Observations of two types of Pc 1–2 pulsations in the outer dayside magnetosphere


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1Analysis of high time resolution magnetometer data from the Polar satellite and from an array of high-latitude ground stations in Antarctica has identified 20 simultaneously observed Pc 1–2 wave events in the outer dayside magnetosphere during the first 17 months of Polar operations. In contrast to most earlier satellite studies of Pc 1–2 waves, based on data from equatorial satellites near apogee which moved only slowly across L shells if at all, the initial orbit of Polar allowed it to rapidly cross outer magnetospheric L shells, but significantly away from the magnetic equator. Consistent with several previous studies of outer magnetospheric Pc 1–2 waves, the majority of these events (75%) were associated with significant compressions of the magnetosphere. Seven of the events occurred simultaneously in satellite and ground data, with wave bursts temporally associated with compressions. These events, most at L values > 9, confirm the suggestion of Anderson and Hamilton (1993) that the outer dayside magnetosphere is often near marginal stability for electromagnetic ion cyclotron (EMIC) wave generation, so waves can be stimulated by even modest magnetospheric compressions. However, 10 of the wave events (five associated with compressions, and five not) were highly localized in L shell. In these “spatially localized” cases, continuous wave emissions were seen on the ground for extended periods of time, while in space waves were observed for only a few minutes and occurred only in radially narrow regions. The noncompressional events, all spatially localized, appear to be the first examples identified in space of the class of wave events known as Pc 1–2, sustained narrow-band emissions which have durations at high-latitude ground stations of the order of 10 hours in the day and dusk local time sectors. All 10 of the spatially localized events, whether compressional or not, followed intervals of at least 12 hours of sustained very quiet magnetospheric conditions. Energetic ion observations from Polar confirm earlier suggestions that drifting plasma sheet ions are the source of dayside Pc 1–2 waves in the outer dayside magnetosphere, but they also show different particle configurations for the spatially localized and temporally ordered event categories. Events in both categories occurred within radially extended regions with ring-like, moderately anisotropic distributions of ~5 keV protons and with deep minima in the flux distributions at energies <5 keV. However, spatially localized wave events occurred only in association with radially localized regions that also contained highly anisotropic fluxes of ~0.5–3 keV protons, at a considerable distance from the magnetospheric boundary. In contrast, no such radial structure was evident in any of the temporally ordered events, or in three “uncertain” events. The association of the spatially localized events with highly structured populations of plasma sheet protons of keV and higher energies indicates an important but unanticipated role for these protons in destabilizing plasma in the outer dayside magnetosphere, possibly through increasing the local plasma beta near the

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1. Introduction

[2] Pc 1 and 2 waves (magnetic field - guided electromagnetic waves with frequencies from ~0.1 to 5 Hz) are a common feature of the outer magnetosphere. There is a large amount of evidence and theory suggesting that they are generated by the electrostatic cyclotron (EMIC) instability, a plasma instability which requires the presence of hot, anisotropic ions [Carruthers, 1965; Kennel and Petchek, 1966; Leschon, 1967] in agreement with theoretical work reviewed by Horne and Thorne [1993]. The observations of Anderson et al. [1996b] showed that these waves appeared to be generated close to the magnetic equator.

[3] Although EMIC waves on closed field lines clearly have an internal source, there has been considerable evidence that their occurrence can also be influenced by external variations in the solar wind and IMF, increases in solar wind pressure, including but not limited to sudden impulse events, often cause wave onsets and/or intensifications. The class of EMIC pulsations must often be observed in the early years of space physics appeared to originate near the plasmapause and/or synchronous orbit, and in fact did not show much solar wind control. However, Kueh and Kivelson [1979] showed, using data from the OGO-5 satellite near the dusk equator at L values from 7 to 14, that all of the 11 events they observed were associated with enhanced pressure regions in the solar wind, and with a southward component of the interplanetary magnetic field two hours prior to the event. They also inferred that the generation region at larger L is longer-lived than that at synchronous orbit.

[4] Anderson et al. [1992a, 1992b], who conducted the first large-scale study of equatorial Pc 1 and 2 wave occurrence beyond synchronous orbit, using data from the equatorial-orbiting AMPTE CCE satellites, found that EMIC wave occurrence was considerably higher in the outer dayside magnetosphere than near the plasmapause, occurring primarily for J ~ 7 during daytime hours, a region not naturally associated with large fluxes of cold plasma. These observations led them to conclude, consistent with earlier theoretical studies, that growth rate can be expected to increase with radial distance.

[5] A followup study of the AMPTE CCE data by Anderson and Hamilton [1993] confirmed the association between increases in solar wind pressure and onsets or intensifications of wave activity in the outer dayside magnetosphere, which typically occurred at the lower frequency, end of the Pc 1–2 Pc frequency band, typically from 0.1 to 0.8 Hz. They also used energetic particle data from AMPTE CCE to confirm theoretical suggestions by Olson and Lee [1983] that compressions cause increased temperature anisotropies of hot protons. Anderson and Hamilton [1993] noted (1) wave occurrence increased monotonically with L, irrespective of compression events, and (2) the relative change in magnetic field strength from compressions and expansions is largest near noon in the outer magnetosphere. Taken together, these two observations led them to conclude that the plasma in the outer dayside magnetosphere is often close to marginal stability, and to suggest that wave occurrence should increase beyond the equator of the AMPTE CCE orbit (~L ~ 9) to near the dayside magnetopause.

[6] Ground-based data at high latitudes also show a strong correlation between EMIC waves and compressions. Olson and Lee [1983] and Kangas et al. [1986] characterized the EMIC wave response to sudden impulses (SI), showing that the ULF emissions were most frequently observed to follow an SI when the observatory was near local noon, and that the stimulation of different types of ULF emissions by SI reflects the state of the magnetosphere at the time of the SI. Arnoldy et al. [1996] found that short-lived Pc 1 and 2 emissions occurred during roughly 70% of the isolated magnetic impulse events (MIIIs) they observed in several years’ data from high-latitude ground sites in both hemispheres. A recent statistical study by Cochrer [2000] of the influence of solar wind dynamic pressure on the power of dayside 0.1–1.0 Hz pulsations observed at three high-latitude ground stations mapping to the outer dayside magnetosphere (A from 69 to 74°) found a better than 80% correlation between large increases/decreases in solar wind dynamic pressure and enhancements/depletions of wave power. A recent study by Fivelor and Russell [2001] using data from the Polar satellite confirmed this general result, but pointed out the local time dependence of the compression effect: magnetospheric compressions cause local decreases in B on the dayside, but cause local decreases at high latitudes and/or on the flanks. They noted one case a pre-dawn local time in which the wave amplitude decreased.

