) to 40 mHz (blue). Comparison of the frequencies marked with white dashed lines in B_φ and E_r shows that the resonant frequencies with maximum power in the magnetic field in Figure 1 are consistently higher than the frequencies in the electric field in Figure 2 by a factor of ~2, indicating that the fundamental toroidal mode of FLRs is observed in the electric field, whereas the second harmonic mode is observed in the magnetic field. Since the THEMIS probes are relatively close to the magnetic equator, a node (antinode) is expected for magnetic (electric) fluctuations for the fundamental mode. The periods with no data correspond to crossings of the plasmasphere or magnetosheath; magnetopause and bow shock crossings are marked with orange and black dashed lines respectively.

[9] In Figure 3 we focus on the period from 02:30 to 04:30 UT when an intensification is observed simultaneously at different THEMIS probes between ~03:15 and 03:30, as shown in the lower right panels of the THEMIS B_φ spectra. Figure 3 (bottom left) shows magnetic field measurements from GOES-12 and Geotail, as well as OMNI solar wind measurements propagated to the bow shock. The OMNI solar wind measurements show a sharp increase in solar wind dynamic pressure from 0.7 to 1.4 nPa, a corresponding drop in interplanetary magnetic field strength from 4.5 to 3 nT and a drop in solar wind velocity, coinciding with the observed excitation of enhanced FLRs at all THEMIS probe locations. Geotail is located close to the magnetopause boundary at that time, as shown in Figure 3 (top left), and observes a short drop-off in the magnetic field; we interpret this as a temporary compression or inward-then-outward motion of the magnetopause, caused by the pressure pulse; shortly after 03:50 Geotail crosses the magnetopause again, exiting the magnetosphere for that orbit. The increase that is observed in GOES-12 B_z, located in the pre-midnight region (~2220 LT) at the time of the arrival of the pressure pulse, could be interpreted as a small-scale dipolarization, which is also probably localized, as similar features are not observed by the trailing GOES-13 and GOES-11 (data not shown), located at ~2020 LT and ~1820 LT respectively. In the upper left panel the locations of all spacecraft involved are shown for the time of the pressure pulse arrival; "MP" and "BS" indicate the locations of the magnetopause and bow shock respectively.

[10] ACE measurements show that the earth crossed into a high speed stream on September 3, two days prior to this event, with solar wind speeds reaching >500 km/s on September 4. Within this Corotating Interaction Region (CIR) the components of the interplanetary magnetic field fluctuate, whereas the magnetic field magnitude remains nearly constant, thus indicating the presence of Alfvénic waves in the solar wind. The density briefly reached a peak of >20 cc^{-1} on September 3, but returned to lower values prior to entering the CIR.

3. Discussion

[11] The excitation of FLRs in the Earth magnetosphere has been a subject of great interest over the past 40 years, and toroidal mode FLRs have been attributed to a number of source mechanisms, including coherent oscillations in the solar wind, cavity mode pulsations, the Kelvin Helmholtz instability in the magnetosphere flanks, pressure pulses in the solar wind and high-latitude current/conductivity perturbations. Modeling has shown that any of these mechanisms can be viable under certain conditions; however positively identifying a source mechanism has proven to be rather difficult due to limitations in measurements. In this event, as observed by THEMIS and GOES, toroidal mode ULF waves are excited globally over the entire dayside magnetosphere, and appear to occur for the entire day on September 5, 2008. The pulsations are well-defined in frequency and extend mostly in the azimuthal (toroidal) direction. The computed Poynting flux is largest in the direction of the magnetic field (figures not shown), consistent with energy being "lost" to the ionosphere. The global extent of FLRs and the apparent submergence of the magnetosphere in the high-speed solar wind stream indicate that the day-side ULF waves are possibly driven by the solar wind variations. Similarly to the study by *Sarris et al.*

