JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. A6, PAGES 12,361–12,371, JUNE 1, 1999

Simultaneous satellite and ground–based observations of a discretely driven field line resonance

M. R. Lessard[1] and M. K. Hudson
Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire

J. C. Samson
Department of Physics, University of Alberta, Edmonton, Alberta, Canada

J. R. Wygant
Department of Physics, University of Minnesota, Minneapolis

Abstract. An analysis is presented of a set of toroidal field line resonances observed on the ground by CANOPUS magnetometers and scanning auroral photometers on December 13, 1990, following a substorm onset at 0750 UT and intensification at 0850 UT. Magnetic and electric field data from the CRRES satellite provide evidence that the resonance was also observed in the magnetosphere. To our knowledge, this is the first report of discretely driven resonances observed by ground–based magnetometers and photometers and confirmed using satellite data. A spectral peak at 2.1 mHz is present in all data sets at approximately the same invariant latitude and universal time, indicating that CANOPUS and CRRES are observing the same resonance. Peaks are also present at 1.4 and 1.7 mHz in the ground–based magnetometer and CRRES data at a slightly higher latitude with corresponding spectral peaks apparent in the photometer data. The ground signature for each resonance indicates an antisunward phase velocity, suggesting that the excitation source is in the vicinity of the dayside magnetosphere, consistent with a waveguide model of the magnetosphere but not with a cavity model. This fact, combined with a possibly enhanced solar wind dynamic pressure, suggests that the substorm was not directly responsible for exciting the resonances. The interaction of the resonances with the substorm remains unclear except for the luminosity fluctuations associated with the resonances.

1. Introduction

Dungey [1963, 1968] investigated the possibility that ULF pulsations might result from standing waves in the magnetosphere. In his analysis, he studied the characteristics of waves in a cold plasma using a cylindrical geometry. Whether a cylindrical geometry or a dipolar geometry is used [*Radoski and Carovillano*, 1966], the system of equations decouples in two limits. The large–scale limit is usually associated with global phenomena and is characterized by a low azimuthal wave number ($m \to 0$), while the small–scale limit is relevant for local disturbances with scale size a small fraction of the magnetosphere and is characterized by a high azimuthal wave number ($m \to \infty$). For the purposes of this study, we concentrate on the $m \to 0$ limit. In this case, the equations decouple to reveal the possibility of two types of waves. One type, often called the toroidal mode, refers to waves where velocity and magnetic field perturbations are azimuthal, while electric field perturbations are radial, corresponding to a transverse Alfvén wave. The other possibility is a global scale fast mode wave, with associated magnetic field perturbations parallel to the background magnetic field.

Although it is possible in principle for either of these modes to exist in pure form, in nature this is not the case ($m \neq 0$), and there is normally some degree of coupling present. It has been suggested [*Allan and Poulter*, 1984; *Atkinson and Watanabe*, 1966; *Southwood and Hughes*, 1983] that this coupling allows the transfer of fast mode wave energy, excited by a stationary Kelvin–Helmholtz instability at the flanks of magnetopause, to toroidal resonances in the magnetosphere with low (< 10) azimuthal wave number. In this case,

[1] Now at Institute for Space Research, Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada.

Paper number 1998JA900117.
0148-0227/99/1998JA900117$09.00

the relatively broadband (and stationary) spectrum of the source couples to field lines over a significant range of L shells. A satellite crossing these field lines radially observes oscillations in the azimuthal component of the magnetic field with a frequency that changes smoothly as a function of radial distance. Satellites observe this type of structure most often and excellent examples of fundamental and harmonic resonances driven by broadband sources have been observed with AMPTE/CCE and have been reported by *Engebretson et al.* [1986], *Zanetti et al.* [1987], and *Anderson et al.* [1989, 1990].

On the other hand, the possibility of fast mode waves having discrete spectra also exists. *Kivelson et al.* [1984] developed a model where the magnetosphere acts as a cavity capable of supporting global standing fast mode waves which can couple to toroidal waves. These waves stand between an outer boundary such as the magnetopause [*Kivelson and Southwood*, 1985, 1986] or the bow shock [*Harrold and Samson*, 1992] and an inner boundary, usually the inner turning point for the wave. Inward of this turning point, the wave becomes evanescent but can couple its energy to field lines via tunneling if the frequency of the fast mode wave matches the natural frequency of the field line, setting up a field line resonance (toroidal mode oscillation). The fast mode waves (standing in the radial direction), have a quantized frequency spectrum and, since coupling efficiency should be significantly enhanced when a fast mode frequency matches a toroidal mode frequency (or a harmonic), the discrete spectrum of the fast mode waves should also be present in the toroidal mode waves.

Initially, it was thought that observations of "cavity-mode pulsations" should be straightforward. Since the fast mode waves have discrete spectra, a satellite moving through the magnetosphere in the presence of such a mode should detect oscillations at a single frequency (or, possibly, a set of discrete frequencies) in the magnetic field component along the direction of the background magnetic field (the compressional component). In principle this wave mode fills the magnetospheric cavity, so this signature should be independent of L shell and magnetic local time. In addition, if coupling to a toroidal mode is present, a satellite should also observe wave power in the azimuthal component at the same set of frequencies as the compressional component. The amplitude of this signal, however, should vary as the satellite crosses L shells. Since the coupling efficiency is significant only where frequencies match, in principle a satellite crossing L shells in the presence of a discretely driven field line resonance should observe an azimuthal signature of constant frequency but one that increases in amplitude as the satellite approaches the resonance and decreases in amplitude as the satellite moves away from the resonance. This signature could be present at the fundamental and harmonic frequencies of the field line (assuming these frequencies are present in the fast mode waves), keeping in mind that the position of the turning point of a fast mode wave depends on its frequency, so the cavity-mode frequencies will not obey the simple relation $f_n = nf_1$, where f is the frequency, f_1 is the fundamental and n indicates a harmonic [*Samson et al.*, 1991a]. However, the problem is somewhat complicated because, in reality, a transient frequency is also excited [*Allan et al.*, 1985, 1986] and the combined response of the driver and the transient appears to have a frequency variation with L shell [*McDiarmid and Allan*, 1990].

A number of authors have reported ground-based observations of discretely driven toroidal pulsations and associated them with cavity modes. *Crowley et al.* [1987] showed such data from radar and magnetometer observations associated with a sudden impulse. *Samson et al.* [1991a, 1992], *Ruohoniemi et al.* [1991], and *Ziesolleck and McDiarmid* [1994] used various combinations of radar and magnetometer data to show the presence of stable, discrete peaks in the frequency spectrum of resonances which they attributed to cavity modes. However, satellite observations have been sparse except for the report of a narrowband resonance by *Hughes et al.* [1978] and the work of *Kivelson et al.* [1984]. In fact, attempts to confirm ground-based observations with satellite observations have proven largely unsuccessful, with the exception of *Ziesolleck et al.* [1996], who used data from GOES 7 and CANOPUS to describe some statistical properties of these resonances. *Anderson et al.* [1989] determined that AMPTE/CCE does not observe either of the expected signatures of the presence of a cavity mode: a stable, L-independent discrete peak in the spectrum of the compressional component (evidence for the presence of a fast mode wave) or a corresponding discrete azimuthal signature over some narrow L shell (evidence for the resulting field line resonance). The same conclusion is reached by M. J. Engebretson and B. J. Anderson (A search for global mode ULF waves in the AMPTE/CCE data set, unsubmitted manuscript, 1995) using a more detailed analysis of AMPTE/CCE data and *Hughes and Singer* [1993], who used CRRES and GOES data and searched for persistent narrowband emissions in the compressional component. The difficulties involved in using satellites to observe narrowband resonances were explored by *Allan et al.* [1997], who simulated spacecraft transits across such resonances, demonstrating that elliptical orbits like that of AMPTE/CCE result in measurements that are too brief to obtain adequate spectral information. They also emphasize that the presence of a node at the equator (for fundamental resonances) complicates the observations. However, using data from the geosynchronous GOES 7 satellite (located $\sim 9°$ above the magnetic equator), *Ziesolleck et al.* [1996] succeeded in correlating signals with data from the CANOPUS chain, showing that the ground stations and satellite had the same discrete spectra and that they determined that these signals were associated with resonances, based on characteristics of the ground-based data.

Treatment of the magnetosphere as a closed cavity, however, is an approximation that does not take the shape of the magnetotail into account, and more recent work showed that that the stimulated toroidal resonances are better understood if the magnetosphere is characterized as a waveguide [*Samson and Harrold*, 1992]. *Walker et al.* [1992] also carried out a thorough analysis of radar data to refine the temporal and spatial character of field line resonances and associated them with a waveguide structure. Subsequently, numerical models that essentially considered the magnetosphere to be cylindrical with one end closed (representative of the dayside magnetosphere) and the other extending infinitely tailward were developed by *Wright* [1994] and *Rickard and Wright* [1994]. In this configuration, frequencies of fast mode waves that propagate along the axis of the cylinder are not quantized and waveguide modes just above the waveguide cutoff frequency are responsible for excitation of resonances. This means that the constant frequency fast mode wave that is independent of local time should not be observed in a waveguide (as would be expected with a cavity mode). Using such a model, *Rickard and Wright* [1995] successfully emulated field line resonance observations reported by *Lin et al.* [1992]. In addition, they were able to show that the fast mode signature associated with the waveguide model would not likely be observed by a satellite because its evanescent nature means that it will quickly decay in regions distant from the source.

Whether discretely driven resonances are excited by a cavity mode, a waveguide or some other source, their observation may be distinguished from those driven by stationary broadband sources. In the former case, wave power is observed over a narrow range of L shells, as thin as 0.3 to 0.6 R_E in the equatorial plane [*Samson and Rankin*, 1994]. *Mann et al.* [1995] showed that a resonance excited impulsively will initially be broadband but will become narrower, with spatial and spectral width nominally decreasing as $1/t$ to a final width proportional to $1/\sigma_P$. As long as the resonance is not excited again in an interval shorter than the time required for it to become narrow, an elliptically orbiting satellite would observe large fluctuations in the azimuthal component only during the brief period when it passes through the resonance, when it should detect a discrete frequency. In the stationary broadband case, however, all field lines (within some region) are excited by the source (assuming a relatively flat spectrum). Satellites moving through such regions commonly observe field line resonances of nearly constant amplitude but continuously changing frequency, since field line frequencies depend inversely on the Alfvén transit time, which increases with higher L [*Samson and Rostoker*, 1972].