[7] Not all of the outer magnetospheric EMIC events were related to compressions, however, whether observed in space or on the ground. Waves designated as Pc 1–2 in the Fakahasti et al. [1981] classification, sustained events with duration of several hours and frequencies between 0.1 and 0.4 Hz, often occurred without such compressions. Although such sustained Pc 1–2 waves were most common in later afternoon, they could in some cases extend continuously across the entire dayside. There have been no published observations of these events simultaneously in both ground and satellite data, and their source location and generation mechanism have remained elusive.

[8] Many studies of EMIC waves associated with the plasmapause also found them to be associated with anisotropic ring current ions of 10–100 keV energy and increased levels of cold plasma [Young et al., 1981; Lussi et al., 1982; Fraser, 1985], and a recent study by Elshorn and Udor- dsky [2001] confirmed frequent associations of such waves with magnetic storms. Waves in the outer magnetosphere,
however, and in particular Pc 1–2 waves, do not appear to be associated with wildly disturbed magnetospheric condi-
tions. Popenoe et al. [1993] used a ground-based survey of these events from three stations, South Pole (\( \lambda = -74^\circ \)), Sodankylä (\( \lambda = -74^\circ \)), and Siple (\( \lambda = -63^\circ \)), to show that these events had an occurrence peak between 12 and 18 MLT, but showed no tendency to occur with (or without) any particular solar wind or IMF parameter, even with southerly \( B_z \) for 1 or 2 hours prior to wave observations. In agreement with Kaye and Kivelson [1979], however, they also found no correlation of these events with either storm main or recovery phase. Popenoe et al. [1993] concluded that the ions responsible for the waves they observed might have their origin in the plasma sheet, from whence they drift sunward on the dusk side of the magnetosphere. Hansen et al. [1992] even inferred a boundary layer location for wave generation for high-latitude compression-related Pc 1–2 events, because of the relatively low energies of the ions they were able to associate with these waves, based on evidence of precipitating ions measured by low-altitude DMSP satellites. Similarly, on the basis of particle observa-
tions Anderson et al. [1996b] concluded that plasma sheet ions develop sufficient temperature anisotropy to generate EMIC waves on a routine basis in their drift from the nightside to the dayside and that plasma sheet ions on open drift paths rather than ring current ions on closed drift paths present the greatest source of equatorially generated EMIC waves at higher latitudes.

[5] Earlier ground-satellite studies [e.g., Erlandson et al., 1994; Hansen et al., 1995; Anderson, 1996a] have confirmed that individual Pc 1–2 wave events can be observed both in space and on the ground. Erlandson et al. [1994] reported multipoint ground-based observations of an intense Pc 1 wave event occurring during a magneto-
ospheric compression during the recovery phase of a geo-
netropic storm. This event was also observed in magnetic and electric field data from the Viking satellite. Hansen et al. [1995] compared ground observations of Pc 1–2 oscilla-
tions from Mawson, Antarctica to magnetic field observa-
tions from the Viking satellite near its apogee over the sout-
hem hemisphere. Anderson et al. [1996a] identified such oscil-
lations and spatial compressions related pulsation bursts with nearly identical frequencies at AMPTE CCE while it was in the outer equatorial magnetosphere on the subsolar point, and at South Pole Station, Antarctica.

[6] Although Pc 1–2 waves are field-guided while in the magnetosphere, they are also known to propagate horizon-
tally a few hundreds of km once they reach the ionospheric F region waveguide [Topley and Landhoff, 1966; Frese, 1975; Popenoe et al., 1993]. As a result, individual ground stations can provide only limited information about source locations. Arrays of such stations, however, can provide extended temporal monitoring of wave occurrence in the regions traversed only infrequently by satellites.

[7] The orbit of a given satellite also provides significant spatial/ temporal constraints on the information that can be obtained about the region of wave generation. Equatorially orbiting satellites such as AMPTE CCE probed the equato-
rial regions in the outer magnetosphere out to \( L \approx 9 \), but could not provide information on the radial extent of individual wave events. Satellites at or near geosynchronous orbits provided even more limited information about radial extent. In contrast, polar-orbiting satellites such as DE-1, Viking, and Polar spend significant amounts of their orbits crossing outer magnetospheric field lines,CLS and latitudes, away from the expected generation region near the magnetic equator. Because the field-guided nature of ULF L Waves ensures that Pc 1–2 waves generated on a given flux tube will remain on that flux tube, a satellite even at off-equatorial latitudes can reliably observe many proper-
ties of these waves. (Equatorial observations of ULF L Waves are limited by the lack of equatorial satellites, which may be changed in transit to the ground, such as polarizability and electrification [Johnson and Cheng, 1999], is beyond the scope of this paper but will be the subject of future study.)

[8] The combination of observations from a ground-
based array from Polar and from AMPTE provided unprece-
tented ability to determine both temporal and spatial characteristics of Pc 1–2 wave events in the outer magne-
tosphere. During the first 18 months of Polar's operations, its \( R_g \) apogee was located over the northern hemisphere. This made possible rapid inversions of dayside field lines from the cusp to the plasmapause. Of the greater than 100 Pc 1–2 wave events observed by Polar during this interval, twenty were also observed at a set of high latitude Antarctic ground stations. During these events Polar traveled along magnetic field lines in the northern hemisphere whose footpoints in the Antarctic ionosphere mapped within 3 hours of local time of the location of these stations.

[9] This paper presents detailed observations of four of these events in the context of solar wind variations and magnetospheric compressions (or their absence) and simultane-
ously observed plasma sheet particle fluxes, as well as a summary of the entire set. We find that events fall into two categories, distinguishable both by wave observations and by the spatial pattern of proton fluxes. Wave events denoted as temporally oriented appeared simultaneously in space and on the ground, and were generated over at least a moderate range of \( L \) shells. Observed frequencies in space and on the ground were nearly identical. Spatially localized events, which appear to be a substantial class of Pc 1–2 wave events, are temporally more complicated. Those denoted as spatially localized appeared for up to several hours on the ground, but only a few minutes in space, as Polar passed through the region of the events. Temporally spaced events correspond to the observed free energy for the IMC instability that drives the waves. Temporally ordered compressional events also occur in regions where protons are structured in velocity space, but no radial structure is evident in the hot protons during these events.

### 2. Data Set

[10] The deployment of Automated Geophysical Observ-
atory (AGOs) on the Antarctic continent by both the U.S. and the U.K. since the early 1990s has made possible the establishment of an array of search coil magnetometers at geomagnetic latitudes ranging from \( \sim 66^\circ \) to \( 83^\circ \) and geo-
netropic longitudes from \( 15^\circ \) to \( 40^\circ \). The Antarctic stations used in this study are listed in Table 1, and shown on the map in Figure 1. They include South Pole Station (SPS),
two (P2 and P3) of the six automated geophysical observatories (AGOs) of the U. S. Polar Experiment Network for Geophysical Upper-Atmosphere Investigations (PENGUIN) program [Rowan and Doddiet, 1994]; and two of the four AGOs (A80 and A81) deployed by the British Antarctic Survey (BAS) [Dudgen et al., 1997]. The search coil magnetometers at South Pole and the AGOs record vector components of $dB/dt$ in a local geomagnetic coordinate system, with X northward and Y eastward [Taylor et al., 1975; Engelage et al., 1997].

