GEOTAIL, POLAR, and WIND Observations of Auroral Kilometric Radiation

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Auroral kilometric radiation (AKR) is the plasma wave/radio phenomenon most clearly associated with substorms and increased geomagnetic activity. The GEOTAIL and POLAR Plasma Wave Instruments (PWI) both included sweep frequency receivers that had an upper frequency limit of 800 kHz and the WIND WAVES Thermal Noise Receiver (TNR) and Radio Receiver Band 1 (RAD1) went to 256 kHz and 1024 kHz, respectively. We have thus been able to observe the majority of the AKR spectrum in better detail than with earlier instrumentation and many important new discoveries have been made. Terrestrial low frequency (LF) bursts are a part of AKR observed during strong substorms. Although a limited portion of the LF burst spectrum is often detected on the dayside of the Earth and in the upstream solar wind, the complete spectrum is most frequently detected by spacecraft in the nightside magnetosphere or geomagnetic tail. Frequently these observations show that the LF bursts have a tapered tail centered on the present or recent past solar wind plasma frequency. We have found that on the dayside and in the upstream solar wind the high frequency AKR is detected during LF burst events only if the path from the AKR source is not blocked by the earth or dense plasmasphere. POLAR observations from high over the AKR source region show that the AKR increases in intensity and its lower frequency limits decrease when LF bursts are observed indicating that the AKR source region is expanding to higher altitudes. Frequently the upper frequency limit also increases indicating that the source region is then also expanding to lower altitudes. Data from both satellite and ground-based experiments show that the LF bursts are well correlated with expansive phase onsets and occur during very geomagnetically-disturbed periods. High resolution (in both time and frequency) data from the POLAR Wide Band Receiver have yielded exciting data on the fine structure of AKR as well as details on the structure of LF bursts.

INTRODUCTION

Plasma wave and radio measurements from the GEOTAIL, POLAR, and WIND spacecraft which were a part of the International Solar Terrestrial Physics/Global Geospace Science (ISTP/GGS) program [*Acuna et al.,* 1995] have provided both in situ and remote observations of numerous plasma wave phenomena related to geomagnetic storms and substorms. Observations of auroral kilometric radiation (AKR) [*Gurnett,* 1974; *Voots et al.,* 1977; *Kaiser and Alexander,* 1977b], the phenomenon most clearly associated with substorms and increased geomagnetic activity, provide remote or in situ (depending on the orbit) indicators of the timing, dynamics, and strengths of geomagnetic storms and substorms as well as characteristics of the source region and the generation mechanisms. The ISTP/GGS spacecraft were well instrumented to advance our understanding of AKR and related phenomena [*Anderson et al.,* 1997, 1998, 2001]. The GEOTAIL Plasma Wave Instrument (PWI) [*Matsumoto et al.,* 1994] included a sweep frequency analyzer (SFA) that went up to 800 kHz with a sweep period of 8 seconds and a multichannel analyzer (MCA) that went up to 311 kHz and could produce a spectrum every 1/4 second. The POLAR PWI [*Gurnett et al.,* 1995] included sweep frequency receivers (SFR) that also went up to 800 kHz with a sweep period of 2.4 seconds and an MCA that went up to 311 kHz and produced a spectrum every 1.3 seconds. The POLAR PWI also included a Wide Band Receiver (WBR) that provided both high-time resolution and high-frequency resolution data (up to 249,000 samples per second) with up to a 90 kHz bandwidth and a translatable frequency offset covering much of the AKR spectrum. The radio science experiment WAVES on WIND [*Bougeret et al.,* 1995] included a Thermal Noise Receiver (TNR) that covered 4 kHz to 256 kHz and a Radio Receiver Band 1 (RAD1) that went to 1024 kHz but both had somewhat poorer time resolution than GEOTAIL or POLAR.

The initiation or intensification of AKR occurs coincident with substorm onset. *Fairfield et al.,* [1998,1999] showed that AKR onsets and intensifications observed by WIND WAVES, GEOTAIL PWI, and POLAR PWI were coincident and closely associated with high-velocity earthward flow bursts in the inner magnetotail identified with substorm onset. In order to calculate the sizes of plasmoids and the locations of the near-Earth X-line, *Murata et al.,* [1995] used GEOTAIL PWI AKR observations to identify substorm onset (and the release or initiation of plasmoid flow) and in situ measurements of the magnetic fields from the GEOTAIL Magnetic Field Experiment (MGF) [*Kokubun et al.,* 1994] and magnetic noise bursts from the MCA data to determine the timing of the passage of a plasmoid/flux rope over the spacecraft. *Liou et al.,* [1999] in an investigation of relative timing in substorm signatures found that the start of enhanced AKR observed by POLAR when the spacecraft was in the midnight sector was coincident with a sudden auroral brightening indicative of an auroral breakup. These and other studies have shown that for spacecraft with an adequate view of the auroral zone, the initiation or intensification of AKR can be a very accurate identifier of substorm onset.

A 38-month data set of GEOTAIL plasma wave observations of AKR from 100 kHz to 600 kHz was used by *Kasaba et al.* [1997] to examine the dependence of the angular distribution of AKR. While *Green et al.* [1977] and *Green and Gallagher* [1985] had found using the IMP-6 and Hawkeye MCA data (with a 178 kHz upper frequency limit) that the AKR illumination pattern broadens with increasing frequency from 56.2 kHz to 178 kHz, *Kasaba et al.* [1997] found using the GEOTAIL SFA data (with a 800 kHz upper frequency limit) that the AKR illumination pattern then becomes narrower above 300 kHz. Such differences are basically explained by propagation. The GEOTAIL study also found that the illumination region of AKR extends duskward as geomagnetic conditions become more disturbed especially for the low frequency range which suggests a duskward extension of the AKR source. *Kasaba et al.* [1997] speculated that the lack of such a feature in the high frequency range could be caused by insufficient density depression in the duskside auroral plasma cavity especially at lower altitudes. *Hashimoto et al.* [1998] compared AKR simultaneously observed by GEOTAIL PWI and WIND WAVES and found using ray tracing that most observations were explained by an AKR source around 21-22 MLT (Magnetic Local Time) but during substorms the source extended around to 19 MLT.

Several studies using the POLAR and/or GEOTAIL PWI measurements in comparison with data from the POLAR imaging experiments have shown clear associations between electron precipitation and AKR. Plasma wave and bremsstrahlung x-ray data from the POLAR PWI and PIXIE [*Imhof et al.*, 1995] experiments were used by *Imhof et al.* [1998] to find a 0.51 correlation coefficient over a six hour local time range in the premidnight sector for a satellite pass that had several short term enhancements in the intensities of both AKR waves from 60 kHz to 800 kHz and 2 to 12 keV x-ray emissions. Other POLAR PWI and PIXIE [*Imhof et al.*, 1998; 1999; 2000] and GEOTAIL PWI and PIXIE [*Imhof et al.*, 2001] correlative studies found that the cross-correlation coefficient of auroral x-rays and AKR emissions was enhanced over an MLT interval of six hours or less and the maximum occurred for x-rays emitted slightly before local midnight. In another GEOTAIL PWI and PIXIE correlative study of the dependence of AKR production on the intensity and energy spectra of auroral bremsstrahlung x-rays, *Imhof et al.* [2003] found that the x-rays with higher e-folding energy were correlated with higher AKR frequency (implying lower altitude of generation). This was interpreted as being due to the increased energy of the primary electrons resulting from acceleration through an increasing potential difference at lower altitude. *Imhof et al.* [2003] also found that higher x-ray fluxes were associated with lower AKR cutoff frequencies.