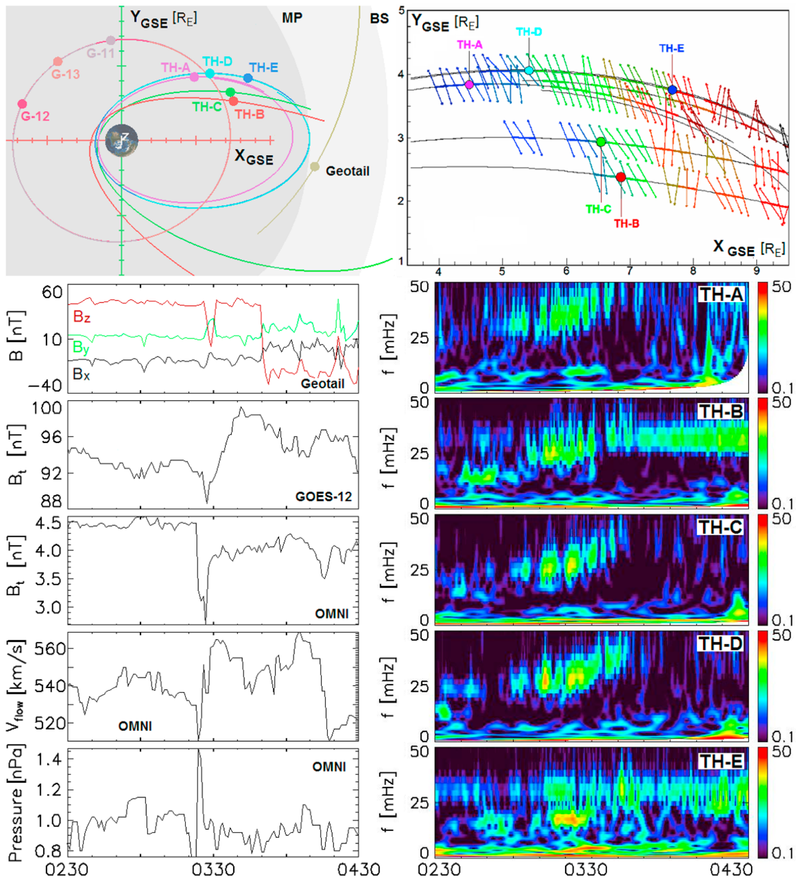

Figure 3. (bottom left) Measurements of the response of the magnetosphere (Geotail and GOES-12) to a solar wind pressure pulse (OMNI). (bottom right) Dynamic power spectra of the azimuthal components of the magnetic field, B_φ from the five THEMIS probes. (top left) Orbits and spacecraft locations at 03:20. (top right) Polarization vectors of the magnetic field along the orbit for the same time period; the color scale represents the measured FLR frequency, ranging from 3 mHz (red) to 40 mHz (blue).

[2009], the measured wave frequency characteristics were found to vary across the L-shells in a manner consistent with the FLR models of *Rankin et al.* [2006] and *Kabin et al.* [2007] (results not shown). We note that the oscillations of individual field lines with their natural frequencies, such as described by these models, are generally interpreted as representing time-asymptotic states of the Alfvénic oscillations in the magnetosphere [e.g., *Radoski*, 1967; *Kabin et al.*, 2007].

[12] For one instance during this day, a sharp density increase of short duration is observed by ACE and is estimated to have reached the Earth at ~03:20; at this instance the magnetosphere appears to respond to this pressure pulse by an instantaneous compression, and subsequently the ongoing FLRs appear to intensify. Thus, most likely, a compression of the magnetopause generates compressional fast waves throughout the magnetosphere; toroidal FLRs are subsequently excited locally by coupling of the compressional power to shear Alfvén waves. This description is similar to the magnetospheric response seen in the simulations of *Rickard and Wright* [1994]. A similar scenario was described by *Glassmeier et al.* [1984] using ground magnetometer measurements; instead in this event the pulsations are observed across multiple L-shells in the inner magnetosphere using a distributed network of satellites.

[13] Interestingly, the current event indicates that this asymptotic state of the magnetospheric oscillations can be achieved almost instantaneously, without lengthy transient regime, in agreement with, e.g., *Wright* [1992] and *Mann et al.* [1995]. If the event of September 5, 2008 represents typical magnetospheric response, our results may have important implications for modeling ULF waves in the magnetosphere and justify using uncoupled FLR models under a variety of circumstances.