Although the generation of field line resonances with discrete spectra is an intrinsically interesting problem, the role that these resonances play in substorm processes may be an equally important one. *Samson et al.* [1991b, 1992] and *Xu et al.* [1993] reported discrete peaks in substorm–related auroral arcs that appeared to be associated with resonances as indicated by magnetometer or radar data. In addition, observations reported by *Samson et al.* [1992] and *Xu et al.* [1993] show the presence of resonances before substorm onset, suggesting that the resonances may have something to do with substorm onset.

This work uses data from CRRES, GOES 6 and GOES 7 in combination with the CANOPUS chain in order to make direct comparisons of satellite to ground data during a time interval when a discretely driven field line resonances were observed on the ground. The combination of these three satellites is ideal for this type of study. While GOES 6 and GOES 7 provide geosynchronous data near the CANOPUS chain, CRRES (approaching apogee) slowly scans L shells on which the field line resonances are observed on the ground, allowing for the possibility of detecting a few cycles of oscillations within the very thin structure. In addition, data from the electric field instrument on CRRES are used to verify the existence of the resonances. The event discussed here is associated with a substorm and discrete spectral peaks are visible in scanning photometer data, although it is not possible to verify that the resonances were present before substorm onset. However, this study presents what we believe to be the first observation of field line resonances with discrete spectra observed on the ground in the magnetic and optical data and confirmed by a satellite.

We consider data from a single event on December 13, 1990. We first show that a resonance is observed on the ground just after substorm onset using magnetometer and photometer data (section 2). We then map the position of CRRES to the ground to confirm that it is near the same region and then demonstrate that it also detects the resonance (section 3). Finally, we use GOES data to search for a possible excitation source and show data suggesting that the origin of the fast mode waves may be associated with a moderate storm on the previous day (section 4). Section 5 provides a summary of our results with conclusions.

2. Ground–Based Measurements

We begin by discussing magnetometer and scanning photometer observations obtained at sites located along the Canadian Auroral Network for the OPEN Program Unified Study (CANOPUS) chain. Data were selected from the eastern meridional chain, an array of stations located near Hudson Bay, in order to obtain latitudinal information at approximately the same local time as that of the GOES satellites. Data were also selected from the east–west chain to obtain longitudinal information. The geographic locations of the stations are shown in Figure 1. A ring core fluxgate magnetometer at each site measures all three components of the Earth's magnetic field (recorded at 5–s intervals) with its axes aligned geographically so that X points to the

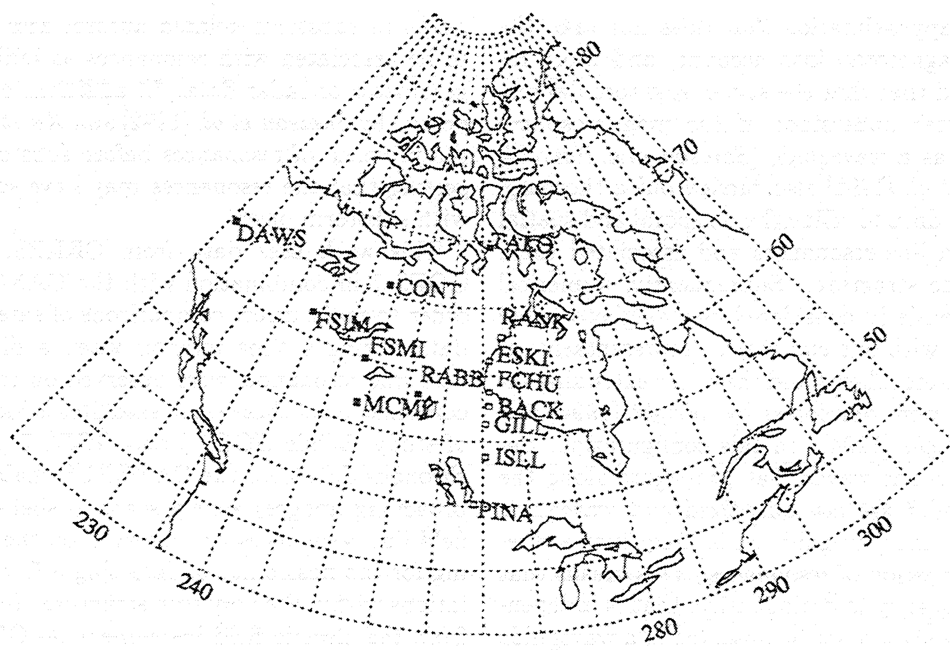

Figure 1. The geographic locations of stations in the CANOPUS chain. Data for this study were obtained at the eastern meridional sites, including Rankin Inlet, Eskimo Point, Fort Churchill, Back, Gillam, Island Lake, and Pinawa. Magnetic local time for all stations along the meridian is calculated approximately as LT=UT-6.7. Longitudinal information was extracted from data obtained at Dawson, Fort Simpson, Fort Smith, Rabbit Lake and Gillam.

north, Y to the east, and Z vertically downward. The declination (deviation from magnetic north) of the stations used in this study is less than or equal to 7.5°, so the X component of the data is used without modification and is taken to be basically aligned with magnetic north.

Meridian scanning photometers operate at Rankin Inlet, Gillam, Pinawa, and Fort Smith. Each site records auroral emissions at 4709, 4861, 5577, and 6300 Å, as well as background levels near 4800, 4935, and 6250 Å. Scans are completed every 30 s, during which time 510 samples are accumulated for each channel which are then averaged into 17 latitudinal channels, centered on the latitude of the station. These data are then averaged to yield a data period of 1 min. Bins are spaced 0.5° apart and are 0.5° wide (in magnetic latitude) for low–altitude emissions (110 km for 4709, 4861, and 5577 Å) and approximately 1.0° wide for high–altitude emissions (230 km for 6300 Å).

2.1. Magnetometer Observations

Figure 2 shows the X component of CANOPUS magnetic field observations on December 13, 1990, from 0600 to 1600 UT. The onset of a substorm (visible as a sudden decrease in the X component due to the presence of an auroral electrojet) can be seen to begin at approximately 0750 UT, just as the station passes local midnight, followed by an intensification near 0850 UT. Figure 3 shows the locations of the CANOPUS stations along with CRRES and the GOES satellites.

Substorms and auroral arcs have been associated with field line resonances by *Samson et al.* [1992, 1996], who showed that resonances associated with discrete arcs may play a role in substorm intensification. *Samson*

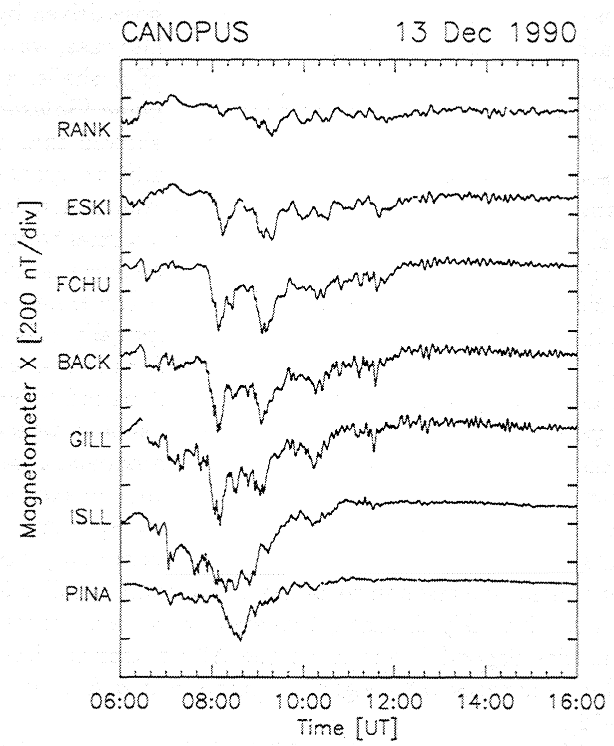

Figure 2. The X component of magnetic fields measured by the CANOPUS magnetometers. A substorm signature, visible as a sudden decrease in intensity due to a westward auroral electrojet, is apparent at 0750 UT, followed by an intensification near 0850 UT.

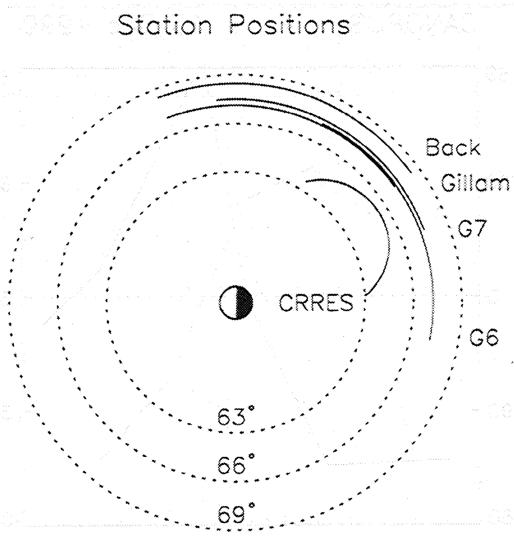

Figure 3. The locations of ground stations and satellites from 0900 to 1400 UT on December 13, 1990. Information is plotted in a polar coordinate system where magnetic invariant latitude is represented as the radial component and magnetic local time as the angular component. The labels (CRRES, Gillam, G6, etc.) indicate the location of each station at 0900 and the solid lines represent the paths of each station until 1400 UT. The outermost line represents the location of Back, the station at highest invariant latitude.

et al. [1996] showed that a resonance and a discrete auroral arc occurred before substorm onset (indicated by the presence of an auroral electrojet similar to that shown in Figure 2). They were also able to show the presence of Pi 2 pulsations in the magnetic field data, again occurring before the onset of an electrojet, and correlate these data with intensifications of the arcs. While it would be desirable to study this event in this context, the AE index jumps rapidly to values exceeding 200 nT at approximately 1700 UT on the day before this event and remains at elevated values throughout the period. The elevated activity during this time means that determining whether a resonance occurs before the substorm or vice versa is impossible with this data set. However, we show below that a resonance was observed shortly after the onset near 0750 UT and intensification near 0850 UT.

We point out that in order for a resonance to be observed on the ground, conductivity in the ionospheric E region must be significant [*Hughes*, 1974]. A standing Alfvén wave has a magnetic field component aligned primarily in the east–west direction and an electric field component that is oriented in the north–south direction. The Pedersen conductivity, in combination with the wave electric field, gives rise to a north–south Pedersen current, $\mathbf{j} = \sigma_P \mathbf{E}_\perp$. This current induces a magnetic field that cancels the wave magnetic field below the ionosphere. At the same time, the Hall conductivity enables an east–west current, $\mathbf{j} = -\sigma_H(\mathbf{E}_\perp \times \mathbf{B})/B$, that induces a secondary magnetic field which becomes the wave magnetic field observed on the ground. From these arguments, two important points emerge. First, if the Hall conductivity is too low, a magnetic signature may not be detectable on the ground. This is often the case in the nightside magnetosphere unless auroral activity (with its associated electron precipitation) is present. Such activity would be spatially nonuniform, implying that the ground signature would represent an incomplete measurement of the resonance. The second point is that a resonance observed on the ground will have a magnetic field component that is rotated 90° relative to its magnetospheric signature, meaning that the wave magnetic field of a resonance will be observed in the north-south direction on the ground instead of the east-west direction seen in the magnetosphere.