The primary generation mechanism presently considered for AKR, the electron cyclotron maser instability [*Wu and Lee,* 1979], requires a small plasma frequency to cyclotron frequency ratio. AKR is generated near the local electron cyclotron frequency Fce such that high frequency AKR is generated at a lower altitude than the low frequency AKR. High time and frequency resolution measurements by the FAST satellite have confirmed that the AKR source is in a density depleted cavity and the AKR emissions are very close to and sometimes slightly below the cold plasma Fce down to the relativistic Fce [*Ergun et al.*, 1998]. The frequency of AKR thus identifies the location along a magnetic field line where it is generated. For example, on a 71 degree invariant latitude (L=9.4) field line typical for an AKR source region, Fce equals 500 kHz at a geocentric radial distance of 1.47 Re, 400 kHz at 1.58 Re, 300 kHz at 1.74 Re, 200 kHz at 1.98 Re, 100 kHz at 2.47 Re, 50 kHz at 3.09 Re, 30 kHz at 3.60 Re, and 15 kHz at 4.52 Re. Subtracting 1 Re yields the altitude. In the duskside plasmasphere, the electron density is enhanced so that the density in the auroral plasma cavity should be hard to decrease enough to satisfy the condition for the electron cyclotron maser instability. Therefore, generation of high-frequency AKR at lower altitudes is expected to be blocked on the duskside hemisphere.

Kasaba et al. [1997] found that at both 200 kHz and 500 kHz the frequency of occurrence of AKR was positively correlated with the Kp index and that this was more evident for the 200 kHz data. The latter agreed with an earlier finding of *Kaiser and Alexander* [1977a] that the frequency of the peak flux of AKR was inversely correlated with the AE index. These results indicate that the AKR source region moves up in altitude under disturbed geomagnetic conditions. *Kasaba et al.* [1997] also found that the illumination region increased in size during active times with an equatorward extension common at both frequencies which is believed to be due to the equatorward shift of the auroral plasma cavity in the disturbed phase expected from the inward motion of the plasmapause just after the onset of substorms. For the duskside region and at higher magnetic latitudes, the illumination pattern became larger for 200 kHz than for 500 kHz as the geomagnetic activity increased. This was believed to be due to the influence of the evening plasmaspheric bulge on the AKR propagation especially at the lower altitudes.

An important new result from *Kasaba et al.* [1997] was that AKR is more active on the winter hemisphere especially for the high frequency range. Possible reasons include asymmetry of the population of precipitating electrons on the auroral field lines and insufficient density depression in the auroral plasma cavity on the summer hemisphere especially at lower altitudes which are most sensitive to ionospheric outflow. Frequently the upper frequency limit increases indicating that the source region is then also expanding to lower altitudes. The changing upper and lower frequency limits observed during substorms can be used to study the dynamics of the plasma in the AKR source region.

Terrestrial low frequency (LF) bursts are a part of AKR often observed during geomagnetic storms and strong substorms [*Steinberg et al.,* 1988, 1990, 1998; *Kaiser et al.,* 1996; *Anderson et al.,* 1997, 1998, 2001]. Frequently the LF bursts occur during a period of the lower cutoff frequency of AKR continually decreasing. *Alexander and Kaiser* [1976] first reported that the AKR lower cutoff frequency tended to move to lower frequencies during geomagnetically disturbed periods. The POLAR WBR has yielded exciting data on the fine structure of AKR as well as details on the structure of LF bursts. Data from the plasma wave instruments on GEOTAIL and POLAR and the radio science experiment on WIND will be used here to study the characteristics and relationship of AKR and LF bursts. These three spacecraft and the CANOPUS [*Rostoker et al.,* 1995] ground magnetometer network which provided data for this study were all parts of the ISTP/GGS program. We will examine a number of events that illustrate the nature of AKR and LF bursts and their relationships to other measures of geomagnetic activity.

OBSERVATIONS

February 23, 1994, Events

An interesting characteristic of many of the LF bursts that we have observed is that they occur as a part of a series of quasi-periodic AKR bursts whose lower cutoff frequencies progressively decrease. After the LF burst occurs, a series of quasi-periodic AKR bursts whose lower cutoff frequencies increase progressively to higher frequencies often follows. An example of this is shown in Figure 1 which displays the GEOTAIL PWI Sweep Frequency Analyzer (SFA) data on linear frequency scales from 12.5 kHz to 100 kHz and from 100 kHz to 800 kHz on February 23, 1994, 94-054, from 03:00 UT to 05:00 UT. GEOTAIL was about 85 Re behind and towards the dusk side of the Earth in the solar wind just outside the early evening magnetosheath at GSE (X, Y, Z) = (-47.7 Re, 69.5 Re, -4.6 Re) and GSM (X, Y, Z) = (-47.7 Re, 64.1 Re, 27.4 Re). Five distinct events occur between 03:30 UT and 04:45 UT in which the AKR intensifies and its lower frequency cutoff progressively decreases (until 04:00 UT) and then increases (after 04:05 UT). The decreasing lower cutoff frequency means that the conditions required for the generation of AKR are moving to higher altitudes. These conditions include the local Fp in the source region being significantly less than the local Fce and that there be a source of free en- Figure 1 ergy from a positive slope in the perpendicular electron velocity distribution.

A LF burst is evident beginning near 30 kHz at 04:00 UT and reaching about 15 kHz before 04:05 UT. The nearly-constant-frequency emission line near 15 kHz is at the local electron plasma frequency Fp. The frequent enhancements in intensity are Langmuir waves excited when the region is magnetically connected to the Earth's bow shock *Kasaba et al.,* 2000]. The weak narrow emission line just above 30 kHz is the 2Fp line which is generated near the Earth's bow shock on or just downstream of magnetic field lines tangent to the Earth's bow shock [*Reiner et al.,* 1996;]. The LF burst after falling below the 2Fp line approaches the Fp line with increasingly longer delay times. This long diffuse tail is an identifiable characteristic of the LF bursts. A very weak LF burst also is detected between 30 kHz and 15 kHz beginning at 03:48 UT and lasting for about five minutes.