Observations of ULF waves on Polar are obtained by the Magnetic Fields Investigation [Russell et al., 1995], which samples the ambient vector magnetic field at 0.12-s intervals. The data presented here are routed into a field-aligned local coordinate system.

The 'Sidral Imaging Mass-Angle Spectrograph (TIMAS) instrument on Polar [Shelley et al., 1995] provides information on the plasma populations over the energy range from 15 eV to 25 keV and over 98% of the unit sphere on the field line along which the observed waves propagate, and on which they presumably have originated. However, a significant disadvantage of Polar's initial orbit is that it crossed outer magnetospheric field lines at geomagnetic latitudes near 45°, so it could not sample the relevant plasma populations in the equatorial region where the waves originate. It is relatively easy to model the movement and evolution of plasma sheet ions through the magnetosphere at the geomagnetic equator (e.g., Li et al., 2000). It is significantly more difficult to model the movement and evolution of particles mirroring at off-equatorial latitudes (X. Li, personal communication, 2001). Because of the complexity of the proton distributions observed during these events, it is a significant challenge, one subject to tenuous assumptions, to extrapolate from the locally observed populations to the equatorial populations. On the other hand, TIMAS can easily resolve ions in the loss cone at these latitudes.

Solar wind plasma data are obtained by the Solar Wind Experiment (K. Ogilvie, PI) on theWind satellite and accessed using the CDAWEB facility http://cdaweb.gsfc.nasa.gov at NASA-Goddard Space Flight Center. Measurements of the total ambient magnetic field at geosynchronous orbit were obtained by the GOES 8 satellite [Singer et al., 1996], located at 75° west geographic longitude (local noon about 17 UT, from 1.5 to 3 hours local time west at the Antarctic ground stations). At those times when GOES 8 is located near local noon, this total field serves as a useful indicator for the onset time of magnetospheric compressions.

3. Observations of Spatially Localized Events

In this section we show two examples of wave events that were highly localized in L shell. The first event occurred during a strong magnetospheric compression, while no compression was observed during the second. In both cases sustained wave activity was observed on the ground, while in space Polar observed the waves for only a few minutes.

The first and second panels of Figure 2 show Fourier spectrometers of X (south–north) component search coil magnetometer data from PAS AGO A81 and U.S. AGO P3, respectively, from 0200 to 0300 UT April 8, 1996 (yearday 960999). We have used two complementary methods to check for the occurrence of magnetospheric compressions associated with Pc 1–2 wave events, as shown in those panels. (1) The white tape in the first panel shows the magnitude of the magnetic field observed by the GOES 8 satellite, situated ~3 hours MLT west of the ground sites. (2) The white trace in the second panel shows the solar wind pressure observed by the Wind satellite, located upstream of the Earth at GSE coordinates X ~ 82, Y ~ 27, Z ~ 3 Re. The solar wind pressure data have been delayed by 28 min to correct for the transit time from the location of WIND to earth, using only the observed X component velocity of the solar wind, also observed by Wind. It is evident that at both 1240 and 1340 UT sudden sharp increases in wave power match very well with both the increased total field at GOES 8 and the time-shifted solar wind pressure at WIND. The sustained wave activity after 1400, strongest at the lower-latitude station (A81), is consistent with the sustained high level of pressure (up to a factor of 2.5) for the duration of the wave event. The more complex and somewhat weaker

![Figure 1](image-url)

Figure 1. Map showing the locations of the Antarctic ground stations used in this study. Geographic coordinates are shown by dotted lines, and corrected geomagnetic coordinates are shown by solid lines. Also shown is the trace of the mapping of the Polar satellite’s orbit from 1400 to 1424 UT April 8, 1996 along geomagnetic field lines to the southern hemispheric, indicating a close magnetic conjunction with AGOs A81 and P3.
Figure 2. Fourier spectograms showing Pc 1–2 pulsations observed by BASS AGO A81 and U.S. AGO P3 in Antarctica and by the Polar satellite in the northern outer magnetosphere on April 8, 1996 (yesterday 96099). The panels show the north–south (X) component of search coil magnetometer data from A81 and P3 and the component of the magnetic field perpendicular to the local field line in the spin plane at the Polar satellite in the northern outer magnetosphere. The upper two panels show ground data from 0200 to 1800 UT, while the lower three panels show ground and satellite data from 1500 to 1500 UT. Superposed on the first and third panels is the magnetic field magnitude (in nT, white = right) observed by the Geotail satellite at geosynchronous orbit ~3 hours MLT west of the ground station. Superposed on the second and fourth panels are the solar wind dynamic pressure (in nPa, scale at right) observed at the location of the Wind satellite upstream of Earth, and time shifted 28 min as explained in the text.
wave signals from 0700 to ~ 1300 coincide with earlier solar wind pressure variations. Note that because of the diurnal variation of the total magnetic field at synchronous orbit, the total field at GOES is not a good indicator of solar wind pressure variations when it is in the night or pre-dawn sectors.

Figure 1 also shows the trajectory of the Polar satellite on closed field lines as it traveled north from the magnetic equator toward the cusp, as mapped from the satellite’s position to the southern hemisphere ionosphere using NASA’s SSCWEB utility (http://sscweb.gsfc.nasa.gov). As Figure 1 indicates, the Polar satellite passed through the outer dayside magnetosphere on field lines that map close to two of the Antarctic ground stations, AGOs AS1 and P3, between 1400 and 1424 UT.

In the lower three panels of Figure 2, which cover a two-hour time interval from 1300 to 1500 UT, we compare the signatures of the last wave event on this day with those obtained by the Polar satellite, which observed similar waves from 1420 to 1428 UT during its northward pass through the outer dayside magnetosphere. It is apparent that Polar detected waves during only a small portion of the interval of increased solar wind pressure, compressed magnetospheric field, and intense wave activity evident at the ground stations.

Although the L shell value listed at the bottom of Figure 2 are based on model calculations, and are likely to be overestimated at high latitudes because of the ongoing compression of the magnetosphere, comparison of the frequencies observed at Polar and on the ground suggests reasonably good agreement. Figure 3 shows details of the power as a function of frequency during the interval 14:22–14:30 UT, at which time the satellite crossed magnetic field lines mapping nominally to very near the latitude of P3. The good (but not perfect) agreement in frequency spectrum, with peak power between 0.3 and 0.6 Hz, suggests that the waves are generated on magnetic field lines over a limited range of latitudes near to or slightly lower than that of P3.