The spectral signatures of the X components of the magnetic field measured at Gillam and Back on December 13, 1990, from 0800 to 1300 UT are shown in Figure 4. Data were first detrended by subtracting a sliding average from the raw data (of approximately 30-min duration) and then a Hanning window was applied before calculating the Fourier transform. Units of power are arbitrary. We concentrate on the peaks at 1.4, 1.7, and 2.1 mHz but emphasize that activity during substorms is usually very complex and isolating narrow spectral peaks that may be associated with resonances can be difficult. We also point out that observation of the resonance after substorm onset does not necessarily mean that the resonance was absent before the substorm occurred. As discussed above, the increased Hall conductivity due to auroral electron precipitation is often necessary for detection of the signal on the ground.

The ground signature of field line resonances has been well studied observationally [*Ruohoniemi et al.*, 1991; *Samson*, 1972; *Samson and Rostoker*, 1972; *Ziesolleck and McDiarmid*, 1994] as well as theoretically [*Chen and Hasegawa*, 1974; *Southwood*, 1974]. For isolated resonances excited by a discrete source such as that under consideration here, two important features are

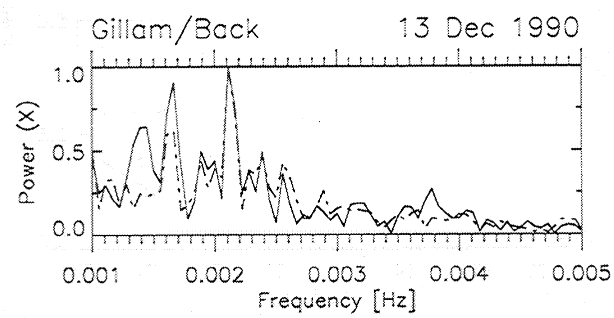

Figure 4. Spectra of the X component of Gillam and Back magnetometers on December 13, 1990, from 0800 to 1300 UT. Data were first detrended by subtracting a 30-min sliding average from the raw data and then a Hanning window was applied before calculating the Fourier transform. Gillam data are shown with a solid line, and Back data are shown with the dashed line.

predicted. First, the amplitude of the signal at the frequency of the resonance should vary with latitude, peaking at the latitude of the resonance. Typically, resonances observed using radar are only 1° or 2° in latitudinal width, while those measured using ground-based magnetometers are observed to be approximately 5° wide because of spatial integration. In addition to the amplitude variation, a change in the phase of the X component (as a function of latitude) should occur relative to the signal at the latitude of the resonance. Signals at latitudes higher than that of the resonance should lag the signal at resonance by up to 90° while those at lower latitudes should lead by as much as 90°. Figure 5 shows the amplitude and phase of the 2.1-mHz oscillations as a function of latitude. The results shown use magnetometer data from 1000 to 1200 UT, detrended as described above and then bandpass filtered from 2.0 to 2.3 mHz. The amplitude can be seen to peak near 68° latitude with the phase leading by 90° at lower latitudes and lagging by 90° at higher latitudes, providing evidence for a resonance near 68° latitude. Note that the phase is not plotted for latitudes where the power at 2.1 mHz becomes insignificant. Figure 6 shows the same information for the 1.4-mHz peak, using data from 1030 to 1200 UT which was band pass filtered from 1.2 to 1.6 mHz. Similarly, Figure 7 shows the characteristics of the 1.7-mHz peak over the same time interval, filtered from 1.5 to 1.8 mHz. These latter figures indicate the presence of two resonances occurring simultaneously at approximately 69° latitude. While the presence of a fundamental resonance coincident with a harmonic resonance is possible, the similar frequencies in this case seem to indicate that this is not the case here. There are at least two other possible reasons for detecting apparent resonances on the same field line. *McDiarmid and Ziesolleck* [1996] showed that resonances excited by a sequence of impulses may undergo amplitude or phase modulation that results in apparent phase jumps or skips in the data. Traditional analysis of these data will then show an altered spectrum that reflects a mix of the excitation and field line natural frequencies. It is also possible that the observation of simultaneous resonances is due to a significant spectral (and spatial) width of separate resonances. As discussed in the introduction, *Mann et al.* [1995] demonstrated that a resonance excited impulsively will initially be broadband but will become narrower, with spatial and spectral width nominally decreasing as $1/t$ to a final width proportional to $1/\sigma_P$, which could be $\sim 2-5\ R_E$ on the nightside.

Once the presence of a resonance has been verified, information regarding its propagation can be extracted by examining the relative phase of the signal with respect to longitude. By using magnetometer data from stations along the same approximate latitude (Dawson, Fort Simpson, Fort Smith, Rabbit Lake, and Gillam in Figure 1), we were able to conclude that for each resonance, the phase increased with longitude (not shown), suggesting westward propagation. Since the local time of the stations was after midnight for this event, the westward direction is antisunward. *Wright and Rickard* [1995] showed that field line resonance phase velocity is

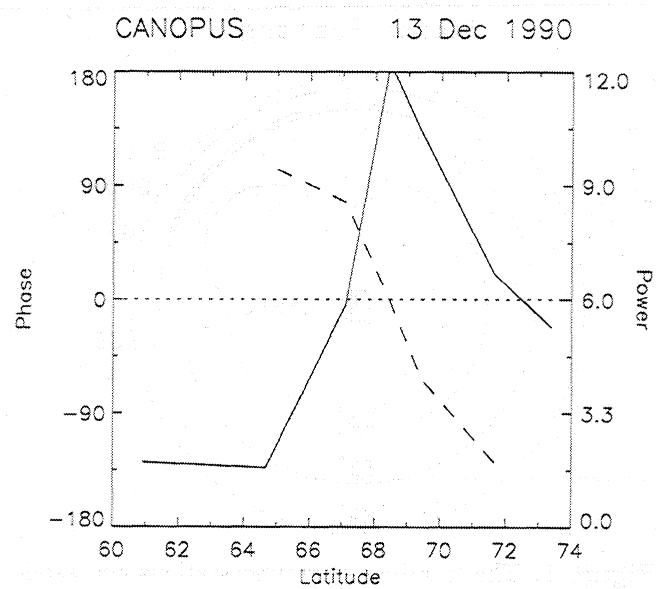

Figure 6. Amplitude and phase of 1.4-mHz oscillations in the X component of CANOPUS magnetometers from 1030 to 1200 UT on December 13, 1990. Data were detrended and band pass filtered from 1.2 to 1.6 mHz before calculating phase differences. The peak in amplitude occurring near 69° indicates the presence of a resonance at that latitude.

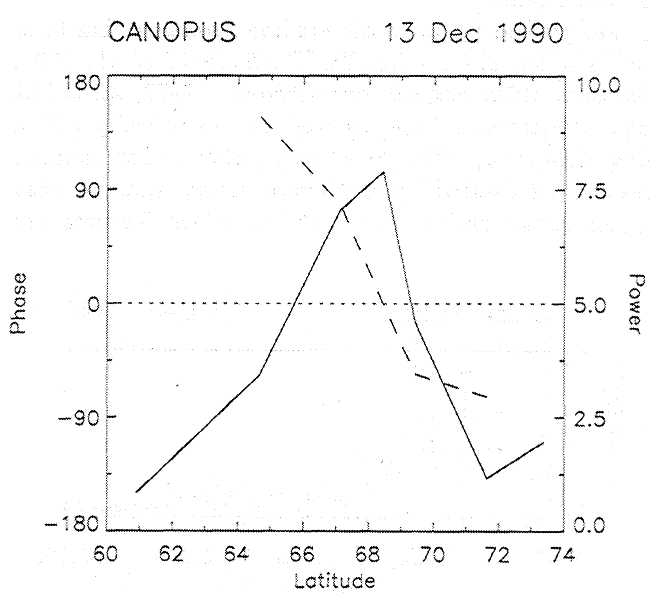

Figure 5. Amplitude and phase of 2.1-mHz oscillations in the X component of CANOPUS magnetometers from 1000 to 1200 UT on December 13, 1990. Data were detrended and band pass filtered from 2.0 to 2.3 mHz before calculating phase differences. The peak in amplitude occurring near 68° indicates the presence of a resonance at that latitude.

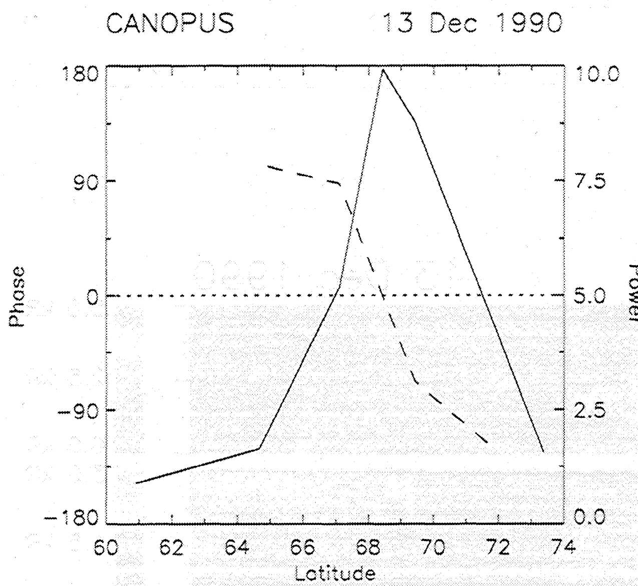

Figure 7. Amplitude and phase of 1.7–mHz oscillations in the X component of CANOPUS magnetometers from 1030 to 1200 UT on December 13, 1990. Data were detrended and band pass filtered from 1.5 to 1.8 mHz before calculating phase differences. The peak in amplitude occurring near 69° indicates the presence of a resonance at that latitude.

always directed away from the source of the fast mode waves, suggesting strongly that the source of the resonances was at or near the dayside.