The geomagnetic conditions were moderately active with Kp = 3+ and DST = -57 nT. Slightly more than one day earlier a strong storm produced Kp = 8- and DST = -144 nT. The north-south (X) components of the CANOPUS array ground magnetometer data for 0300 UT to 0500 UT on February 23, 1994, are shown in Figure 2. Panel A is unfiltered and Panel B is high-pass filtered with fc = 7 mHz which highlights Pi2 oscillations associated with expansive phase onsets. The locations of the twelve stations for which there are data are listed in Table 1. Strong negative bays of the order of several hundred nT and strong Pi2 oscillations are evident especially in the Fort Churchill and Eskimo Point data for the first three distinct events and also in the higher latitude Rankin Inlet data for the final two. Both are indicative of expansive phase onsets. The LF burst beginning at 04:00 UT and the AKR lower cutoff frequency reaching its lowest value are coincident with the strongest Pi2 oscillation observed for the two-hour period.

Figure 2

Table 1

The solar wind speed measured by the GEOTAIL Comprehensive Plasma Instrument (CPI) [*Frank et al.,* 1994] was high at about 700 km/sec (K. L. Ackerson, Private Communication). *Desch et al.* [1996] and *Desch* [1997] found that the occurrence of LF bursts were well correlated with the solar wind speed and somewhat less correlated with the azimuthal direction of the IMF. The LF bursts tended to occur in the sectors when the IMF was pointed towards the sun. They concluded that the LF bursts were a signature of a large-scale process of magnetospheric energy dissipation. They suggested a viscous-like interaction between the solar wind and the magnetosphere. For this event, the solar wind speed was higher than normal but the measurements were made in an away sector.

April 11, 1997, Events

Interesting LF bursts were detected by GEOTAIL, POLAR, and WIND between 01:00 UT and 07:00 UT on April 11, 1997, 97-101, during coronal-mass-ejection related substorms [*Brueckner et al.,* 1998;*Berdichevsky et al.,* 1998] which included three episodes of the AKR moving in bursts to lower and lower frequencies [*Anderson et al.,* 1998]. For the first nine hours of April 11, 1997, Kp was 5, 7-, and 5-. Between 04:00 UT and 05:00 UT DST reached a minimum for the day of -82 nT. Figure 3 displays the POLAR PWI Sweep Frequency Receiver (SFR) Eu (electric field measured by one of two long-wire antennas perpendicular to the spacecraft spin axis) observations for 01:00 UT and 07:00 UT. The data are plotted logarithmically from 10 kHz to 800 kHz and the plotted dynamic range is 50 dB. The white line identifies the electron cyclotron frequency determined from the POLAR Magnetic Field Investigation (MFI) [*Russell et al.,* 1995]. The strong signals above 100 kHz after 0648 UT near the end of the plot and just before perigee are preamp oscillations that occur in the highest density regions. POLAR was inbound from apogee to perigee near local midnight. The three AKR episodes began at about 01:15 UT, 02:35 UT, and 04:45 UT, respectively. The CANOPUS ground magnetometer data and Meridian Scanning Photometer Array (MPA) data (see Figures 1 and 3 of *Anderson et al.,* [1998]) show substorm expansive phase onsets near or shortly after the beginning of each AKR episode. The initiation or intensification of AKR observed by an appropriately located satellite high over the night auroral region or in the geomagnetic tail well identifies substorm onset. Figure 3

The GEOTAIL PWI SFA electric field data are plotted in Figure 4 for the same time period. The data are plotted on linear scales from 12.5 kHz to 100 kHz and from 100 kHz to 800 kHz and the plotted dynamic range is 100 dB. GEOTAIL was at R = 14 Re in the upstream solar wind just outside the subsolar bow shock. The two emission lines beginning slightly above 40 kHz and 80 kHz are at Fp and 2Fp. The horizontal striations from about 100 kHz to 500 kHz, most prominent in the first two hours, are enhanced high frequency escaping continuum radiation referred to as kilometric continuum [*Hashimoto et al.,* 1999]. This is a newly identified plasma wave phenomenon associated with plasma deep within the plasmasphere drifting around the Earth and striking more dense portions of the plasmasphere having steep density gradients. The POLAR data show that for the first expansive phase onset period, the AKR lower cutoff frequency was about 100 kHz and the AKR was considerably weaker than for the next two periods. The observed kilometric continuum could easily have masked any AKR that otherwise might have been seen Figure 4 in the GEOTAIL spectrogram.

The second and third expansive phase onset periods produced LF bursts clearly detectable with their diffuse tails in the GEOTAIL and WIND (see Figure 2 of *Anderson et al.,* [1998]) spectrograms beginning about 02:58 UT, 05:35 UT, and 05:50 UT. WIND was 231 Re upstream of the Earth (GSM X,Y,Z = 229.7 Re, 0.5 Re, 22.9 Re, R = 230.9 Re). The POLAR PWI SFR data show the AKR for the 02:58 UT LF burst case extending down to a minimum in frequency of about 30 kHz around 03:31 UT . For the second case, enhanced AKR extending down to about 35 kHz at 05:35 UT was observed. Tapered-tail diffuse emissions centered on 40 kHz with no spin modulation followed the AKR reaching its minimum frequency for these two cases. However, for the third case, POLAR was able to observe the AKR down to only about 50 kHz around 05:50 UT. No tapered tail diffuse emission was observed. An unusual emission that is spin-modulated was observed from 50 kHz down to 15 kHz between 05:48 UT and 05:53 UT. We believe the higher lower-frequency-cutoff of AKR and the lack of a diffuse tail were probably due to the shielding and refraction caused by the nearby plasmasphere. Examination of high-time resolution GEOTAIL plots showed that in the GEOTAIL data the LF burst beginning at 02:58 UT was spin modulated above 80 kHz and isotropic below 80 kHz. The presence of spin modulation indicates a compact source region. Between about 05:20 UT to 05:30 UT the Fp line increased from 40 kHz to slightly more than 50 kHz and stayed high for about one hour. The LF bursts beginning at 05:35 UT and 05:50 UT were isotropic below 100 kHz. The AKR above 100 kHz was clearly spin modulated. The POLAR SFR data also showed that during these events when the AKR increased in intensity, the upper cutoff frequency also often increased, indicating that the conditions required for AKR generation were also moving to lower altitudes.

The POLAR Wide Band Receiver (WBR) was fortuitously in the 0-90 kHz mode for several hours on April 11, 1997, and we are able to examine the low frequency end of the AKR spectrum with both high-time resolution and high-frequency resolution during one of the episodes of interest. Figure 5 shows the WBR data from the Eu electric antenna for 03:00 UT to 04:00 UT over a 40 dB dynamic range. The data above 90 kHz should be ignored as it is out of the pass band for the 0-90 kHz mode. From 03:00 UT to 03:30 UT the lower cutoff frequency of the AKR moved in bursts to lower and lower frequencies. This is similar to the behavior observed in the February 23, 1994, case discussed above except here the lower frequency AKR is more continuous. In this April 11, 1997, case we see indications of the diffuse tail dominating the lowest frequency end of the AKR spec-

Figure 5

tra as early as about 03:23 UT. After 03:30 UT, the AKR lower cutoff dropped even further and the diffuse tail formed a tapered tail that was centered on 40 kHz. From the GEOTAIL data we see that at this time the solar wind plasma frequency in front of the Earth's bow shock was about 38 kHz but had been around 40 kHz one to two hours earlier.