[14] A closer examination of the power of the resonant waves after the arrival of the pressure pulse shows that the outer probes observe waves with larger amplitudes than the inner ones; thus THEMIS-E, located at an estimated L-shell of ~9, observes waves with an average amplitude of 0.27 nT; THEMIS-B, C and D at L-shells of 7.6, 7.4 and 7.0 respectively observe waves with average amplitudes of ~0.20 nT; and the innermost probe, THEMIS-A, observes waves with the smallest amplitude, 0.16 nT. Amplitudes were averaged over 5 minutes after the pulse arrival. This dependence of the wave amplitudes on L-shell yields a corresponding L-dependence of the conversion efficiency of the pressure pulse in initiating FLRs. A further investigation of a statistically significant ensemble of similar events would yield the underlying relationship between the power of broadband, fast-mode waves, which are initiated at the

magnetopause by a solar wind pressure pulse, and the power of the excited FLRs.

4. Summary and Conclusions

[15] Using THEMIS electric and magnetic field and GOES magnetic field measurements we investigated an event where toroidal mode, narrow-band FLRs are observed to be excited globally at different frequencies that match the local FLR frequency. The earth is within a high speed solar wind stream during this time. Using an instance when the intensification in FLR power coincides with a sharp increase in solar wind pressure and density, we are able to identify the impinging solar wind pressure pulse as an additional instantaneous and global excitation mechanism. The FLRs excited by the solar wind pressure pulse show an L-dependence of the amplitudes indicative of an L-dependence of the conversion efficiency of fast-mode compressional pulsations to FLRs.

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References

Agapitov, V., and O. K. Cheremnykh (2008), Natural oscillations in the Earth magnetosphere associated with solar wind sudden impulses, *Ukr. J. Phys.*, *53*(5), 506–510.

Agapitov, O., et al. (2009), Surface waves and field line resonances: A THEMIS case study, *J. Geophys. Res.*, *114*, A00C27, doi:10.1029/2008JA013553.

Auster, U., et al. (2008), The THEMIS fluxgate magnetometer, *Space Sci. Rev.*, *141*, 235–264, doi:10.1007/s11214-008-9365-9.

Baumjohann, W., H. Junginger, G. Haerendel, and O. H. Bauer (1984), Resonant Alfvén waves excited by a sudden impulse, *J. Geophys. Res.*, *89*, 2765–2769, doi:10.1029/JA089iA05p02765.

Bonnell, J., et al. (2008), The electric field instrument for THEMIS, *Space Sci. Rev.*, *141*, 303–341, doi:10.1007/s11214-008-9469-2.

Engebretson, M. J., L. J. Zanetti, T. A. Potemra, and M. H. Acuna (1986), Harmonically structured ULF pulsations observed by the AMPTE CCE Magnetic Field Experiment, *Geophys. Res. Lett.*, *13*, 905–908, doi:10.1029/GL013i009p00905.

Engebretson, M., et al. (1991), The role of the ionosphere in coupling upstream ULF wave power into the dayside magnetosphere, *J. Geophys. Res.*, *96*, 1527, doi:10.1029/90JA01767.

Glassmeier, K.-H., H. Volpers, and W. Baumjohann (1984), Ionospheric Joule dissipation as a damping mechanism for high latitude ULF pulsations: Observational evidence, *Planet. Space Sci.*, *32*, 1463–1466, doi:10.1016/0032-0633(84)90088-6.

Glassmeier, K.-H., et al. (1999), Magnetospheric field line resonances: A comparative planetology approach, *Surv. Geophys.*, *20*, 61–109, doi:10.1023/A:1006659717963.

Hasegawa, A. (1969), Drift mirror instability in the magnetosphere, *Phys. Fluids*, *12*, 2642, doi:10.1063/1.1692407.