2.2. Observations of Auroral Arcs

Plate 1 shows scanning photometer data at 5577 and 6300 Å observed at Fort Smith, Gillam, and Pinawa. Data are plotted as a function of magnetic invariant latitude, calculated using Altitude Adjusted Corrected Geomagnetic Coordinates (AACGM) [*Bhavnanni and Hein*, 1994]. This coordinate system is a development of the PACE coordinate system of *Baker and Wing* [1989]. The figure also shows the location of the CRRES satellite based on magnetic field models described below. The presence of aurora spanning 66° to approximately 69° at 5577 Å can be seen in the Gillam data from approximately 0930 through 1200 UT, corresponding to 0252 through 0522 magnetic local time. Fort Smith lags behind Gillam approximately 1.6 hours (see Figure 1) but still observes the arc at the same latitude.

Figure 8a shows the auroral intensity at 5577 Å observed from Gillam. The data displayed are centered at 68.5° and represents the average of 2 of the 17 latitudinal bins available. Figure 8b shows the spectrum of the data in Figure 8a and was obtained by first applying a Hanning window to the data and then calculating its Fourier transform. If we include bins at higher or lower latitudes in the spectrum calculation, the relative power at 2.1 mHz is significantly reduced, indicating that the spectral peak is associated with features occurring at 68.5°, effectively the same latitude as the resonance observed by the magnetometers. Note that Gillam is located at 67.4° magnetic latitude, so that the modulated arc is located approximately along the zenith direction. If this were not the case, oscillations in luminosity might be difficult to detect because they could be obscured by other adjacent arcs. Note, also, that no spectral peak at 2.1 mHz was observed in the 6300 Å data, which may mean that the precipitating electrons are fairly energetic, the order of several keV. If auroral electrons have energies of 2 or 3 keV, 6300 Å emissions are a factor of 20 or 30 less intense than 5577 Å emissions [*Steele and McEwen*, 1990].

Figure 9 shows data (processed in the same way) acquired at Fort Smith, located at 67.9° magnetic latitude or approximately 0.5° degrees northward of Gillam. The data displayed are centered at 69.0° in this case. Although no sign of a spectral peak at 2.1 mHz is present, peaks can be seen at approximately 1.3 and 1.8 mHz. Observation of these spectral peaks 0.5° degrees northward of the location of the 2.1–mHz peak is consistent with magnetometer observations and suggests that the resonances modulate the auroral luminosity.

3. CRRES Observations

The Combined Release and Radiation Effects Satellite (CRRES) was launched on July 25, 1990, into an elliptical orbit with a period of 9.87 hours, an inclination of 18.2° and an apogee of 6.3 R_E. The orbit of CRRES is ideal for this study because the decreased velocities near apogee mean that it crosses L shells near the region of interest relatively slowly, providing the opportunity for obtaining detailed latitudinal information. The slow speeds also mean that Doppler shifts of resonant frequencies due to satellite motion are negligible since the local Alfvén speed is at least 2 orders of magnitude greater than the satellite speed in the radial direction.

The white traces in Plate 1 show how the position of CRRES maps to magnetic invariant latitudes for this event. The dashed line in the figure was obtained by first using the T96 magnetic field model [*Tsyganenko*, 1996; *Tsyganenko and Stern*, 1996] to determine the geographic footprint of CRRES on the surface of the Earth. This information was then used as input to the AACGM model to calculate the corresponding magnetic invariant latitude in the same manner as for the photometer data. The solid white trace in Plate 1 was determined using the Olsen-Pfitzer magnetic field model [*Olsen and Pfitzer*, 1974]. While it shows that the apogee of CRRES occurred on field lines that mapped well to the aurora, the T96 model indicates that it occurred at field lines that mapped approximately 1.8° southward of the aurora. *Reeves et al.* [1996] evaluated the accuracy of a number of magnetic field models including the Olsen-Pfitzer model and older versions of the Tsyganenko models (not including the T96 model) using data from geosynchronous and DMSP

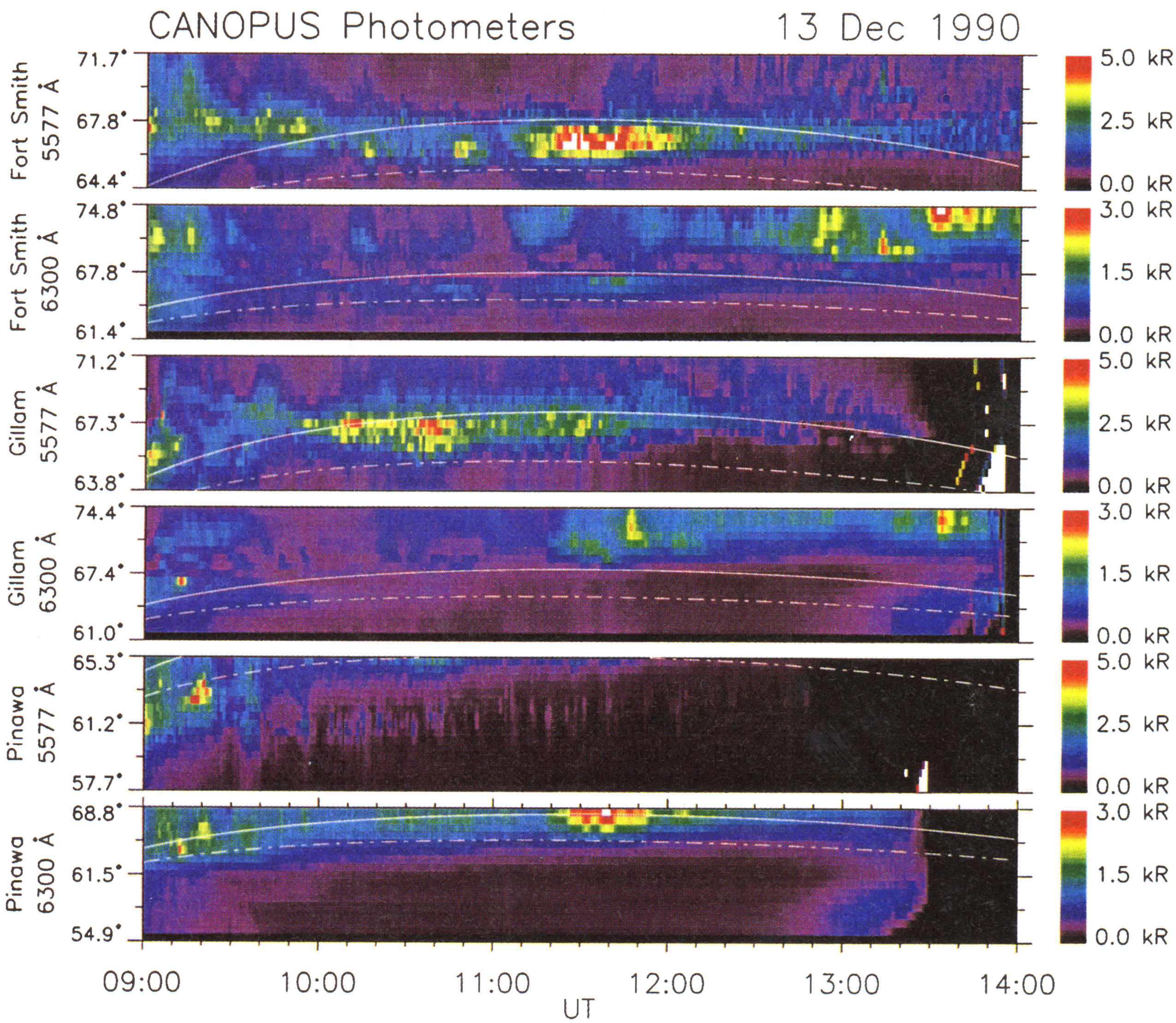

Plate 1. Meridian scanning photometer observations at Fort Smith, Gillam and Pinawa. The solid white line represents the mapping of CRESS using the Olsen-Pfitzer model. The dashed line represents the mapping of CRRES using the T96 model in combination with the AACGM model.

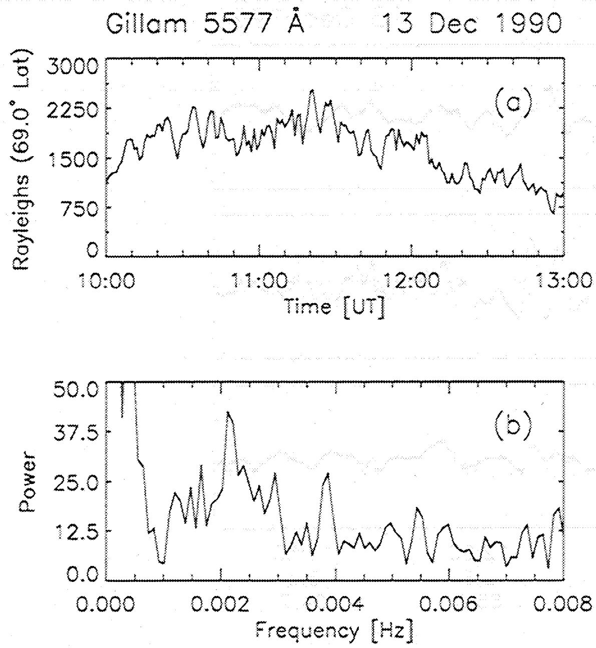

Figure 8. (a) Auroral intensity at 5577Å observed from Gillam at 68.5° invariant latitude. (b) The spectral power of the data in the upper panel. The presence of the 2.1-mHz peak is consistent with the magnetometer data in providing evidence for the presence of a field line resonance at that latitude.

spacecraft. They showed that these models tend to be accurate within 3° in fewer than 68% of the cases and that the models tended to err by predicting the latitude to be too low, as may be the case here. We take the observation of the 2.1-mHz resonance by CRRES (shown below) as an indication that the spacecraft did encounter the field lines that mapped to the aurora.

Figure 10 shows CRRES magnetic field data in a VDH coordinate system. In this system, which is cylindrical, V is in the magnetic meridian perpendicular to the dipole axis (radial at the magnetic equator), H is antiparallel to the dipole axis (parallel to the field at the equator) and D completes the triad, pointing eastward. The data are detrended by subtracting a background field, calculated point by point as follows [*Zhu and Kivelson*, 1991]. For each data point, a segment consisting of approximately 30 min worth of data (900 data points), whose midpoint occurs at the time of the data point, is fitted with a straight line. The value of the midpoint of the fitted line is taken to be the value of the background field at the time corresponding to the data point. Spectral information for the interval from 0900 to 1300 UT is shown in the bottom panels of Figure 10. The analysis was completed by applying a Hanning window to the detrended data and estimating the spectral power using a Fourier transform.