The diffuse tails of the LF bursts are believed to be due to the lowest frequency portion of the AKR waves scattering far down the tail where the plasma frequency of the magnetosheath reaches the solar wind plasma frequency. Nearer the Earth these waves are reflected by the high density encountered at the magnetopause. As an electromagnetic wave approaches a region where the plasma frequency is near the wave frequency, the group velocity decreases and the delay time increases. The closer the frequency of the wave is to the plasma frequency, the slower it travels and the more likely it is to be scattered. As the magnetosheath density decreases further down the tail, it approaches the solar wind density. The scattering can thus carry the waves out into the solar wind. This results in a very large apparent source size for the radiation which would have no spin modulation.

The solar wind speed measured by the GEOTAIL CPI was between 400 and 450 km/sec for this time period (K. L. Ackerson, Private Communication). In one hour the local plasma would be convected about 225 to 255 Re down the tail. The fact that the tapered tail in the POLAR data for the 05:35 UT LF burst centered on 40 kHz implies that the magnetosheath density approached the solar wind density beyond 225 to 255 Re down the tail. If it occurred closer, one would expect the latter tapered tail to be centered on or above 50 kHz. Careful examination of of the GEOTAIL SFA data shows that the LF burst starting at 02:58 UT never quite reached the local plasma frequency. This implies that there was a region of somewhat higher density between GEOTAIL and the source or scattering region. As we have noted above, the local plasma density which would be convected down the tail was slightly higher one to two hours earlier.

We examined the POLAR PWI WBR data in high-time resolution to investigate the characteristics of the observed AKR during the LF burst events. Two 48-second spectrograms are shown in Figure 6 starting at 03:23:36 UT. The nulls occurring every three seconds (half the spacecraft spin period) indicate that the signal is spin modulated. Clear spin modulation is evident in both panels down to 50 kHz or lower and near the beginning of the first panel it even extends down to near 40 kHz. A variety of fine strucure is apparent including rising tones, falling tones, and nearly horizontal features, as has been seen earlier on ISEE [*Gurnett et*

Figure 6

al., 1979; *Gurnett and Anderson,* 1981], DE 1 [*Benson et al.,* 1988; *Menietti et al.,* 1996], EXOS-B [*Morioka et al.,* 1981] and Galileo [*Menietti et al.,* 1996]. Some of the features are spin modulated and some appear not to be. The stripe-like negative-frequency-drift emissions studied by *Menietti et al.,* [1996] which are most apparent here below 70 kHz after 03:24 UT often appear not to be spin modulated. A diffuse band with no spin modulation is evident below the spin modulated AKR emissions. This band gradually increases in intensity and forms a tapered tail. *Calvert* [1995] offered explanations for the fine structure base on his maser cavity feedback model [*Calvert,* 1982] for the source of AKR. *Farrell* [1995] proposed a Fermi acceleration process for the AKR fine structure.

May 15, 1997, Event

Much of mid-day on May 15, 1997, 97-135, was highly disturbed due to a CME that was observed by SOHO on May 12 [*Brueckner et al.,* 1998]. For 06-15 UT, Kp was 7-, 7-, and 6+. Between 12:00 UT and 13:00 UT DST reached a minimum for the day of -115 nT. In a brief interval from about 12:55 UT to 12:59 UT, POLAR, GEOTAIL, and WIND all detected a LF burst [*Anderson et al.,* 1998], the first of two seen the entire day. The AKR detected by all three spacecraft became enhanced and quickly and briefly extended down to below 30 kHz. A diffuse tail which trailed the lowest frequency portion was evident below 35 kHz after 12:57 UT. POLAR was at 8.8 Re, 81 degrees magnetic latitude, and 17 hrs MLT. GEOTAIL was in the magnetosheath near dusk (GSM X,Y,Z = 7.7 Re, 28.7 Re, -0.5 Re, R = 29.7 Re, MLT = 17 hrs, and magnetic latitude = -0.9 degrees). WIND was 190 Re upstream of the Earth (GSM X,Y,Z = 189.6 Re, 2.2 Re, 17.4 Re, R = 190.4 Re). A strong injection of energetic electrons was detected near 17.6 hrs LT just before 13:00 UT coincident with the LF burst. At the same time, auroral images from the POLAR VIS instrument [*Frank et al.,* 1995] showed a strong auroral enhancement near dusk.

The POLAR WBR was again fortuitously in the 0-90 kHz mode for several hours on May 15, 1997. Figure 7 shows the WBR data from the Eu electric antenna for 12:54 UT to 13:00 UT over a 40 dB dynamic range. Note again that the data above 90 kHz should be ignored as it is out of the pass band for the 0-90 kHz mode. We see that from 12:55 UT to 12:57 UT the lower cutoff frequency of the AKR moved in bursts to lower and lower frequencies. This is similar to the behavior for the previous two cases discussed above except on a shorter time scale. After the AKR lower cutoff reached a minimum around 12:57 the diffuse lowest frequency portion of the AKR formed a tapered tail that was centered on about 27 kHz. A high-time-

Figure 7

resolution 48-second spectrogram in Figure 8 shows that the beginning of a diffuse tail dominating the lowest frequency end of the AKR spectra started as early as about 12:56:30 UT. In contrast to the WBR spectrograms in Figure 6 for April 11, the May 15 event shows that the spin modulation nulls were deeper indicating a more compact source.

Figure 8

January 28, 1997, Event

On January 28, 1997, 97-028, the WIND spacecraft was 174 Re upstream of the Earth near the Earth-Sun line at GSE X = 172 Re, GSE Y = -20 Re, and GSE Z = -16 Re. The solar wind speed (from the WIND comprehensive plasma experiment SWE [*Ogilvie et al.,* 1995]) was high at about 650 km/s such that the local solar wind parameters would reach Earth in about 28 minutes. Two LF bursts that were detected at Wind in the second half of the day will be examined here to better understand their relationship to the AKR observed. One began at 13:42 UT and the second began around 19:05 UT. Geomagnetic activity was moderately active with with Kp from 12 UT to 21 UT being 4, 4, and 4+. Figure 9 shows the WIND/WAVES Thermal Noise Receiver (TNR) spectrogram for the 4 kHz to 256 kHz logarithmic frequency range from 13:00 UT to 15:00 UT. The intensity is color coded over a 10 dB range relative to the receiver background. The emission line near 20 kHz at the beginning of the plot is at the local electron plasma frequency Fp. The narrow emission line near 40 kHz at the beginning of the plot and which decreases to about 35 kHz by the end of the plot is the 2Fp line which is generated near the Earth's bow shock. The LF burst began between 40 and 70 kHz in frequency at 13:42 UT and fell below the 2Fp line at 13:44 UT and then approached the Fp line with increasingly longer delay times. The other emissions above 2Fp are AKR.