Figure 4 shows wave and proton data for the Pc 1–2 event of April 8, 1996. The upper panel shows a Fourier spectrogram of the component of the magnetic field perpendicular to the local field line in the spin plane at Polar from ~410 to 1510 UT. TIMAS proton energy spectrograms, covering the energy range from 15 eV to 25 keV, are shown in the lower panels of Figure 4 for two pitch angle ranges: 80°–100° and 160°–180°. The spectrogram for the pitch angle range 0°–20° (not shown) was very similar to that for 160°–180°. The other plasma instruments on Polar indicate that there were no significant changes of protons above 25 keV during this interval (J. L. Rosner, personal communication, 2001).

The TIMAS spectrograms show the presence of three distinct H populations. Protons above 5 keV drift westward under the influence of the so-called gradient drift. This population is most often observed on the dusk side of the magnetosphere [see, e.g., Li et al., 2000]. The intensity of ions below 3 keV is dominated by the core plasma, and decreases as the energy increases. The relative rate and direction of ion drift depends on the pitch angle as well as the energy. The result of these energy/pitch angle dependent drift rates is complicated energy spectra, which have been shown to vary significantly as a function of distance from the equator (e.g., as reviewed by Kistler et al. [1999]). Protons below about 100 eV are the hot tail of the dense (~100 cm⁻³) core plasma, most of which is below the 15 eV energy threshold of the TIMAS instrument.

During its poleward movement from L ~ 7 to L ~ 15 the satellite encountered (1) relatively intense proton fluxes decreasing in energy from ~15 keV near 1415 to ~3 keV near 1445 UT; and (2) less intense fluxes of 500 eV – 3 keV ions beginning near 1424 UT. Fluxes in the deep gap between these two proton populations and below the lower-energy proton population were reduced by one to two orders of magnitude. The duration of the Pc 1–2 wave event, 1422–1428 UT, overlapped in spatial/temporal extent with the time interval during which Polar encountered a nose-like feature in the lower-energy (~1 keV) proton population.

The temporally and spatially extended gap between the two energetic populations (with energy ~5 keV at the time of the wave burst) is most likely a direct result of the convection of plasma sheet ions of different energies from the nightside magnetosphere. Such gaps have been observed by, for example, Lennartsson et al. [1979], Li et al. [2000], and McDade et al. [2001]. The empirical model of low-energy ring current ions developed by Collin et al. [1993] on the basis of CRRES data shows a similar gap in proton fluxes between 3 and 5 keV in the range of 5 < L < 6 and local times between 12 and 16 hours (their Figure 3). This indicates that the energetic ion B drifts oppose each other along the particle trajectories. Below this energy cutoff, ions E × B drift eastward and above this
Figure 4. PC 1–2 pulsations observed by the Magnetic Fields Investigation (MFI) and proton fluxes observed by the Temporal Imaging Mass-Angle Spectrograph (TIMAS) on the Polar satellite as it passed through the northern outer magnetosphere from 14:40 to 15:10 UT, April 8, 1996. The upper panel is a Fourier spectrogram of the magnetic field perpendicular to the local field line in the spin plane at the Polar satellite. Wave power in this panel is color-coded according to the color bar at the right as a function of UT (horizontal scale) and frequency (vertical scale). The middle and lower panels show spectrograms of proton fluxes from the Polar TIMAS instrument at the 80°-100° and 160°-180° pitch angle ranges, respectively.

Figure 5 shows the southern hemisphere mapping of the flux tube sampled by Polar from 14:15 to 15:00 UT, October 8, 1997 (year day 297), indicating a close magnetic conjunction with U.S. AGO P3 near 14:10 and with BIS AGO ASI near 14:30 UT.

In contrast to the first event, the upper three panels of Figure 6 show that this event was characterized by a steady pulsation event that was observed for many hours, from 09:00 to 10:00 UT. Although AGO P3 data for this day were contaminated by noise (some of which is also present at AGO ASI), very similar pulsation activity was evident at ASI, P2, and South Pole, with nearly equal amplitude and little change in frequency.

The upper two panels of Figure 6 also show that the time-shifted (eastward) storm pressure was relatively steady throughout the day, with a slow increase from 1.0 mPa at 0900 to 1.2 mPa at 1400 to 1630 but with more rapid but still small variations from 1445 to 1715. The GOES 8 magnetic field magnitude displayed a typical daily variation, maximizing shortly before local noon, but also appeared to reflect the core of the small pressure variations noted at Wind. Variation in pulsation amplitude after 1600...
appear to match the modest variations in pressure evident in both the GOES 8 [B] and the time-shifted WIND PS_traces, but there are no evident compressions related to the most intense wave signals between 1300 and 1600 UT.

[1] The lower three panels of Figure 6 provide an expanded view of the wave activity between 1300 and 1500 UT, during which interval Polar moved southward from the cusp region toward the plasmapause near 1300 MLT. Both at A81 and P3 the waves extend nearly con-
tinuously across the 1300 to 1500 UT time span, although there is evidence of occasional “pea-sized” dispersive features within the band of increased wave power. The Polar data show broadband activity from 1300 to 1315 UT, associated with the cusp, but thereafter no activity except for a short narrowband burst from 1416 to 1422 UT at L values from 10.6 to 9.7. The superposes GOES and Wind data again show no temporal association between the wave burst and any compressional signature.

[2] Figure 7 shows simultaneous power spectra for this interval from A81, South Pole, and Polar. The frequency of peak power, ~250 mHz, is nearly the same at each location, which suggests that the satellite passed through the L shell on which the bulk of the waves were generated.

[3] Figure 8 shows magnetic field and particle data for this event. Both the pulsation burst in the top panel and the particle data (lower two panels) show considerable resem-
blance to those of the first event. A population of ions with energy increasing from 5 to ~10 keV is evident in both the near-polar and near-parallel flux spectrograms, along with a nearly parallel extended flux minimum that increases in energy from 2 keV at 1400 UT to 3–4 keV after 1430 UT, and a nose-like feature from ~1420 to 1430 UT. A second flux minimum was again evident below the “nose,” with energies roughly from 200–300 eV down to below 100 eV. We point out that during this event the wave interval appeared on the high-L side of the nose, while during the first event the wave activity occurred on the low-
L-side of the nose.