As discussed above, a field line resonance in the magnetosphere should be polarized in the azimuthal direction. We see from the spectra that peaks near 1.4, 1.7, and 2.1 mHz are present in the D component but not in either of the other components, implying that azimuthally polarized wave power is present at these frequencies. Other spectral peaks (in all components) of unknown origin are also present which may result from substorm activity whose onset occurred near 0750 UT followed by an intensification near 0850 UT. With ground-based evidence for the presence of resonances at 1.4, 1.7, and 2.1 mHz, reinforced by the presence of azimuthally polarized wave power observed by CRRES at these frequencies, we next seek to verify the observations of the resonances as observed by CRRES and to determine their spatial location.

If an Alfvén wave is set up as a standing wave, the electric and magnetic fields will no longer be in phase but will be out of phase by 90°. This characteristic has been used as evidence for the presence of a standing wave in the past [*Singer et al.*, 1982]. In order to show that this is the case here, we plot the Hilbert transform of the electric field data along with the magnetic field data. Since the Hilbert transform of a signal simply induces a phase shift of 90° in all Fourier components of the signal, the fields of a standing wave plotted using this technique should appear to be in phase [*Dubinin et al.*, 1990]. Figure 11 shows the Y component of magnetic field data (solid line) and the Hilbert transform of the X component of electric field data (dashed line) in a GSE coordinate system. This system is used here because the orientation of CRRES was such that its spin axis was roughly parallel to the Y component of a GSE system. Electric fields were measured in a plane per-

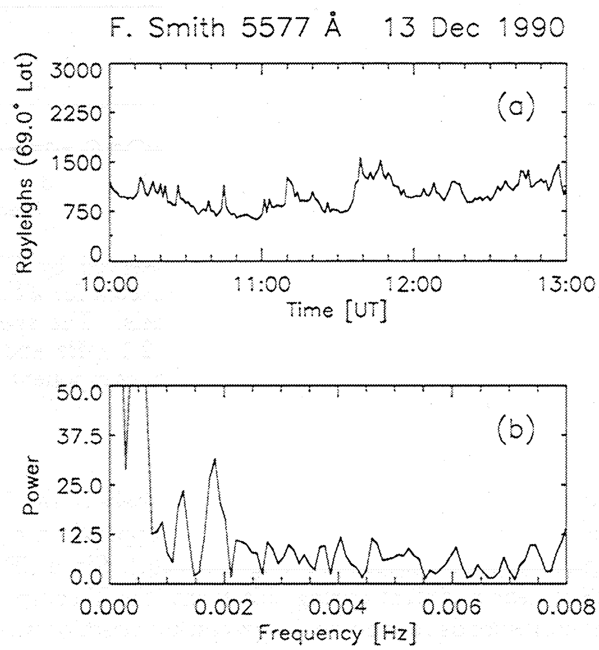

Figure 9. (a) Auroral intensity at 5577Å observed from Fort Smith at 69.0° invariant latitude. (b) The spectral power of the data in the upper panel. The presence of spectral peaks near 1.3 and 1.8 mHz observed slightly northward of the location of the 2.1-mHz peak is consistent with magnetometer observations and suggests that the resonances modulate the auroral luminosity.

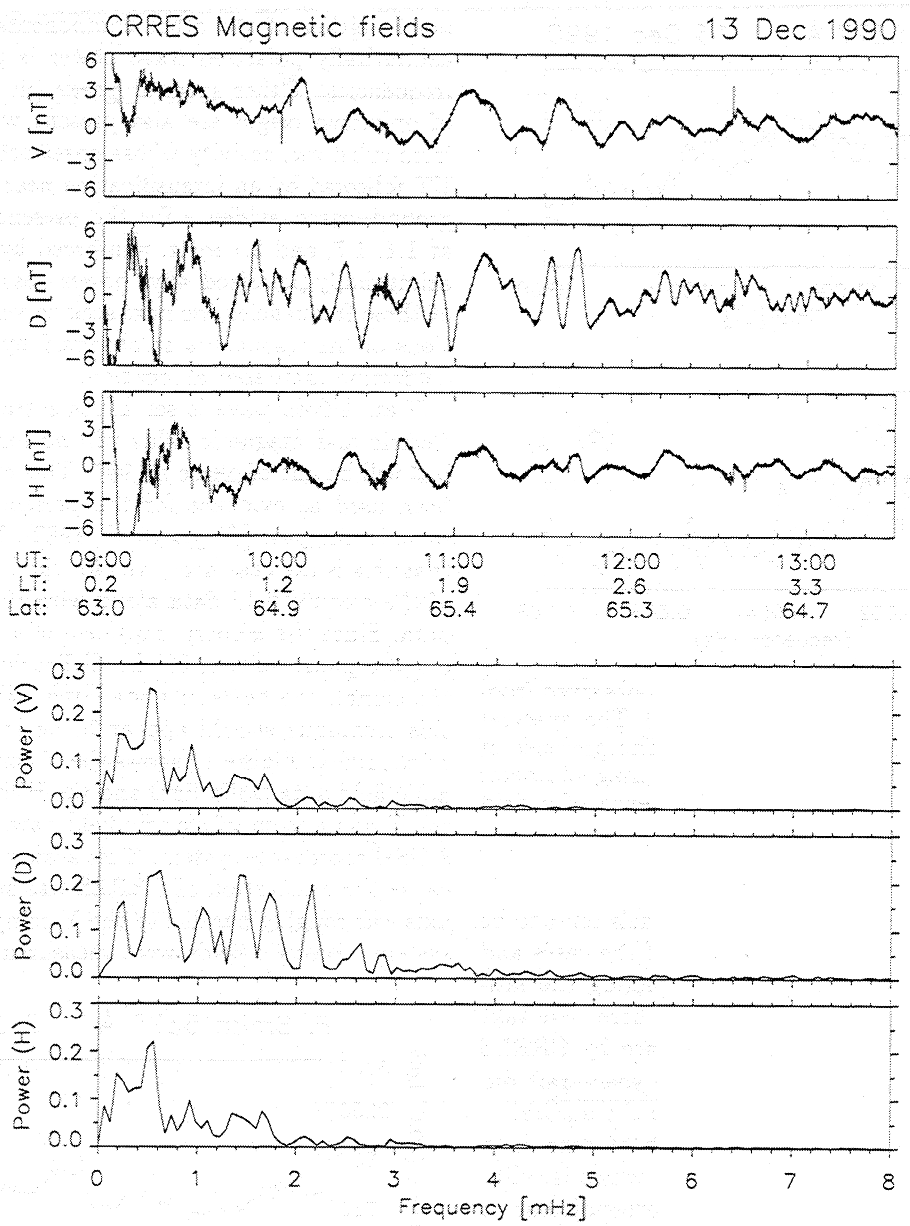

Figure 10. Magnetic fields observed by CRRES. Data are presented in a VDH coordinate system, described in the text. Spectra for all components are calculated using the entire interval and are shown in the lower panels. The spectrum of the D (eastward azimuthal) component shows distinct peaks at 1.4 and 2.1 mHz and a less distinct peak at 1.7 mHz. A signal having dominant power in the azimuthal component is typical of the signature of a field line resonance observed by a satellite.

pendicular to the spin axis, or approximately in the X direction (recall that the Z direction is approximately aligned with the background magnetic field). Since CRRES is near midnight during this event, the Y component corresponds roughly to the azimuthal direction and X is approximately radial. For each panel, data are filtered using a band pass filter with low and high cutoffs chosen to isolate the spectral peaks. Figure 11a shows data filtered from 1.3 to 1.6 mHz, isolating the 1.4 mHz peak. The amplitudes of both signals increase gradually after 1000 UT as the satellite approaches apogee and their phases merge (indicating the presence of a resonance) as their amplitudes peak near 1120 UT. According to the magnetic field models we used (T96 and AACGM), apogee occurs at 1111 UT at an invariant latitude of 65.4°. Since the amplitudes peak at apogee, we conclude that CRRES may not have actually passed through the resonance, although it is reasonable to estimate the center of the resonance to be near this latitude.

Figure 11b shows the same format using data filtered from 1.6 to 2.0 mHz, isolating the 1.7 mHz peak. The signature at this frequency is almost identical to that of the 1.4 mHz peak, suggesting the presence of an additional resonance at this latitude. The apparent presence

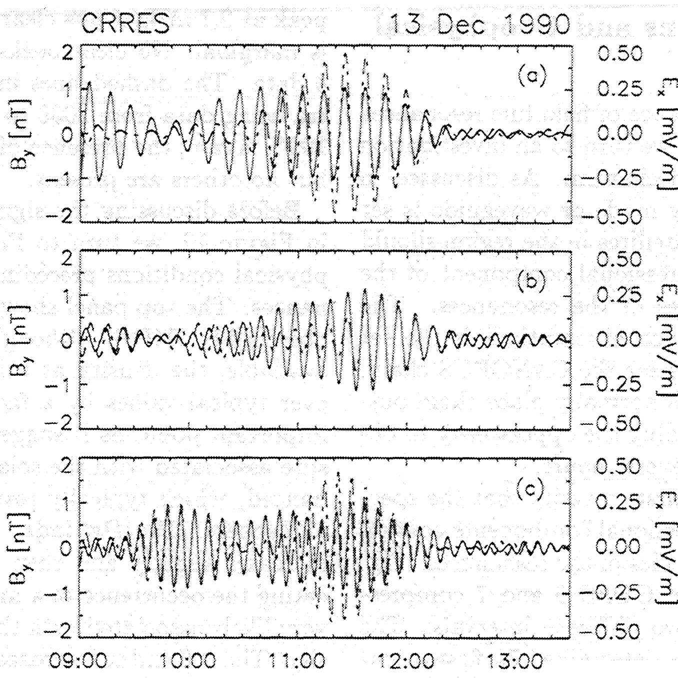

Figure 11. Magnetic fields (solid line) and the Hilbert transform of electric fields (dashed line) observed by CRRES. Because a Hilbert transform induces a phase shift at all frequencies, when both signals appear to be in phase in this figure they are actually 90° out of phase, indicating a standing wave structure. (a) Data filtered from 1.3 to 1.6 mHz to isolate the spectral peak at 1.4 mHz; (b) data filtered from 1.6 to 2.0 mHz to isolate the 1.7 mHz peak; (c) data filtered from 1.9 to 2.5 mHz to isolate the peak at 2.1 mHz.

of two resonances at the same latitude was also noted in the analysis of ground magnetometer data, discussed above, where it was noted that such a characteristic may result from spectral modification due to a sequence of impulsive excitations [*McDiarmid and Ziesolleck*, 1996] or may simply be an artifact of two separate resonances whose spectral and spatial width is initially relatively broad [*Mann et al.*, 1995].