Figure 9

The GEOTAIL and POLAR PWI data for the same two-hour period are shown in Figures 10 and 11, respectively. Figure 10 displays the GEOTAIL PWI SFA data in five linear frequency bands: 25 Hz to 200 Hz, 200 Hz to 1600 Hz, 1.6 kHz to 12.5 kHz, 12.5 kHz to 100 kHz, and 100 kHz to 800 kHz. The intensity is color coded over a 70 dB dynamic range. The black and white line near the bottom of the spectrogram indicates the local electron cyclotron frequency determined from the GEOTAIL MGF experiment. GEOTAIL was about 30 Re down the tail at GSE X = -28.3 Re, GSE Y = 10.2 Re, and GSE Z = -3.2 Re and was moving toward the center of the tail. The 2 kHz lower cutoff of the continuum radiation (which here extends from 2kHz to 12 kHz) is at the local plasma frequency and indicates low number densities around 0.04 e/cc. Several times throughout this period the lower cutoff frequency of the AKR fell below 100 kHz. In the pe-

Figure 10

riod from 13:30 UT to 15:00 UT we see that when the AKR emissions appeared below 100 kHz that the AKR above 100 kHz was enhanced and that strong extremely low frequency (ELF) emissions (from 25 Hz to 1-3 kHz) occurred simultaneously. These elf emissions accompany the bursty bulk flows that have been identified with substorms and AKR intensifications [*Fairfield et al.*, 1998,1999]. However, only one of these episodes produced a clear LF burst that was also detected by WIND. Just before 13:40 UT the lower cutoff frequency of the AKR began to fall and reached below 20 kHz at 13:44 UT. A tapered diffuse tail centered very near 20 kHz is evident for about ten minutes after 13:44 UT.

Figure 11 displays the POLAR PWI SFR Ez (the electric field measured by the antenna along the spacecraft spin-axis) data logarithmically from 10 kHz to 800 kHz. The intensity is color coded over a 50 dB dynamic range. POLAR is in the pre-dawn sector (4.5 MLT) approaching the plasmasphere. The white line which crosses 10 kHz just before 14:00 UT is the electron cyclotron frequency determined from the ambient magnetic field measurements of the POLAR MFI experiment. The LF burst with the tapered tail centered on 20 Khz is clearly evident beginning at 13:44 UT. Note that the strong AKR observed on GEOTAIL after 14:40 UT is not present in the POLAR data. It has been refracted away by the dense plasmasphere.

Figure 11

The WIND/WAVES TNR data from 18:00 UT to 20:00 UT over a 12 dB range relative to the receiver background are shown in Figure 12. The LF burst begins above 256 kHz and falls below the 2Fp line at 19:05 UT and approaches the Fp line with increasingly longer delay times. Fp and 2Fp have fallen slightly from five hours earlier to 18 kHz and 36 kHz, respectively. The GEOTAIL PWI SFA data over a 70 dB dynamic range for the same two-hour time period are shown in Figure 13. A LF burst with a tapered tail centered on 20 Khz is clearly evident from about 19:05 UT to 19:15 UT. Note that the strong ELF waves believed to be associated with bursty bulk flows occur from 18:50 UT to 19:13 UT simultaneously with the lower cutoff frequency of AKR being very low. The POLAR PWI SFR Ez data are shown in Figure 14. Polar near dusk (18 MLT) has exited the plasmasphere and is headed for its north pole apogee. Diffuse emissions down to about 15 kHz are present from 19:05 UT to 19:15 UT. Very intense AKR reaches as low as 32 kHz at about 19:13 UT.

Figure 12

Figure 13

Figure 14

POLAR PWI WBR data in the 0-90 kHz mode were available for the 19:05 UT LF burst. Figure 15 shows the WBR data from the Eu antenna for 18:38 UT to 19:14 UT. Between 18:38 UT and 18:57 UT there are several periods when the AKR (usually the higher frequency portion near 90 kHz) is enhanced and the lower cutoff frequency of the AKR moves progressively

Figure 15

lower. Then for about four minutes only AKR above about 85 kHz is enhanced. Beginning aqround 19:01 UT the AKR again begins extending to lower frequencies. Figure 16 contains two high-time-resolution 48-second spectrograms beginning at 19:04:00 UT. Around 19:04:30 UT the AKR becomes more enhanced and the lower cutoff frequency decreases abruptly. Figures 15 and 16 show that there is a distinct difference in the higher frequency AKR in this case as compared to the lower frequency AKR. The higher frequency AKR is more intense and the discrete structure is spin modulated and at least initially is predominantly rising in frequency. In the lower frequency portion the discrete emissions are dominated by falling frequency stripe-like features that are not always well spin-modulated. Near the end of the WBR data after about 19:11 UT the lower cutoff frequency of the more intense higher frequency AKR has dropped to about 32 kHz and the weaker lower frequency portion extends below 20 kHz. What we have seen here is that POLAR does observe AKR that is detected as a LF burst by GEOTAIL and WIND but that the lowest frequency portion is less intense and has different discrete structure. One possibility is that a more intense lower frequency portion is generated near or earlier than local midnight that is more visible to GEOTAIL situated close to local midnight.

Figure 16

October 19, 1996, Events

In the ten-hour time period from 13:00 UT to 23:00 UT on October 19, 1996, 96-293, enhanced AKR and two terrestrial LF bursts were detected by the GEOTAIL PWI and the WIND WAVES experiment during substorms observed in the IMAGE magnetometer network data and in the Los Alamos National Laboratory (LANL) geosynchronous satellite energetic particle data. The x-component data of 11 stations of the IMAGE magnetometer network near the longitude of Finland for the ten-hour period are shown in Figure 17. Strong negative bays indicative of substorm expansive phase onsets are evident in the higher latitude stations beginning around 15:00 UT and shortly after 21:00 UT. In the LANL 1994-084 (local midnight occurs at 17 UT) and LANL 1991-080 (local midnight occurs at 21:20 UT) geosynchronous satellite data large abrupt nearly dispersionless injections of energetic electrons and protons were detected near 15:00 UT and of energetic electrons shortly after 21:00 UT [Geoff Reeves, Private Communication]. Such observations are also indicative of substorm expansive phase onsets. For the period from 12:00 UT to 24:00 UT Kp was at quite disturbed levels of 5, 5+, 3+, and 5+.

Figure 17

The GEOTAIL PWI SFA electric field data are plotted in Figure 18 for the ten-hour period from 12.5 kHz to 100 kHz and from 100 kHz to 800 kHz over a 70 dB

Figure 18

dynamic range. GEOTAIL was in the solar wind at its 30 Re apogee just before dawn. Fp and 2Fp were at 20 kHz and 40 kHz, respectively, at the beginning of the plot and 18 kHz and 36 kHz at the end. The lower frequency cutoff of the AKR decreased abruptly and LF bursts with their diffuse tails were observed just before 15:00 UT and just after 21:00 UT. The drifting tones above 2Fp but here primarily below 100 kHz are discrete bursts of enhanced continuum studied by *Kasaba et al.* [1998] that at higher frequencies become a part of the escaping kilometric continuum [*Hashimoto et al.*, 1999].