[4] Figure 9 presents a contour plot and line plot of proton velocity distributions for a one-minute interval from 1417:37 to 1418:57 UT, near the middle of the Pc 1–2 wave activity. The contour plot (upper panel) is a plot in the Z direction (parallel to B) and X direction (perpendicular to B and is the spacecraft spin plane) through the spin plane of the TIMAS instrument, and is constructed from data accumulated within one angular resolution width (22°) of the spin plane. Contours are shown for 12-keV values of the proton velocity space density. The lowest contour displayed corre-
sponds to a velocity space density of 10−10 cm−3 s−1. The locations of the centers of data points indicated in the average contour plots are indicated by the dots. The line plot (lower panel) is a one-dimensional cut in the X direction, perpendicular to B and in the spin plane through contours of the velocity space density. The dotted line in this panel represents the 1 count response level. All the data shown are well above noise levels. As in the first event, the more energetic proton population with velocity >800 kn/s appears twin-like, with modest positive temperature aniso-
tropy, while the population with velocity below 800 kn/s is strongly anisotropic with a deep minimum in the directions along B.

4. Observations of Temporally Ordered Events

[1] In contrast to the previous examples of spatially localized Pc 1–2 wave events, the third and fourth events exhibit a temporally ordered rather than spatially localized character. Figures 10 and 11 show the filtered footprint of the Polar trajectory from 1400 to 1439 UT on April 16, 1997 (yearday 970106), indicating that the satellite moved toward higher L shells near A81 and P3. Unfortunately, the auto-
mated field line mapping algorithm on this day produced open field lines at 1399 UT, at a geomagnetic latitude of only 70° in the southern hemisphere.

[2] The ground and satellite pulsation data for this event are shown in Figure 11, which cover the interval from 1230 to 1430 UT. The first and second panels show spectrograms of near-south component search coil data from A81 and P3, respectively, and the third panel shows a spectrogram of the component of the magnetic field perpendicular to the local field line in the spin plane at Polar. Solar wind dynamic pressure data from Wind, time-shifted 64 min to correct for the propagation of the observed variations from Wind’s upstream location at GSE coordinates X = 227, Y = 5, Z = 23 R̅̅₆, showed a two-step increase shortly before and during this interval. Pressure increased slowly from 0.6 nPa at the beginning of this day to 1.1 nPa at 1225 UT, at which time there was a rapid jump to ~2 nPa (not shown), followed by another rapid jump near 1320 UT to over 4 nPa. Total field data from GOES 8 are in rough temporal agree-
ment with the time-shifted Wind data for both of these increases.

[3] Although modest wave power is evident from 1230 to 1320 UT at the ground stations, generated in response to the
increase in solar wind pressure that reached the magnetosphere near 1225 UT, no such power is evident at Polar. A nearly simultaneous intensification of wave power is evident at all three locations beginning near 1320, in good coincidence with the magnetic field intensification seen at GOES 8. The weakening of the signals at Polar is also in rough agreement with that seen at P3 and with a more modest weakening at A81.
During this event, the two wave bursts (1320–1330 and 1340–1355 UT) occurred in temporal coincidence with similar bursts observed on the ground.

[6] The proton spectrometers during this wave event are again highly structured in energy and pitch angle. In this case, however, there was no tendency for the proton population to decrease in energy of both of the hot components over the entire interval shown. Those with the highest energies appear at the upper end of the TIMAS instrument's energy range beginning near 1400 UT and fall gradually in energy; data from the CAMMIE instrument on Polar (J. L. Rebecca, personal communication, 1996) indicates that the energy of the upper beam of protons is continuously falling with time. A wide, deep gap separates this component from a component of warm protons below 10 eV. As in the previous cases, both populations are anisotropic, but the lower-energy population is much more so. Proton velocity distribution plots (not shown) indicated that throughout the interval both proton populations formed ring-like distributions, but in this case the lower of the two had a 1:2 order of magnitude drop in fluxes in a loss cone with half-angle of 40°.

[7] On September 26, 1996 (yearday 26720) Polar's orbit again mapped near to A81, as shown in Figure 14, as the satellite traveled to lower f shells near 3345 MLT. The upper two panels of Figure 15 show data from A81 and Polar, respectively, from 1300 to 1500 UT, indicating a series of pulsation bursts both in space and on the ground. The observed wave frequency at Polar more than doubled in one hour, from ~1330 to ~1430, while on the ground there was only a modest increase. On this day the time-shifted solar wind pressure held steady near 1.4 nPa from midnight to ~1240 UT, rose slowly to ~2 nPa near 1425 UT, and then increased more rapidly to over 4 nPa by 1500 UT. GOES 8 total field data reflect these same increases after 1300 UT.

[8] The various small increases in total field at GOES, near 1335, 1346, 1422, and 1432, show small (~3 min) and decreases (~10 min) to the corresponding increases in wave power at A81 and Polar. These delays are most likely due to the propagation time for fast mode waves from the disturbance (the local time of A81 and Polar) to the midmorning location of GOES 8 during this interval, as it moved from 0830 to 0930 local time.

[9] Figure 16 shows stacked power spectra from A81 and Polar for two intervals. Figure 16a shows the spectra during the first pulsation burst (1328–1334 UT), when the satellite was considerably poleward of A81, and Figure 16b shows the last burst (1428–1434), when Polar and A81 were at roughly the same latitude. During the first interval, pulsation power at Polar was enhanced over a relatively broad range from 200 to ~500 mHz. Wave power at A81 was enhanced at considerably higher frequencies, from 450 to 750 mHz, with a peak near 600 mHz. A small peak was present near 280 mHz but did not resemble that at Polar. During the second interval, the major peaks showed good agreement in frequency, with lower bounds near 556 and 600 mHz and peaks near 700 mHz.

[10] This event is similar to the series of wave bursts observed by Anderson et al. [1996a] nearly simultaneously.
at South Pole Station and AMPTE CCE over a 3-hour interval. Unfortunately, no solar wind data were available for that event, but magnetospheric compressions could be inferred from comparisons of the two data sets. In both cases wave bursts increased in frequency both in space and on the ground. But whereas AMPTE CCE was near apogee and hence avoided lower L shells during the bursts, resulting in good satellite-ground agreement in pulsation frequencies, the case here Polar moved rapidly toward lower L shells, and frequencies differed only near the end of the burst interval. We note that because of the increasing magnetospheric compression and resulting distortion of the field during this time, the L values shown beneath the bottom panel of Figure 11, which are based on static models, are again most likely too high during the first part of the two-hour interval shown.

Figures 8 and 9 show particle data from Polar for the September 26, 1996 wave event. The proton spectrograms for this interval (lower two panels) again show an extended flux minimum in the energetic proton distribution, initially centered near ~500 eV at 1105 UT, but increasing to ~2500 eV at 1300 UT. Two plasma sheet proton populations are evident above this band. They are clearly separated near 1330 UT, the upper centered near 20 keV and the lower covering a broader energy range from 1 to 10 keV. As the satellite moved toward lower L shells, the energy of the lower population rose until it merged with the upper band near 1430 UT. As with the previous event, there are no features in these plasma sheet proton distributions that match the times of ULF wave bursts.