Figure 11c shows magnetic and electric field data filtered from 1.9 to 2.5 mHz in order to characterize the 2.1–mHz peak. The phases can be seen to merge and the amplitudes reach a maxima at 1000 UT, indicating a resonance at this time, corresponding to approximately 64.9° invariant latitude. A second maxima in amplitude occurs at 1120 UT (at the same time that the other resonances were observed), but the frequencies of the electric and magnetic fields are slightly different, and this does not appear to be the signature of a resonance.

To summarize what we have discussed so far, first, the spectral signature of ground based magnetometer data immediately following a substorm was shown. Three spectral peaks were noted and we demonstrated for each case that when its amplitude is plotted as a function of latitude a clear peak is present, providing an indication of a possible resonance at that latitude. The observation of a resonance at each frequency was verified by plotting phase differences as a function of latitude and showing that a 180° shift occurs across the resonance. In addition, the longitudinal phase characteristics were investigated at each frequency, and we determined that the excitation mechanism must be antisunward of the station locations, or in the vicinity of the dayside magnetosphere. It was then shown that corresponding spectral peaks were also present in scanning photometer data, suggesting (as has been done previously by other authors) that the resonances are related to auroral luminosity.

Having determined that resonances are observed on the ground, we then turned to data from the CRRES satellite. The T96 and AACGM models were used to show that the position of CRRES maps closely to the invariant latitude of the observed resonances. A spectral analysis of CRRES magnetic field data was carried out, and it was shown that the same three spectral peaks are present primarily in the azimuthal component. The waveform at each frequency was then isolated by band pass filtering the data and showing that it was 90° out of phase with the electric field data that had been filtered in the same way, providing strong evidence for the presence of a standing wave. The 2.1–mHz resonance was observed to occur at a lower invariant latitude than those at 1.4 and 1.7 mHz, which appeared to occur at the same latitude. These results are consistent with the ground based results.

4. GOES Observations and Geophysical Conditions

With data providing evidence of field line resonances on the ground and in space, we turn to an investigation of the possible excitation mechanism. As discussed in the introduction, if a cavity mode or waveguide is set up in the magnetosphere, satellites in the region should observe power in the compressional component of the magnetic field at frequencies of the resonances. The best platform for making such observations is the set of GOES satellites, located near the CANOPUS chain. Their geosynchronous orbits normally place them outside the plasmapause, providing the opportunity to obtain continuous data over several hours.

The approach we take is first to verify that the spectral signature of the compressional components contain discrete peaks at the frequencies of the resonances. Figure 12 shows the spectra of GOES 6 and 7 compressional data calculated at two different intervals. The compressional waveform was determined by first calculating the background field as a 30-min sliding average of the raw data. For each component, the average field was then subtracted from the raw data to yield the wave magnetic field. The compressional component is then $\mathbf{b} \cdot \mathbf{B}/B$, where $\mathbf{B}$ is the background field and $\mathbf{b}$ is the wave magnetic field. A Hanning window was applied to the data which were then Fourier transformed to estimate the spectral power. The solid lines in the figure represent spectra using data from 1000 to 1330 UT on December 13, approximately the same time interval that CRRES observed the resonances. While the

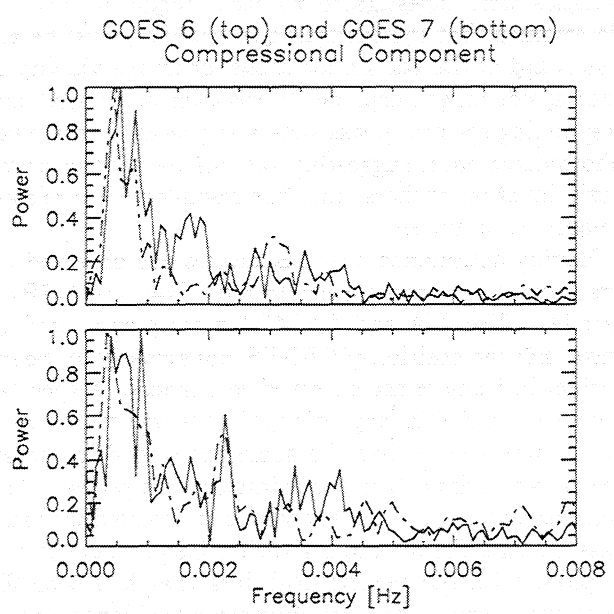

Figure 12. Spectra of the compressional components of GOES 6 and 7. The solid lines represent spectra using data from 1000 to 1330 on December 13, 1990. The dashed lines represent spectra using data from 2030 to 2300 on December 12. We regard the only significant peak to be near 2.1 mHz using the GOES 7 data.

peak at 2.1 mHz seems clear, power at 1.4 and 1.7 mHz is marginal. No clear peaks are present in the GOES 6 data. The dashed lines in the figure represent spectra using data from 2030 to 2300 UT on December 12, 1990. Again, the presence of a peak at 2.1 mHz is clear but no others are present.

Before discussing the significance of the data shown in Figure 12, we turn to Figure 13, which shows geophysical conditions preceding observations of the resonances. The top panel shows the solar wind density as observed by IMP 8. Although only a few data points are available, the density at this time is clearly enhanced over typical values by a factor of 3 or 4. This is an important point, as it suggests that the dynamic pressure associated with the solar wind must have been enhanced, which typically results in a compressed magnetosphere. The *Dst* index (shown in the third panel) increases slightly and then drops to ~ -40 nT, indicating the occurrence of a moderate storm at this time, very likely associated with the increased solar wind density. The AE index increases abruptly shortly after the *Dst* begins to decline, signifying the onset of a substorm. Varying levels of increased substorm activity continue until $\sim$ 0930 UT, just before the resonances are observed. The peak in AE at 800 nT is apparently associated with the substorm that occurred initially at 0750 with a subsequent intensification at 0850 UT in the CANOPUS data. The fourth panel shows the unfiltered northward component of the magnetic field measured by GOES 6 and 7. Although a diurnal effect routinely manifests itself as an increase in this component as the satellites cross the dayside, the level associated with this event exceeds the norm by at least 30 nT. All of the information presented here indicates that the magnetosphere was compressed by an increase in solar wind density (and likely the velocity, although these data are not available).

The conditions described here should be favorable for setting up cavity mode or waveguide pulsations. In either case, the scenario is that a relatively quiet magnetosphere is perturbed by a jump in solar wind intensity. The perturbation sets up fast mode waves that comprise the discrete set required to excite toroidal resonances at discrete frequencies. With these ideas in mind, we look for evidence of the discrete fast mode waves in the GOES data.

The two bottom panels of Figure 13 show the compressional components of GOES 6 and 7 beginning at 1000 UT on December 12. The data have been filtered from 2.0 to 2.3 mHz in order to isolate the waveform corresponding to the spectral peak at 2.1 mHz, although we do not mean to suggest that an intensification at this frequency will necessarily be narrowband. The filtered data are displayed along with magnetic indices in an attempt to identify the time and geophysical conditions present when compressional power at 2.1 mHz intensified. From Figure 13, it is clear that there is no point where a distinct increase occurs followed by generally

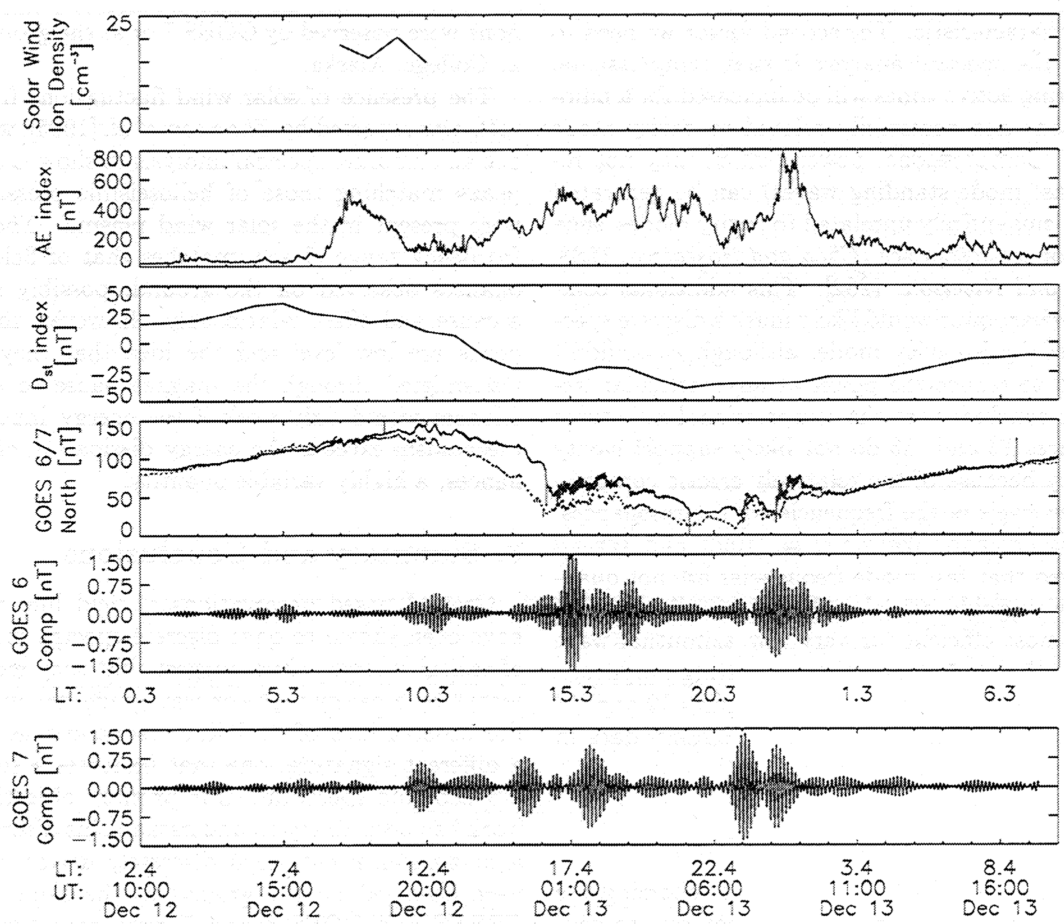

Figure 13. Top panels show the solar wind density, the *AE* index and the *Dst* index beginning at 1000 UT on December 12, 1990. A magnetic storm results in an increase in *Dst* followed by a decrease, resulting from the intensified ring current. The increase is associated with a compression of the magnetosphere, visible as an increase of the northward components of magnetic fields observed by the GOES satellites. The compressional signal at 2.1 mHz at each satellite is presented in the lower panels. Activity at this frequency appears to begin to increase simultaneously near 2000 UT.

higher power at this frequency. However, both satellites do observe a modest increase near 1900 UT on December 12, when they were located near local noon. The waveform after this time continues to show variable power levels at both satellites. A similar analysis was carried out for the 1.4– and 1.7–mHz signals (not shown). The waveform at both of these frequencies was quiet before the *Dst* index began to decrease. At 1700 UT, coincident with the rapid increase in AE, both of the satellites observed a clear increase in wave power at both frequencies. As in the case of the 2.1–mHz signal, power levels then fluctuated significantly at both satellites.