The WIND/WAVES TNR data from 4 kHz to 256 kHz for the same ten-hour period are plotted in Figure 19 over a 10 dB range relative to the receiver background. WIND was near 10 MLT about 131 Re from the Earth at GSM X = 111 Re, GSM Y = -68 Re, and GSM Z = 19 Re. The solar wind speed was high at about 600 km/s such that the local solar wind parameters would reach Earth in about 20 minutes. Fp and 2Fp were nearly the same at WIND as they were near the Earth as measured by GEOTAIL. The LF bursts with their diffuse tails are clearly evident just before 15:00 UT and just after 21:00 UT. The drifting tones above 2Fp observed on GEOTAIL are also observed but here they extend up to over 200 kHz. The other emissions above 2Fp which have primarily vertical frequency structure are AKR. The higher visibility of the escaping kilometric continuum on WIND as compared to GEOTAIL, especially notable between about 17:00 UT and about 20:25 UT, is due to several factors. *Hashimoto et al.* [1999] found that kilometric continuum was primarily a day-side phenomenon. Thus since WIND was closer to local noon than GEOTAIL, one would expect a higher observation rate for WIND. Another factor is that the observations on GEOTAIL are masked by the AKR above 100 kHz. The closer a spacecraft is to local midnight, the better opportunity it has to detect AKR. Thus GEOTAIL near dawn (6 MLT) should expect to see more AKR than WIND near 10 MLT. It is clear from the GEOTAIL data that the overall intensity of AKR between 17:00 UT and 20:25 UT was lower than either earlier or later. We should remember that from 18 UT to 21 UT Kp was only 3+ as compared to 5+ immediately before and after. Since WIND is further from the Earth than GEOTAIL, the intensity of the AKR at WIND will be much lower and less likely to be detected and less likely to mask the escaping kilometric continuum observations.

Figure 19

The POLAR PWI SFR Ez data are displayed logarithmically from 10 kHz to 800 kHz over a 60 dB dynamic range in Figure 20. At the center of the plot POLAR was at apogee in the pre-dawn sector (4.8 MLT). It was near local midnight in the first half of the

Figure 20

plot and near mid-to-late morning in the second half. At the time of the first LF burst seen on GEOTAIL and WIND, POLAR does detect enhanced AKR down to almost 30 kHz. At the time of the second LF burst observed on GEOTAIL and WIND, POLAR does see enhanced AKR down to about 80 kHz. A weak enhancement is also seen between 60 kHz and 30 kHz and there is a another weak enhancement below that with a tapered tail centered on 22 Khz beginning at about 21:10 UT. The lack of enhanced AKR below 80 kHz around 21 UT may be due to the mid-to-late morning local time of the observations which is far from the near-midnight or earlier location expected for the peak of AKR generation.

November 24, 1996, Event

The benefits of multiple spacecraft observations are highlighted by the November 24, 1996, isolated substorm which was first studied by the INTERBALL researchers at a Workshop in Finland in February, 1998, the details of which can be found at the URL: http://www.iki.rssi.ru/interball/workshop/intervals/C/ and in *Jacquey et al.* [1998] and *Petrukovich et al.* [1998]. Prior to the time of the isolated substorm, geomagnetic activity had been low to moderate. Kp for the day was 0+, 1-, 2-, 3-, 3-, 3-, 2-, and 5-. From the IMAGE Scandinavian magnetometer network it was determined that the substorm onset time was between 22:25 UT and 22:27 UT. At this time, POLAR was at R=6.8 Re and 8.5 hrs MLT over the northern hemisphere. GEOTAIL was in the equatorial plasmasheet about 27 Re down the tail at GSE (X, Y, Z) = (-25.2 Re, -8.1 Re, -3.2 Re). Figure 21 shows the POLAR PWI SFR electric Ez data plotted on a linear scale from 0 to 800 kHz over a 44 dB dynamic range for 22:00 UT to 24:00 UT. The AKR began at 22:24 UT at 350 kHz. Figure 22 shows the GEOTAIL PWI SFA electric field data from 12.5 kHz to 100 kHz and from 100 kHz to 800 kHz over a 50 dB dynamic range for the same time period. A weak band of AKR from 300 kHz to 500 kHz is evident around 22:20 UT and it began to intensify about 22:25 UT and expanded both upward and downward in a somewhat bursty way. By about 22:30 UT the AKR lower frequency cutoff had dropped to 100 kHz and by 22:35 UT it was down to less than 15 kHz. An LF burst with a diffuse extended tapered tail centered on between 30 and 35 kHz is evident in the GEOTAIL data beginning at about 22:35 UT. The precise frequency is difficult to determine because it is blended in with the rising escaping continuum present. The LF burst is not evident in the POLAR data. In fact in the POLAR data the lower frequency cutoff of the AKR did not go below 100 kHz. This is probably due both to POLAR being on the morning side (9 MLT) and the fact that it

Figure 21

Figure 22

was approaching the plasmasphere. An enhanced continuum burst is evident in the GEOTAIL spectrogram beginning around 20 kHz at 23:03 UT.

A very unusual feature found in comparing the POLAR and GEOTAIL observations is the gap in the POLAR AKR band from about 22:36 UT to 22:38 UT that is not evident in the GEOTAIL AKR band. This is confirmed in Figure 23 which shows the spectral density (volt**2/meter**2/Hz) in the POLAR 355.9 kHz SFR channel and in the GEOTAIL 325 kHz, 357.8 kHz, and 407.1 kHz SFA channels for 22:00 UT to 23:30 UT. Several POLAR AKR gaps or depressions in intensity are evident which do not have corresponding depressions in intensity in the GEOTAIL data. One possible explanation is that POLAR temporarily moved out of the AKR emission cone pattern. It may also be that regions of dense plamsa were actually blocking the AKR from getting to POLAR. A combination of the two might also be possible.

Figure 23

The WIND/WAVES TNR spectrogram from 4 kHz to 256 kHz for 22:00 UT to 24:00 UT on November 24, 1996, over a 10 dB range relative to the receiver background is shown in Figure 24. WIND was upstream at GSE (X, Y, Z) = (73.1 Re, -17.8 Re, 8.2 Re). The emission line slightly above 30 kHz is the local Fp and the line slightly above 60 kHz is the 2Fp line from the vicinity of the Earth's bow shock. The LF burst is evident shortly after 22:35 UT between the Fp and 2Fp lines. Note that while GEOTAIL on the Earth's nightside observed the AKR at the time of the LF burst extending up to over 400 kHz, WIND close to the Earth-Sun line on the upstream side, detected AKR then only below 200 kHZ. The tapered tail LF burst observed by GEOTAIL was centered on between 30 and 35 kHz. The WIND TNR data from earlier in the day show that as late as about 19 UT the Fp at WIND was 35 kHz. The solar wind speed from the WIND SWE was about 450 km/sec. Taking into account WINDS's position 73 Re in front of the Earth, the local plasma density would be convected about 810 Re behind the Earth in 3 1/2 hours. We believe scattering at or beyond this distance can account for the tapered tail centered on 35 kHz.