5. Summary of Observations

We have shown two examples of each of events that we have classified as spatially localized and temporally ordered, respectively. A summary of the 20 events is presented in Table 2, which includes for each event (1) the magnetic local time and (2) the L shell range, respectively, of the waves observed by Polar; (3) the quality of the conjunction, in terms of the difference in magnetic local time between the satellite and the nearest of the ground stations involved; (4) whether the event was compressional or not; and (5) its classification as spatially localized (S), temporally ordered (T), or mixed or uncertain (U). Column 7 of Table 2 indicates that fifteen of the events were associated with compressions, while five were not. Column 8 indicates the classification of the events, 10 spatially localized, seven temporally ordered, and three others uncertain, based solely on analysis of the pulsation and compression data.

Events in the spatially localized, temporally ordered, and uncertain categories are further compared in Figure 17 in terms of their width in L (vertical axis) and center location in L (horizontal axis), using L values obtained from the Polar satellite data base. Although the highest L values may be expected to have large errors, it is clear that
the temporally ordered and uncertain events are situated at higher $L$ values (from above 8 to nearly 18), than the spatially localized events (from 5 to slightly over 11), and that they also have a much wider spread in $L$. The lone exception in width is the temporally ordered event of October 10, 1996, in which case a temporally limited (7-min) pulse of 60% increased solar wind pressure impinged on Earth. In this case the narrow width in $L$ corresponds to the distance in $L$ traversed by the Polar satellite during the time of this short compression.

[a] The distributions for the compressional and non-compressional spatially localized events overlapped; the weighted average $L$ value for the five CS events was 9.3, while that for the five NS events was 8.8. In contrast, the average $L$ value for the seven temporally ordered events was 12.7, and flat for the three events classified as uncertain was 14.2. The larger $L$ values for the temporally ordered and uncertain events appear to be consistent with the idea that, in those outer magnetospheric regions with relatively similar ion populations and densities, compressions are more likely to drive magnetospheric plasma unstable at higher $L$ values where $\Delta R_B$ will be larger because the dayside magnetospheric field drops off as $L$ increases [Anderson and Hamilton, 1993]. That the spatially localized events occurred at lower $L$ values, both on average and in most individual cases, suggests that the particle conditions associated with these specific flux tubes were such as to either substantially increase wave growth or substantially reduce the local instability threshold for EMIC wave growth. This could then lead to pulsation activity under conditions of either steady convection or convection augmented by magnetospheric compression. In addition, the fact that the width in $L$ of the spatially localized events was in almost all cases narrower than those of the temporally ordered events suggests that some $L$-dependent particle conditions may play a role in their generation. On the contrary, the larger width in $L$ of the temporally ordered events suggests that protons in a wide range of outer magnetospheric $L$ shells may be driven unstable during these events.

[a] With only two exceptions, all of the 20 events in our data set exhibited a clear gap in energy between two populations of energetic protons. TIMAS data were unavailable for April 27, 1996, and the October 23, 1996 event occurred during very disturbed conditions, with $K_p$ up to 7, and was observed in association with bouncing ion clusters.

Figure 9. Proton velocity distributions calculated from data from the Polar TIMAS instrument from 14:17:57 to 14:18:57 UT October 6, 1997. The upper panel shows a two-dimensional cut through the particle velocity distributions with the vertical axis along B, and the lower panel shows fluxes as a function of velocity in the plane perpendicular to B.

Figure 10. Map showing the trace of the footpoint of the Polar satellite's orbit from 1300 to 1339 UT April 16, 1997 along geomagnetic field lines to the southern hemisphere, as in Figure 1, indicating a magnetic conjunction near BAS AGO AS1 and U.S. AGO PJ near 13-45 UT.
[Quinn and McPherron, 1979; Peterson, 1988]. In all other cases, the more energetic of these two proton populations (~10 keV) formed a moderately anisotropic ring distribution. The lower-energy (~1 keV) proton population was consistently more anisotropic, and when this population was spatially limited, its boundaries roughly coincided with, and appeared to determine, the location of the wave generation region of the spatially localized events. In addition, although most of the temporarily ordered or uncertain events exhibited a nose-like spatial variation in the plasma sheet proton population, there was evidence for such a feature in the available data for all of the spatially localized events. This consistent pattern in the wave and particle characteristics of the spatially localized events, based on independent.

Figure 11. Fourier spectrums showing Pc 1-2 pulsations observed by DMSP, GOES-8, and U.S. AGO PS in Antarctica and by the Polar satellite in the northern solar magnetosphere from 1230 to 1430 UT on April 16, 1997, as in Figure 2. GOES 8 magnetic field magnitude and time-shifted solar wind dynamic pressure from WIND are superimposed on panels a and b, respectively.

Figure 12. Stacked power spectra from the A81 and P3 search coil magnetometers and the Polar magnetic field instrument during the intervals from a) 1320 to 1330 and b) 1340 to 1355 UT April 16, 1997.
A further pattern emerges from consideration of the magnetic activity levels preceding these events, and from a comparison of their frequencies. For each of the spatially localized events, the average Kp value for the 12 hours prior to the wave event(s) averaged to 0 or 1, regardless of whether the event was compression-related or not, and the three uncertain events had Kp values of 1 or 3. For the temporally ordered events, however, the average Kp values preceding wave activity ranged from 0 to 4, with a modal value of 2. This pattern suggests that the highly structured particle populations associated with spatially localized pulsations may be produced only under very quiet magnetospheric conditions.

Because as noted earlier Polar observed these Pc 1-2 pulsations fairly far from their assumed origin near the magnetospheric equator, a simple comparison of pulsation frequencies to the local field magnitudes cannot directly identify the wave branch of the pulsations (e.g., H, He, or O), as described by Hsu and Fraser [1994]. However, such a comparison may still have at least qualitative value because Polar traversed roughly the same regions of the daytime magnetosphere during each kind of wave event. For this study, we calculated the ratio of the observed frequency to the local oxygen ion cyclotron frequency. The spatially localized events were tightly clustered in frequency and relatively low, with average $f_{cp}$ of 0.64 ± 0.15. In contrast, for the other events the ratio was much higher and more

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**Figure 13.** Pc 1-2 pulsations and proton fluxes observed by the Polar satellite from 1330 to 1400 UT April 16, 1997, as in Figure 4.