Considering that both satellites continue to observe these waves as they move from noon to beyond midnight, the data in the figure show that compressional power at frequencies of the resonances is present on a global scale. However, the cavity mode scenario requires that the compressional power have a discrete spectrum. We showed above that the spectrum of the GOES 7 data contained modest peaks at the time the resonances were observed. The dashed line in Figure 12 shows spectra calculated using data from 2030 to 2300 UT on December 12, when the satellites were still located near noon. A peak is again present at 2.1 mHz in the GOES data. However, spectral analysis of data at other times shows it to be often broadband and discrete peaks are generally absent.

We now consider what implications these data may have regarding the existence of cavity mode or waveguide pulsations. Two factors influence the spectrum of the compressional signal observed by GOES. First, the compressional fast mode signal, which would be a standing wave in the cavity mode picture, would have nodes and antinodes. As the satellites move in local time, they also move in L shell because of the changing size of the magnetosphere during this time and because of the changing shape, especially near midnight. For these reasons, the filtered waveform, as presented in Figure 13, should not be expected to show a constant amplitude, although the satellites might be expected to observe the same (slowly changing) amplitude versus local time characteristic. The second factor we need to consider in the spectral analysis is that compressional activity during active times will be increased for a number of reasons not necessarily related to cavity mode structures. Compressional power (which may not result from fast mode standing waves) can be generated via mechanisms entirely unrelated to cavity modes, such as a drift bounce resonance [*Chen and Hasegawa*, 1988; *Southwood and Kivelson*, 1982]. This additional compressional wave power would likely mask a discrete spectrum excited by a cavity mode, although it wouldn't be expected to reduce the power at any particular frequency. We conclude that the compressional signatures shown Figures 12 and 13 do not likely support cavity mode theory because of the relatively erratic compressional power levels at the frequencies of the resonances.

On the other hand, *Walker et al.* [1992] and *Wright* [1994] showed that fast mode frequencies are not quantized in a waveguide model and that coupling to resonances is most efficient for very low azimuthal wave numbers. If this is the case, the fluctuating amplitude of the compressional power shown in Figures 12 and 13 have little meaning and the analysis of GOES data in this respect is difficult to interpret.

5. Other Possible Sources

Finally, we briefly discuss other works reporting the existence of discrete spectra that are not due to cavity modes. *Cahill and Winckler* [1992] reported oscillations of the magnetopause at 3 ± 1 mHz associated with the storm on March 24, 1991. They conclude that the oscillations may be related to tailward moving surface boundary waves excited by a Kelvin-Helmholtz instability, although it is not suggested that the instability would emit fast mode waves at this frequency. *Miura and Pritchett* [1982] developed a model of the Kelvin-Helmholtz instability at the magnetopause and showed results predicting that the spectrum of fast mode waves resulting from the instability should be fairly broadband, typically ranging from 3 to 10 mHz, but dependent on the thickness of the velocity shear layer. However, A. Miura (personal communication, 1998) suggests that the southward interplanetary field that was present would result in reconnection that may somehow interact with the Kelvin-Helmholtz instability and be responsible for narrowing the spectral signature. We point out, however, that the resonances reported here occur near midnight, while the Kelvin-Helmholtz instability would tend to occur near the flanks of the magnetopause.

Cahill and Winckler [1992] also considered whether the source of the magnetopause oscillations may be due to solar wind pressure variations at the bow shock. This idea was discounted, however, because compressional pulsations of similar period should then also occur in the dayside magnetosphere and on the ground, however none were observed by GOES 7 or at the ground station at College, Alaska.

The presence of solar wind fluctuations from 1 to 4 mHz was reported by *Thomson et al.* [1995], who carried out an elaborate spectral analysis to show that spectral peaks matching those of helioseismic pressure modes were present in the solar wind plasma. The reported frequency range closely matches that of field line resonances observed on the ground, possibly suggesting a cause and effect relationship. However, the spectral peaks are low level and the idea that they could be transmitted through the magnetopause to excite resonances would only work if the energy input via this mechanism exceeds the energy dissipation of the resonances, a highly variable quantity.

6. Summary and Conclusions

Ground–based observations of field line resonances have been shown to have discrete spectra in a number of earlier studies, which suggest that they may be generated by a cavity mode or waveguide structure. Satellite observations of field line resonances usually have a different signature, one that indicates a source with a broadband spectrum. Our primary objective in this work has been to try to understand this discrepancy by analyzing an event when discretely driven resonances were observed on the ground at the same time that CRRES and GOES 6 and 7 were near the same region. The event considered in this study was observed just after substorm onset, although a limited number of studies report observations of such resonances before onset. The question of what role field line resonances might play in substorms is not answered in this work, although we believe this to be the first report of observations of field line resonances with discrete spectra observed on the ground in the magnetic and optical data and confirmed by a satellite.

We summarize our results as follows:

1. We showed that resonances with antisunward phase velocity were observed using ground based magnetometers and that spectral peaks were present in the associated scanning photometer data. We take this as an indication that auroral luminosity was being modulated by the resonances, consistent with the work of other authors [*Samson et al.*, 1991b, 1992; *Xu et al.*, 1993]. The resonances in this case were observed after the onset of a substorm. We believe that they may have been present before the onset and that the increased Hall conductivity due to auroral electron precipitation was necessary before they could be observed on the ground. It might be suggested that substorm activity was somehow responsible for excitation of the resonances, but a number of previous reports show the presence of resonances before substorm onset. In addition, their antisunward phase velocity indicates that the source of their excitation likely originated at the day-

side magnetosphere, suggesting that the substorm was not the cause of the resonances..

2. We mapped the footprint of CRRES during the same interval and showed that, within the error of the T96 and AACGM models, its apogee was near the invariant latitude of the resonances. We then showed the presence of the same spectral peaks in CRRES data as in the ground data and were able to show that electric and magnetic fields were 90° out of phase at these frequencies, providing strong evidence for standing waves (resonances). The procedure we used is straightforward but relies critically on using data from a satellite whose apogee is near the resonance (CRRES) so that the slower spacecraft speeds allow detection of a number of waveforms. Previous attempts to search for brief, large amplitude azimuthal signals using AMPTE/CCE data have been unsuccessful [*Anderson et al.*, 1989], although *Allan et al.* [1997] showed that the elliptical orbit of AMPTE/CCE, combined with the low-level signal associated with the node of a fundamental resonance near the equatorial plane, would make such observations by AMPTE/CCE very difficult.

3. We then used data from GOES 6 and 7 in an attempt to verify the existence of a cavity mode by showing the presence of the same discrete spectra in the compressional component of their magnetic fields. Although global scale compressional perturbations observed by both GOES satellites appear to be associated with a moderate storm, we have not been able to show that the spectrum is discrete over the interval beginning with the arrival of the storm to the observation of the resonances. We conclude that the GOES data do not provide evidence supportive of a cavity mode, although it does not preclude the presence of a waveguide structure.

The most likely scenario is that the quiet magnetosphere was perturbed by a jump in solar wind intensity (as seen by the increased density observed by IMP 8). The perturbation excited fast mode waves in the waveguide that propagated antisunward and excited the observed field line resonances and subsequent auroral luminosity fluctuations. The role of the substorm associated with this event is not clear except that it likely was responsible for the auroral arcs in some way.

Acknowledgments. We gratefully acknowledge helpful conversations with R. E. Denton, J. Goldstein, J. LaBelle, and W. Lotko. Research by J. C. Samson is supported by the Natural Sciences and Engineering Research Council of Canada. Research at Dartmouth College was supported by NASA grants NAG 5-1098, NAG 5-2252, and NGT 5-500059. The CANOPUS instrument array was constructed and is maintained and operated by the Canadian Space Agency for the Canadian scientific community. CRRES data were supplied by J. Hughes at Boston University under grant NAG5-3868. Principal investigator of the CRRES magnetic field experiment is H. Singer and of the electric field experiment is F. Mozer. Data from the GOES satellites were supplied by NOAA/National Geophysical Data Center. The *AE* index is provisional and was supplied by Sasha Yaknin of the Polar Geophysical Institute.

Janet G. Luhmann thanks Donald R. McDiarmid and Andrew N. Wright for their assistance in evaluating this paper.

References

Allan, W., and E. M. Poulter, The spatial structure of different ULF pulsation types: A review of STARE radar results, *Rev. Geophys.*, *22*, 85, 1984.

Allan, W., S. P. White, and E. M. Poulter, Magnetospheric coupling of hydromagnetic waves – Initial results, *Geophys. Res. Lett.*, *12*, 287, 1985.

Allan, W., S. P. White, and E. M. Poulter, Impulse–excited hydromagnetic cavity and field–line resonances in the magnetosphere, *Planet. Space Sci.*, *34*, 371, 1986.

Allan, W., A. N. Wright, and D. R. McDiarmid, Spacecraft transits across simulated field line resonance regions, *J. Geophys. Res.*, *102*, 14,407, 1997.

Anderson, B. J., M. J. Engebretson, and L. J. Zanetti, Distortion effects in spacecraft observations of MHD toroidal standing waves: Theory and observations, *J. Geophys. Res.*, *94*, 13,425, 1989.

Anderson, B. J., M. J. Engebretson, S. P. Rounds, L. J. Zanetti, and T. A. Potemra, A statistical study of Pc 3–5 pulsations observed by the AMPTE/CCE magnetic fields experiment, 1, Occurrence distributions, *J. Geophys. Res.*, *95*, 10,495, 1990.

Atkinson, G., and T. Watanabe, Surface waves on the magnetosphere boundary as a possible origin of long period micropulsations, *Earth Planet Sci. Lett.*, *1*, 89, 1966.

Baker, K. B., and S. Wing, A new magnetic coordinate system for conjugate studies at high latitudes, *J. Geophys. Res.*, *94*, 9139, 1989.

Bhavnanni, K. H., and C. A. Hein, An improved algorithm for computing altitude dependent corrected geomagnetic coordinates, *Tech. Rep. PL-TR-94-2310*, Phillips Lab, 1994.

Cahill, L. J., Jr., and J. R. Winckler, Periodic magnetopause oscillations observed with the GOES satellites on March 24, 1991, *J. Geophys. Res.*, *97*, 8239, 1992.