Figure 24

DISCUSSION AND SUMMARY

GEOTAIL and POLAR PWI measurements along with those from the WIND WAVES experiment, the CANOPUS ground optical data and magnetograms, the IMAGE Network magnetograms, and POLAR auroral imaging have provided new information on AKR and LF bursts and their relationships to the magnetospheric plasma dynamics. AKR measurements when a satellite can view the nightside hemisphere provide excellent indications of substorm onsets. The absence of higher frequency AKR in some upstream observations of LF bursts can be attributed to propagation blockage by the Earth and dense plasmasphere of the portion of the AKR generated at the lowest altitudes on the night side. The ideal situation for substorm onset identification would include the simultaneous availability of multiple spacecraft observations of AKR covering all local times, worldwide ground all sky camera, magnetometer, and meridian scanning photometer measurements, and space-based auroral imaging. The combination of the high time-resolution and remote sensing capabilities provided by the plasma wave measurements make them very important for studying the triggering, near triggering, and burstiness of substorms and related geomagnetic disturbances.

We have found that LF bursts are the lower frequency portion of AKR and are produced simultaneously with intense isolated substorms. Spacecraft observations often show that the AKR increases in intensity and its lower frequency limits when LF bursts are observed indicating that the AKR source region is expanding to higher altitudes. Since AKR is generated near the local electron cyclotron frequency, the frequency of AKR identifies the location along a magnetic field line where it is generated and the lower the frequency, the higher the altitude. This relationship allows us to investigate some source characteristics. For example, the average speed for the upward movement of the AKR source region for the second event on April 11, 1997, is 3 km/s based on the AKR frequency starting at 300 kHz at 02:34 UT and the lower cutoff falling to 50 kHz by 03:22 UT. The single LF burst observed on May 15, 1997, had an upward AKR source speed of 80 km/s based on the AKR lower cutoff frequency starting at 100 kHz at 12:55 UT and falling to 30 kHz in only 1.5 minutes. Frequently the upper frequency limit also increases indicating that the source region is then also expanding to lower altitudes. In the future we will examine source speeds for all the LF events with measurable upper and lower cutoff frequencies. We will look for geophysical parameters that might correlate with the speeds.

In a limited number of cases that we have been able to examine in detail, CANOPUS ground magnetometer and meridian scanning photometer data show that during the LF burst events the expansive phase onsets start at unusually low latitudes and move poleward and westward. The data also show that the LF bursts occur when the expansive phase onset signatures are most intense. Many of the LF bursts occurred related to CME events observed by SOHO which were identified by the NOAA SEC as being highly geoeffective. Magnetometer data from geosynchronous satellites usually show increased magnetic field dipolarization and the presence of field-aligned currents during LF burst events. Large injections of protons and electrons have also been detected by the GOES and LANL geosynchronous satellites during LF burst events. AKR-produced low frequency bursts which occur during the more intense geomagnetic disturbances thus provide a space weather marker of the geoeffectiveness of the events. We will continue to investigate the global activity that is associated with and leads to LF bursts. The already productive correlative studies with the POLAR x-ray and optical imaging are continuing and will now concentrate on LF burst events.

We will also continue the investigation of the dimensions and shape of the geomagnetic tail using our tapered-tail LF burst observations and solar wind speed and density measurements from available spacecraft. *Anderson et al.* [2001] analyzed the October 19, 1996, 21:05 UT LF burst shown here in Figure 18 with a tapered tail centered on 22 kHz. They concluded from the fact that the last time the solar wind plasma frequency at Earth had been 22 kHz was six hours earlier and that the solar wind speed was 600 km/s, that the emission was scattered into the solar wind (which would indicate the end of the geomagnetic tail) about 2,030 Re down the tail. For the 05:35 UT event on April 11, 1997, shown in Figure 4, we found the length of the tail to be at or greater than 225 Re to 255 Re using a similar technique. For the 22:35 UT tapered tail LF burst on November 24, 1996, shown in Figure 22, we found that the scattering into the solar wind was at or beyond 810 Re. *Desch* [1997] calculated travel times for LF burst emissions and found that observations required the emissions having had to travel as much as 2000 Re down the tail. *Steinberg et al.* [1998] used WAVES direction finding measurements to find that the spin-modulated high frequency portion of LF bursts exited the bow shock from 100 Re to 460 Re down the tail. *Desch and Farrell* [2000] studied a LF burst that was occulted by a strong increase of solar wind plasma density 97 Re down the tail. Thus the LF burst had to have entered the solar wind beyond 97 Re down the tail. *Steinberg et al.* [2003] analyzed 119 LF bursts observed by WIND WAVES when the spacecraft was near the Lagrange Point L1 and concluded that the bow shock still exists beyond 1000 Re.

A topic for future study is determining what solar wind parameters control the length of the Earth's geomagnetic tail. Another worthwhile topic to be pursued is trying to determine the reasons for the quasi-periodic nature of many geomagnetic disturbances and whether or not they contradict the importance of self organized criticality in magnetospheric dynamics. Although *Hashimoto et al.* [1999] concluded that kilometric continuum radiation did not appear to be related to geomagnetic activity, numerous examples similar to ones we have shown here indicate some association between the two. This matter obviously warrants further investigation.

We have well demonstrated in this paper that GEOTAIL, POLAR, and WIND are still valuable resources for the study of the Earth's magnetosphere and the heliosphere.

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Figure 1. The GEOTAIL PWI sweep frequency analyzer (SFA) data for 03:00 UT to 05:00 UT on February 23, 1994. Five distinct enhancements in the AKR that include the lower frequency cutoff significantly decreasing are evident between 03:30 UT and 04:45 UT. The diffuse tail of a terrestrial low frequency (LF) burst is evident beginning near 30 kHz at 04:00 UT and reaching about 15 kHz before 04:05 UT.

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Figure 2. The CANOPUS array magnetometer north-south (X) component data for 03:00 UT to 05:00 UT on February 23, 1994. Full scale for the unfiltered data in Panel A is 650 nT and full scale for the high-pass filtered data in Panel B is 180 nT.

Figure 2. The CANOPUS array magnetometer north-south (X) component data for 03:00 UT to 05:00 UT on February 23, 1994. Full scale for the unfiltered data in Panel A is 650 nT and full scale for the high-pass filtered data in Panel B is 180 nT.

Figure 3. A color spectrogram of the POLAR PWI Eu electric field SFR data for 01:00 UT to 07:00 UT on April 11, 1997.