Hudson, M., R. Denton, M. Lessard, E. Miftakhova, and R. Anderson (2004), A study of Pc-5 ULF oscillations, *Ann. Geophys.*, *22*, 289–302, doi:10.5194/angeo-22-289-2004.

Hughes, W. (1974), The effect of the atmosphere and ionosphere on long period magnetospheric micropulsations, *Planet. Space Sci.*, *22*, 1157–1172, doi:10.1016/0032-0633(74)90001-4.

Jacobs, J., Y. Kato, S. Matsushita, and V. Troitskaya (1964), Classification of geomagnetic micropulsations, *J. Geophys. Res.*, *69*, 180–181, doi:10.1029/JZ069i001p00180.

Kabin, K., R. Rankin, I. Mann, A. Degeling, and R. Marchand (2007), Polarization properties of standing shear Alfvén waves in nonaxisymmetric background magnetic fields, *Ann. Geophys.*, *25*, 815–822, doi:10.5194/angeo-25-815-2007.

Lee, D. H., and R. L. Lysak (1989), Magnetospheric ULF Wave coupling in the dipole model: The impulsive excitation, *J. Geophys. Res.*, *94*, 17,097–17,103, doi:10.1029/JA094iA12p17097.

Liu, W., et al. (2009), Electric and magnetic field observations of Pc4 and Pc5 pulsations in the inner magnetosphere: A statistical study, *J. Geophys. Res.*, *114*, A12206, doi:10.1029/2009JA014243.

Mann, I., A. Wright, and P. Cally (1995), Coupling of magnetospheric cavity modes to field line resonances: A study of resonance widths, *J. Geophys. Res.*, *100*, 19,441–19,456, doi:10.1029/95JA00820.

Radoski, H. R. (1967), Highly asymmetric MHD resonances: The guided poloidal mode, *J. Geophys. Res.*, *72*, 4026–4027, doi:10.1029/JZ072i015p04026.

Rae, I., et al. (2007), Multiple field line resonances: Optical, magnetic and absorption signatures, *Planet. Space Sci.*, *55*, 701–713, doi:10.1016/j.pss.2006.02.009.

Rankin, R., K. Kabin, and R. Marchand (2006), Alfvénic FLRs in arbitrary magnetic field topology, *Adv. Space Res.*, *38*, 1720–1729, doi:10.1016/j.asr.2005.09.034.

Rickard, G. J., and A. N. Wright (1994), Alfvén resonance excitation and fast wave propagation in magnetospheric waveguides, *J. Geophys. Res.*, *99*, 13,455–13,464, doi:10.1029/94JA00674.

Sarafopoulos, D. (1995), Long duration of Pc5 compressional pulsations inside the Earth's magnetotail lobes, *Ann. Geophys.*, *13*, 926–937, doi:10.1007/s00585-995-0926-x.

Sarris, T., et al. (2009), Characterization of ULF pulsations by THEMIS, *Geophys. Res. Lett.*, *36*, L04104, doi:10.1029/2008GL036732.

Sibeck, D., and V. Angelopoulos (2008), THEMIS science objectives and mission phases, *Space Sci. Rev.*, *141*, 35–59, doi:10.1007/s11214-008-9393-5.

Southwood, D. J., and M. G. Kivelson (1990), The magnetohydrodynamic response of the magnetospheric cavity to changes in solar wind pressure, *J. Geophys. Res.*, *95*, 2301–2309, doi:10.1029/JA095iA03p02301.

Southwood, D., J. Dungey, and R. Etherington (1969), Bounce resonant interaction between pulsations and trapped particles, *Planet. Space Sci.*, *17*, 349–361, doi:10.1016/0032-0633(69)90068-3.

Wright, A. N. (1992), Asymptotic and time-dependent solutions of magnetic pulsations in realistic magnetic field geometries, *J. Geophys. Res.*, *97*, 6439–6450, doi:10.1029/91JA02666.

Wright, A. N., K. J. Mills, M. S. Ruderman, and L. Brevdo (2000), The absolute and convective instability of the magnetospheric flanks, *J. Geophys. Res.*, *105*, 385–393, doi:10.1029/1999JA900417.

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