**Figure 14.** Map showing the trace of the footpoint of the Polar satellite’s orbit from 1415 to 1530 UT September 26, 1996 along geomagnetic field lines to the southern hemisphere, as in Figure 1, indicating a magnetic conjugation near US. AGO P3 near 1410 UT and near the latitude of BAS AGO A81 near 1430 UT.
6. Discussion

Study of this set of 20 satellite-ground conjunctions has revealed two complementary patterns in the occurrence of Pc 1 and Pc 1–2 pulsations in the dayside outer magnetosphere. As Anderson and Hamilton [1993] anticipated, our temporally ordered events demonstrate that magnetospheric compressions can generate pulsation bursts across a relatively wide L shell range in the outer dayside magnetosphere, out almost to the magnetoopause. Conditions in this region are evidently often near marginal instability, so that even moderate compressions can stimulate wave growth. However, fully half of the wave events occurred within a limited L range, usually somewhat deeper inside the magnetosphere. The bandwidth of their wave emissions is typically narrow and identical both in space and over a range of latitudes on the ground, suggesting a common
Figure 16. Stacked power spectra from the A81 search coil magnetometer and the Polar magnetic fields instrument during the intervals from a) 1328 to 1334 and b) 1428 to 1434 UT September 26, 1996.

[Diagrams showing power spectra]

localized source, and their duration on the ground far exceeds that observed by Polar as it moved rapidly across outer magnetospheric J shells. We have noted that all of these events occurred after extended intervals of quiet magnetospheric conditions (average $k_{x} = 0$ or 1). In the cases associated with strong compressions, their duration on the ground coincided with the interval of relatively 

enhanced compression, while during the noncompressional events, which could last for many hours, solar wind pressure remained steady and magnetospheric conditions remained very quiet.

[...]

This clear distinction between spatially localized and temporally ordered events was unanticipated, based on ground data. On the basis of this data set however, we suggest that many if not most sustained EMIC wave events observed at high latitudes on the ground, whether compression-related or not, may well be associated with such spatially limited generation regions, and thus fit in our "spatially localized" category. Study of these spatially localized events thus appears to have revealed the source of pulsations in the Pc 1-2 category, and confirms suggestions by Popescu et al. [1993] and others that plasma sheet proton convection surging from the nightside magnetosphere are responsible for their generation.

[...]

The fact that some spatially localized events occurred even when there was no external compression of the magnetosphere is consistent with our current theoretical understanding that such compressions play a contributing role rather than a fundamental one. That is, compressions may increase pitch angle anisotropies, and thus make the

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*Shows for each event are the eccentric dipole magnetic local time of the wave event observed by Polar, its range is L, the difference is magnetic local time between Polar and the closest Antarctic ground station, whether the event was associated with a magnetospheric compression, and whether it was identified as a spatially localized (S) or temporally ordered (T) event.
plasma on a given flux tube more unstable, but by them-
selves they do not generate the waves. The occurrence of
noncompressional events in this study confirms that in some
circumstances the plasma on a given outer magnetospheric
flux tube can evidently reach the instability threshold even
without such external perturbations. We thus turn to a
preliminary discussion of the characteristics of the proton
distributions associated with these most unstable regions.

6.1. Spatial Localization of ~keV Protons

The existence of spatial boundaries in energetic proton
populations in the outer dayside magnetosphere is no
surprise. Three-dimensional calculations of particle con-
vection trajectories by Takeda and Iyemori [1989] showed
that as newly injected magnetotail particles drift
towards the magnetopause, then shock up on the inner
shell of the dayside magnetosphere near noon, consistent with the observations reported
here. Earlier calculations of convection trajectories by Eriji [1978], based on a dipole magnetic field, indicated that one
can expect to find overlapping gradient regions in one or
more populations near the convection boundaries in the
noon sector, with the lower-energy protons having drifted
down the dawn sector and the higher-energy protons
around the dusk sector. We note, however, that the trajec-
tories in both of these studies were calculated assuming
disturbed magnetospheric conditions, rather than the Kp =
0 or 1 conditions appropriate for our spatially localized
events.

The radial orientation of the nose structures in each of
the spatially localized events in our study is consistent
with these model trajectories: the ~keV protons that form
the nose appear at an outward direction from a sharp boundary
whose L value is a function of proton energy and pitch
angle. (The May 22, 1997 event had a nose structure in both
radial directions. It is not clear whether the above models
apply to this as well.) In addition, the gradual decrease in
energy with increasing L seen in each of the four examples
presented here is consistent with conservation of the first
adiabatic invariant as the particles drift sunward into regions of
weaker total field. [87] The energies of both the upper and lower populations vary from event to event, as does the width of the (often deep) gap that separates them. We attribute the variability in
the width of this gap, which is not always present in Polar
data in these regions, to both the time-dependent nature
of the plasma sheet injections that produce the convecting
protons and the variations of magnetospheric activity during
the many-hour travel times of such protons as they convect
sunward toward the dayside. In any case, although their
presence appears clearly relevant to the wave observations,
a detailed study of their formation and variability is beyond the
scope of this paper.

6.2. The Role of ~keV Protons in Wave Generation

This study is consistent with earlier conclusions regarding plasma sheet ions as the source of dayside Pe
1-2 waves in the outer dayside magnetosphere, but con-
tributes new and unanticipated details regarding those
drifting ions. Our observations suggest that the most unsta-
ble regions for EMIC wave growth in this region have an
additional hot proton population near 1 keV. Although the
hotter (~10 keV) population appears in many cases to have
positive temperature anisotropy, consistent with earlier
observations, the somewhat less energetic (~1 keV) pop-
ulation which was not resolved in earlier studies appears to
be more anisotropic and is in many cases more closely
associated with wave occurrence.

[85] Figure 10 of the Anderson et al. [1992b] study of
outer magnetospheric Pe 1 and 2 waves showed curves of
maximum growth rate and normalized frequency (f0') as
a function of perpendicular temperature of the unstable pro-
tons (in keV). Substantial growth rates were indicated for
protons well below 10 keV under conditions of sufficiently
large temperature anisotropy (A (~ 2). Figure 11 also shows that for such large anisotropies, the effect of cold
plasma density on wave growth is negligible. For the active
dawn events they studied, the unstable populations had perpendicular temperatures corresponding to 2.2 to
7.8 keV, with an average of 4.3 keV, while for active noon
events the unstable population had perpendicular temper-
atures from 14 to 40 keV, with an average of 21 keV. We
note that the high-resolution proton data from Polar reveals
even more structure (although well off the equator) than was
evident in the AMPTE CCE data, and shows that the most
isotropic protons had energies typically near 1-2 keV, at
the lower end of the energy range of the directions used in
the Anderson et al. [1996b] study. The wave frequencies and
observed particle energies for these events also match the
'keV' wave branch models in Figure 2 of Jin and Prater
[1994]. These authors also noted that this branch is not
sensitive to cold plasma profiles in the outer magnetosphere.

[86] In their study of dayside Pe 1 and 2 waves, Anderson
et al. [1996b] noted the presence of flux depletion bow
v = 1000 km/s, near the minimum velocity resolvable by the
AMPTE CCE CHEM instrument. They included such
depletions in their instability analysis, but found that the dispersion surfaces were nearly identical with and without the depletions. However, the highly anisotropic ~keV ion populations reported here for the spatially localized wave events were not clearly resolvable in the CHEM data set, and this could not be included in their analysis.