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Figure 4. A color spectrogram of the GEOTAIL PWI electric field SFA data for 01:00 UT to 07:00 UT on April 11, 1997.

Figure 4. A color spectrogram of the GEOTAIL PWI electric field SFA data for 01:00 UT to 07:00 UT on April 11, 1997.

Figure 5. 0-90 kHz POLAR WBR data for 03:00 UT to 04:00 UT on April 11, 1997.

Figure 5. 0-90 kHz POLAR WBR data for 03:00 UT to 04:00 UT on April 11, 1997.

Figure 6. Two POLAR WBR 48-second spectrograms starting at 03:23:36 UT on April 11, 1997.

Figure 6. Two POLAR WBR 48-second spectrograms starting at 03:23:36 UT on April 11, 1997.

Figure 7. 0-90 kHz POLAR WBR data for 12:54 UT to 13:00 UT on May 15, 1997.

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Figure 8. A POLAR WBR 48-second spectrogram starting at 12:56:24 UT on May 15, 1997.

Figure 8. A POLAR WBR 48-second spectrogram starting at 12:56:24 UT on May 15, 1997.

Figure 9. A WIND/WAVES TNR spectrogram from 13:00 UT to 15:00 UT on January 28, 1997.

Figure 9. A WIND/WAVES TNR spectrogram from 13:00 UT to 15:00 UT on January 28, 1997.

Figure 10. A color spectrogram of the GEOTAIL PWI electric field SFA data for 13:00 UT to 15:00 UT on January 28, 1997.

Figure 10. A color spectrogram of the GEOTAIL PWI electric field SFA data for 13:00 UT to 15:00 UT on January 28, 1997.

Figure 11. A color spectrogram of the POLAR PWI Eu electric field SFR data for 13:00 UT to 15:00 UT on January 28, 1997.

Figure 11. A color spectrogram of the POLAR PWI Eu electric field SFR data for 13:00 UT to 15:00 UT on January 28, 1997.

Figure 12. A WIND/WAVES TNR spectrogram from 18:00 UT to 20:00 UT on January 28, 1997.

Figure 12. A WIND/WAVES TNR spectrogram from 18:00 UT to 20:00 UT on January 28, 1997.

Figure 13. A color spectrogram of the GEOTAIL PWI electric field SFA data for 18:00 UT to 20:00 UT on January 28, 1997.

Figure 13. A color spectrogram of the GEOTAIL PWI electric field SFA data for 18:00 UT to 20:00 UT on January 28, 1997.

Figure 14. A color spectrogram of the POLAR PWI Eu electric field SFR data for 18:00 UT to 20:00 UT on January 28, 1997.

Figure 14. A color spectrogram of the POLAR PWI Eu electric field SFR data for 18:00 UT to 20:00 UT on January 28, 1997.

Figure 15. 0-90 kHz POLAR WBR data for 18:38 UT to 19:14 UT on January 28, 1997.

Figure 15. 0-90 kHz POLAR WBR data for 18:38 UT to 19:14 UT on January 28, 1997.

Figure 16. Two POLAR WBR 48-second spectrograms starting at 19:04:00 UT on January 28, 1997.

Figure 16. Two POLAR WBR 48-second spectrograms starting at 19:04:00 UT on January 28, 1997.

Figure 17. IMAGE magnetometer network x-component data for 13:00 UT to 23:00 UT on October 19, 1996.

Figure 17. IMAGE magnetometer network x-component data for 13:00 UT to 23:00 UT on October 19, 1996.

Figure 18. A color spectrogram of the GEOTAIL PWI electric field SFA data for 13:00 UT to 23:00 UT on October 19, 1996.

Figure 18. A color spectrogram of the GEOTAIL PWI electric field SFA data for 13:00 UT to 23:00 UT on October 19, 1996.

Figure 19. A WIND/WAVES TNR spectrogram from 13:00 UT to 23:00 UT on October 19, 1996.

Figure 19. A WIND/WAVES TNR spectrogram from 13:00 UT to 23:00 UT on October 19, 1996.

Figure 20. A color spectrogram of the POLAR PWI Ez electric field SFR data for 13:00 UT to 23:00 UT on October 19, 1996.

Figure 20. A color spectrogram of the POLAR PWI Ez electric field SFR data for 13:00 UT to 23:00 UT on October 19, 1996.

Figure 21. A color spectrogram of the POLAR PWI Ez electric field SFR data for 22:00 UT to 24:00 UT on November 24, 1996.

Figure 21. A color spectrogram of the POLAR PWI Ez electric field SFR data for 22:00 UT to 24:00 UT on November 24, 1996.

Figure 22. A color spectrogram of the GEOTAIL PWI electric field SFA data for 22:00 UT to 24:00 UT on November 24, 1996.

Figure 22. A color spectrogram of the GEOTAIL PWI electric field SFA data for 22:00 UT to 24:00 UT on November 24, 1996.

Figure 23. Line plots of the spectral density in the POLAR 355.9 kHz SFR channel and in the GEOTAIL 325 kHz, 357.8 kHz, and 407.1 kHz SFA channels for 22:00 UT to 23:30 UT on November 24, 1996.

Figure 23. Line plots of the spectral density in the POLAR 355.9 kHz SFR channel and in the GEOTAIL 325 kHz, 357.8 kHz, and 407.1 kHz SFA channels for 22:00 UT to 23:30 UT on November 24, 1996.

Figure 24. A WIND/WAVES TNR spectrogram from 22:00 UT to 24:00 UT on November 24, 1996.

Figure 24. A WIND/WAVES TNR spectrogram from 22:00 UT to 24:00 UT on November 24, 1996.

Table 1. CANOPUS Magnetometer Sites

		Geodedic		Pace			Inv.
Location	Acronym	Lat.	Long.	Lat.	Long.	L	Lat.
Rankin Inlet	RANK	62.8	267.9	73.7	-29.0	12.4	73.5
Eskimo Point	ESKI	61.1	266.0	71.9	-31.8	10.2	71.7
Fort Churchill	FCHU	58.8	265.9	69.7	-30.8	8.2	69.6
Gillam	GILL	56.4	265.4	67.4	-30.9	6.7	67.3
Island Lake	ISLL	53.9	265.3	64.9	-30.3	5.5	64.8
Pinawa	PINA	50.2	264.0	61.2	-31.6	4.3	61.2
Rabbit Lake	RABB	58.2	256.3	67.8	-45.0	6.9	67.6
Contwoyto Lake	CONT	65.8	248.8	73.4	-61.2	12.4	73.5
Fort Smith	FSMI	60.0	248.1	67.9	-57.3	7.1	68.0
Fort McMurray	MCMU	56.7	248.8	64.8	-54.4	5.5	64.8
Fort Simpson	FSIM	61.7	238.8	67.6	-69.9	6.8	67.4
Dawson	DAWS	64.1	220.9	65.9	-90.1	5.9	65.7