Chen, L., and A. Hasegawa, A theory of long–period magnetic pulsation, 1, steady state excitation of field line resonance, *J. Geophys. Res.*, *79*, 1024, 1974.

Chen, L., and A. Hasegawa, On magnetospheric hydromagnetic waves excited by energetic ring-current particles, *J. Geophys. Res.*, *93*, 8763, 1988.

Crowley, G., W. J. Hughes, and T. B. Jones, Observational evidence of cavity modes in the Earth's magnetosphere, *J. Geophys. Res.*, *92*, 12,233, 1987.

Dubinin, E. M., P. L. Israelevich, and N. S. Nikolaeva, Auroral electromagnetic disturbances at an altitude of 900 km: the relationship between the electric and magnetic field variations, *Planet. Space Sci.*, *38*, 97, 1990.

Dungey, J. W., The structure of the exosphere or adventures in velocity space, in *Geophysics, The Earth's Environment*, edited by C. Dewitt, p. 537, Gordon and Breach, New York, 1963.

Dungey, J. W., Hydromagnetic waves, in *Physics of Geomagnetic Phenomena*, edited by S. Matsushita and W. H. Campbell, p. 913, Academic, San Diego, Calif., 1968.

Engebretson, M. J., L. J. Zanetti, T. A. Potemra, and M. H. Acuña, Harmonically structured ULF pulsations observed by the AMPTE CCE magnetic field experiment, *Geophys. Res. Lett.*, *13*, 905, 1986.

Harrold, B. G., and J. C. Samson, Standing ULF modes of the magnetosphere: A theory, *Geophys. Res. Lett.*, *19*, 1811, 1992.

Hughes, W. J., The effect of the atmosphere and ionosphere on long period magnetospheric micropulsations, *Planet. Space Sci.*, *22*, 1157, 1974.

Hughes, W. J., and H. J. Singer, A search for MHD magnetospheric cavity modes using CRRES and GOES magnetometer data, *EOS Trans. AGU*, *74* (43), AGU Fall Meet, 506, 1993.

Hughes, W. J., R. L. McPherron, and J. N. Barfield, Geomagnetic pulsations observed simultaneously on three geostationary satellites, *J. Geophys. Res.*, *83*, 1109, 1978.

Kivelson, M. G., and D. J. Southwood, Resonant ULF waves: A new interpretation, *Geophys. Res. Lett.*, *12*, 48, 1985.

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

Kivelson, M. G., J. Etcheto, and J. G. Trotignon, Global compressional oscillations of the terrestrial magnetosphere: The evidence and a model, *J. Geophys. Res.*, *89*, 9851, 1984.

Lin, N., M. J. Engebretson, L. A. Reinleitner, J. V. Olsen, D. L. Gallagher, L. J. Cahill Jr., J. A. Slavin, and A. M. Persoon, Field and thermal plasma observations of ULF pulsations during a magnetically disturbed interval, *J. Geophys. Res.*, *97*, 14,859, 1992.

Mann, I. R., A. N. Wright, and P. S. Cally, Coupling of magnetospheric cavity modes to field line resonances: A study of resonance widths, *J. Geophys. Res.*, *100*, 19,441, 1995.

McDiarmid, D. R., and W. Allan, Simulation and analysis of auroral radar signatures generated by a magnetospheric cavity mode, *J. Geophys. Res.*, *95*, 20,911, 1990.

McDiarmid, D. R., and C. W. S. Ziesolleck, Contributions of amplitude and phase modulation to geomagnetic pulsation phase and spectrum, *J. Geophys. Res.*, *101*, 127, 1996.

Miura, A., and P. L. Pritchett, Nonlocal stability analysis of the MHD Kelvin–Helmholtz instability in a compressible plasma, *J. Geophys. Res.*, *87*, 7431, 1982.

Olsen, W. P., and K. A. Pfitzer, A quantitative model of the magnetospheric magnetic field, *J. Geophys. Res.*, *79*, 3739, 1974.

Radoski, H. R., and R. L. Carovillano, Axisymmetric plasmasphere resonances: Toroidal mode, *Phys. Fluids*, *9*, 285, 1966.

Reeves, G. D., L. A. Weiss, M. F. Thomsen, and D. J. McComas, A quantitative test of different magnetic field models using conjunctions between DMSP and geosynchronous orbit, in *Radiation Belts: Models and Standards, Geophys. Monogr. Ser.*, vol. 97, edited by J. F. Lemaire, D. Heynderickx, and D. N. Baker, p. 167, AGU, Washington, D. C., 1996.

Rickard, G. J., and A. N. Wright, Alfvén resonance excitation and fast wave propagation in magnetospheric waveguides, *J. Geophys. Res.*, *99*, 13,455, 1994.

Rickard, G. J., and A. N. Wright, ULF pulsations in a magnetospheric waveguide: Comparison of real and simulated satellite data, *J. Geophys. Res.*, *100*, 3531, 1995.

Ruohoniemi, J. M., R. A. Greenwald, K. B. Baker, and J. C. Samson, HF radar observations of Pc 5 field line resonances in the midnight/early morning MLT sector, *J. Geophys. Res.*, *96*, 15,697, 1991.

Samson, J. C., Three dimensional polarization characteristics of high–latitude Pc 5 geomagnetic micropulsations, *J. Geophys. Res.*, *77*, 6145, 1972.

Samson, J. C., and B. G. Harrold, Field line resonances associated with MHD waveguides in the magnetosphere, *Geophys. Res. Lett.*, *19*, 441, 1992.

Samson, J. C., and R. Rankin, The coupling of solar wind energy to MHD cavity modes, waveguide modes, and field line resonances in the Earth's magnetosphere, in *Solar Wind Sources of Magnetospheric Ultra-Low-Frequency Waves, Geophys. Monogr. Ser.*, vol. 81, edited by M. J. Engebretson, K. Takahshi, and M. Scholer, p. 253, AGU, Washington, D. C., 1994.

Samson, J. C., and G. Rostoker, Latitude-dependent characteristics of high-latitude Pc 4 and Pc 5 micropulsations, *J. Geophys. Res.*, *77*, 6133, 1972.

Samson, J. C., R. A. Greenwald, J. M. Ruohoniemi, T. J. Hughes, and D. D. Wallis, Magnetometer and radar observations of magnetospheric cavity modes in the Earth's magnetosphere, *Can. J. Phys.*, *69*, 929, 1991a.

Samson, J. C., T. J. Hughes, F. Creutzberg, D. D. Wallis, R. A. Greenwald, and J. M. Ruohoniemi, Observations of a detached, discrete arc in association with field line resonances, *J. Geophys. Res.*, *96*, 15,683, 1991b.

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.

Samson, J. C., L. L. Cogger, and Q. Pao, Observations of field line resonances, auroral arcs, and auroral vortex structures, *J. Geophys. Res.*, *101*, 17,373, 1996.

Singer, H. J., W. J. Hughes, and C. T. Russel, Standing hydromagnetic waves observed by ISEE 1 and 2: Radial extent and harmonic, *J. Geophys. Res.*, *87*, 3519, 1982.

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

Southwood, D. J., and W. J. Hughes, Theory of hydromagnetic waves in the magnetosphere, *Space Sci. Rev.*, *35*, 301, 1983.

Southwood, D. J., and M. K. Kivelson, Charged particle behavior in low–frequency geomagnetic pulsations, 2, Graphical approach, *J. Geophys. Res.*, *87*, 1707, 1982.

Steele, D. P., and D. J. McEwen, Electron auroral excitation efficiencies and intensity ratios, *J. Geophys. Res.*, *95*, 10,321, 1990.

Thomson, D. J., C. G. Maclennan, and L. J. Lanzerotti, Propagation of solar oscillations through the interplanetary medium, *Nature*, *376*, 139, 1995.

Tsyganenko, N. A., Effects of the solar wind conditions on the global magnetospheric configuration as deduced from data-based field models, in *Proceedings of the ICS-3 Conference on Substorms, Versailles, France, Eur. Space Agency Spec. Publ., ESA SP-389*, p. 181, 1996.

Tsyganenko, N. A., and D. P. Stern, Modeling the global magnetic field of the large–scale Birkeland current systems, *J. Geophys. Res.*, *101*, 27,187, 1996.

Walker, A. D. M., J. M. Ruohoniemi, K. B. Baker, R. A. Greenwald, and J. C. Samson, Spatial and temporal behavior of ULF pulsations observed by the Goose Bay HF radar, *J. Geophys. Res.*, *97*, 12,187, 1992.

Wright, A. N., Dispersion and wave coupling in inhomogeneous MHD waveguides, *J. Geophys. Res.*, *99*, 159, 1994.

Wright, A. N., and G. J. Rickard, ULF pulsations driven by magnetopause motions: Azimuthal phase characteristics, *J. Geophys. Res.*, *100*, 23,703, 1995.

Xu, B. L., J. C. Samson, W. W. Liu, F. Creutzberg, and T. J. Hughes, Observations of optical aurora modulated by resonant Alfvén waves, *J. Geophys. Res.*, *98*, 11,531, 1993.

Zanetti, L. J., T. A. Potemra, R. E. Erlandson, M. J. Engebretson, and M. H. Acuña, Geomagnetic field-line resonant harmonics measured by the Viking and AMPTE/CCE magnetic field experiments, *Geophys. Res. Lett.*, *14*, 427, 1987.

Zhu, X., and M. G. Kivelson, Compressional ULF waves in the outer magnetosphere, 1, Statistical study, *J. Geophys. Res.*, *96*, 19,451, 1991.

Ziesolleck, C. W. S., and D. R. McDiarmid, Auroral latitude Pc 5 field line resonances: Quantized frequencies, spatial characteristics, and diurnal variation, *J. Geophys. Res.*, *99*, 5817, 1994.

Ziesolleck, C. W. S., Q. Feng, and D. R. McDiarmid, Pc 5 ULF waves observed simultaneously by GOES 7 and the CANOPUS magnetometer array, *J. Geophys. Res.*, *101*, 5021, 1996.

M. K. Hudson, Department of Physics and Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755-3528. (maryk@sunset.dartmouth.edu)

M. R. Lessard, Institute for Space Research, Department of Physics and Astronomy, University of Calgary, Calgary, Canada AB T2N 1N4. (lessard@phys.ucalgary.ca)

J. C. Samson, University of Alberta, 412 Avadh Bhatia Physics Bldg., Edmonton, Alberta, Canada T6G 2J1. (samson@space.ualberta.ca)

J. R. Wygant, School of Physics and Astronomy, University of Minnesota, 116 Church St., Minneapolis, MN 55455. (wygant@belka.space.umn.edu)

(Received April 27, 1998; revised October 23, 1998; accepted November 12, 1998.)