[5] Anderson et al. (1996b) also analyzed their wave observations in terms of the limited closure relations developed to parameterize the proton distributions observed in studies of Pe 1 and 2 waves in the subsolar magnetosheath [Anderson and Fuelsier, 1993]. This and subsequent observational studies showed that the energy for Pe 1 and 2 wave growth in this region came from pitch angle anisotropies of energetic protons in the convecting magnetosheath plasma. Dorrer et al. [1993], Gary et al. [1994a], and Gary and Lee [1994] showed both observationally and theoretically the existence of an upper bound on the coupled proton temperature anisotropy and parallel plasma beta, and that these EMC waves were responsible for maintaining that upper bound.

[6] Gary et al. [1994b] showed that a similar anisotropy upper bound to that found in the magnetosheath was observed at geosynchronous orbit in the outer magnetosphere. Their modeling and that of most earlier studies assumed one hot, anisotropic proton component (as well as a cool, initially isotropic proton component). Gary et al. [1994a] cautioned, however, that in contrast to the terrestrial subsolar magnetosheath, many space plasma regimes exhibit two or more important proton components; this would make both observations of instability thresholds and models of closure relations more difficult. Anderson et al. [1996b] in fact found it necessary to use multi-component bi-Maxwellian populations well above 1 keV to adequately fit the proton distributions they observed with AMPTE CCE.

[7] One reason earlier studies assumed large densities of cold plasma to be important for EMC wave growth can be understood using the equation for the cyclotron resonance for protons, $v = (c^2 - k^2)k_p$. We have found that in nearly all of the wave events in this study the more energetic plasma sheet population consists of ~10 keV protons, with parallel velocities near 1500 km/s. The lower-energy proton population typically has 100-700 km/s velocities in the perpendicular direction, but because of the large anisotropy of this population, the parallel component of these is even lower. Only if the waves propagate with a very low group velocity could such streams contribute their free energy to wave growth [Home and Thorne, 1993]. The simplest way to attain this condition is to increase the density of the cold plasma along the flux tube. However, an alternate possibility for influencing wave growth is suggested by the convection boundaries evident in the calculations of Ejiri [1978] and Takahashi and Iyemori [1988]. As shown in these studies, keV-range plasma sheet protons convect around dawn from the nightside along nearly constant L shells until near local noon, when their convection velocity slows and veers sunward. The pileup of these protons near local noon would thus produce nose-like features and a relatively rapid increase in plasma beta in the rest frame of the convecting protons as they move into weaker B fields, such that the local anisotropy-beta relation might reach the instability threshold, with or even without the aid of external compressions or increases in the density of cold plasma.

[8] There are thus two possible roles for the klivolt-energy proton population in these regions. It contains the most anisotropic and thus potentially wave-effective plasma, and it may increase the plasma beta and hence allow wave growth with lower levels of anisotropy.

7. Conclusions

[9] Using coreshotted ground and polar-orbiting satellite observations, we have identified two types of Pe 1-2 emissions in the outer dayside magnetosphere, which are distinguishable through a comparison of duration and frequency on the ground and in space, by their radial extent in space, and by their association with highly anisotropic ~keV proton populations.

[10] Wave events have been denoted as temporally ordered appeared simultaneously in space and on the ground, and were generated over at least a moderate range of L shells. Observed frequencies in space and on the ground rarely coincided. These more descriptions for the suggestion of Anderson and Hamilton [1993] that the outer magnetosphere is indeed often marginally unstable to EMC waves and can be driven unstable over a range of L shells by even modest compressions.

[11] However, half of the events observed show the existence of waves in quite narrow L shell regions nearer, but still well outside, the plasmapause. These appeared for up to several hours on the ground, but only a few minutes in space, as Polar passed through a narrow region of L. Observed frequencies were nearly identical in space and on the ground.

[12] This study appears to have identified the source of quiet-time Pe 1-2 waves, which have not been associated with any dayside external or nightside internal magnetospheric trigger, in the same localized L shell regions that often become unstable during compressions. Such radially localized pulsations appear to have identical characteristics whether they occur with or without magnetospheric compression. The fact that for both classes of spatially localized EMC activity (compressional and non-compressional) prior magnetospheric activity was extremely quiet for many hours suggests that the source of free energy for the Pe 1-2 pulsation class is in highly structured plasma sheets that have convected sunward from the magnetotail.

[13] The fact that Polar's orbit rapidly crosses over magnetospheric L shells has made it possible, in conjunction with simultaneous multisite ground data, to consistently detect such radially localized pulsations, and the improved energy resolution of the TIMAS instrument has revealed unexpectedly detailed structure in the energetic protons on flux tube associated with these waves. To our knowledge, few previous satellite studies have provided evidence of such highly localized wave regions, and none have associated localized wave growth with spatially varying, highly structured energetic proton distributions, either observationally or theoretically, although Anderson et al. [1996b] noted that the variations of anisotropy with energy and the presence of holes in the distributions might both be important for instability. The observers presented here suggest the urgency of theoretical investigations of such
variations. The existence of proton polarizations in the outer oxide magnetostrictive with detailed structure in energy and pitch angle, however, is well understood in principle, and is a direct consequence of plasma sheet thickening.

[5] We have suggested that the structured keV-energy protons may influence wave growth by increasing the local plasma beta, thus helping to drive the local plasma environment across the instability threshold. Further theoretical and modeling work is currently needed, however, to test this suggestion, or to confirm a more direct influence of protons in this range on wave growth.

[6] Because Polar is far from the magnetic equator (at ~45° magnetic latitude), we can only suggest rather than verify that spatially localized increases in the keV proton population play a role in wave generation. Extrapolating the observed complex proton distributions to equatorial latitudes (where the waves presumably originate) using existing simplified or averaged models of outer magnetospheric densities would probably introduce significant errors. Because the motion of ions in the near-Earth magnetosphere is a strong function of energy and pitch angle, and depends on both the corotation electric field and gradient drifts as well as time of flight effects associated with finite ion velocities and possible absorption of wave energy by the plasma, it is quite difficult to infer plasma distributions near the magnetic equator, the assumed region of wave generation, from data at those locations, and is well beyond the scope of this study. In addition, highly anisotropic equatorial populations will simply not appear at these latitudes. Because the apogee of the orbit of Polar processed equatorward, observations from later years in Polar’s mission using this same set of instruments may provide further opportunities to probe such pulsation events, and the plasma distributions associated with wave growth, throughout the region of their generation. However, when its apogee is near the equator, Polar will orbit predominantly along ± shells rather than across them, so it will be correspondingly more difficult to define the spatial boundaries of wave events. Thus, observational confirmation of these ideas may have to await multisatellite missions that can sample both equatorial and off-equatorial ion populations on a given flux tube.

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