Temporal and spatial characteristics of Pc1 waves observed by ST5

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[1] We present the results of a study of Pc1 waves (0.2–5 Hz) recorded by the three spacecraft of NASA's Space Technology 5 (ST5) mission, which operated in a dawn-dusk, 300 × 4500 km Sun-synchronous orbit in a "string-of-pearls" configuration from 26 March through 23 June 2006. Regions with Pc1 wave activity are not only localized to rather narrow L shells but can appear and disappear on the time scales of ~10 s to 10 min as examined by ST5. Only half of the 48 identified events were observed by all three spacecraft, and five events were observed by only one spacecraft. Only seven events were observed below $L = 4$, and only one was observed below $L = 3.6$, consistent with the relatively quiet geomagnetic conditions during this interval. The temporal occurrence distribution of Pc1 events was similar to that recorded at Halley, Antarctica ($L = 4.56$), during this same interval in that the number and intensity of events increased during magnetospheric compressions and during the recovery phase of magnetic storms, but they were reduced or absent during main phase and early recovery phase. This agreement suggests that if Pc1 events occur during main phase, their nearly universal absence in ground records cannot be ascribed to ionospheric screening effects or obscuration by irregular ULF noise generated in the ionosphere. These findings also suggest that although electromagnetic ion cyclotron waves might theoretically cause rapid depletion of radiation belt electrons during the main phase of storms, such waves cannot be assumed to occur during the main phase of all storms.

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1. Introduction

[2] The three microsatellites of the Space Technology 5 (ST5) project were launched on 22 March 2006 on the back of a Pegasus XL rocket as part of the New Millennium Project created by NASA to help create new, innovative technology for future flight missions [*Slavin et al.*, 2008]. The three 25-kg spacecraft were placed into a Sun-synchronous polar orbit with altitudes ranging from 320 km in the Northern Hemisphere to 4500 km in the Southern Hemisphere. The satellites orbited in a "string-of-pearls" formation, allowing for magnetometer readings from all three satellites across the same L shells with only a few minutes delay. The first spacecraft (ST155) was separated from the other two (ST094 and ST224) by more than 5000 km at the beginning of the mission, but this distance decreased to less than 50 km at the end of the mission. The satellites took data for a total of 90 days, from 26 March to 30 June 2006 (Figure 1).

[3] This study uses data from the fluxgate magnetometer on board each ST5 spacecraft to detect electromagnetic ion cyclotron (EMIC) waves, which are understood to be generated in Earth's equatorial magnetosphere and are subsequently guided along magnetic field lines to lower altitudes (see, e.g., the review by *Kangas et al.* [1998]). Each magnetometer system obtained 16 vector samples per second whenever it was operated, but at certain times these data were averaged down to 8 vectors per second to accommodate onboard data storage limitations. The digital resolution of each magnetometer was 1.25 and 0.30 nT in their high and low field ranges, respectively [*Slavin et al.*, 2008].

[4] Two earlier single-satellite studies have surveyed the occurrence of these waves at low altitudes. The first, by *Iyemori and Hayashi* [1989], used 6 months of Magsat fluxgate magnetometer data. Magsat found wave events with amplitudes from 5 to 30 nT and frequencies between 1.3 and 1.5 Hz. Amplitudes on the ground near the Magsat foot point were 2 orders of magnitude smaller than ampli-

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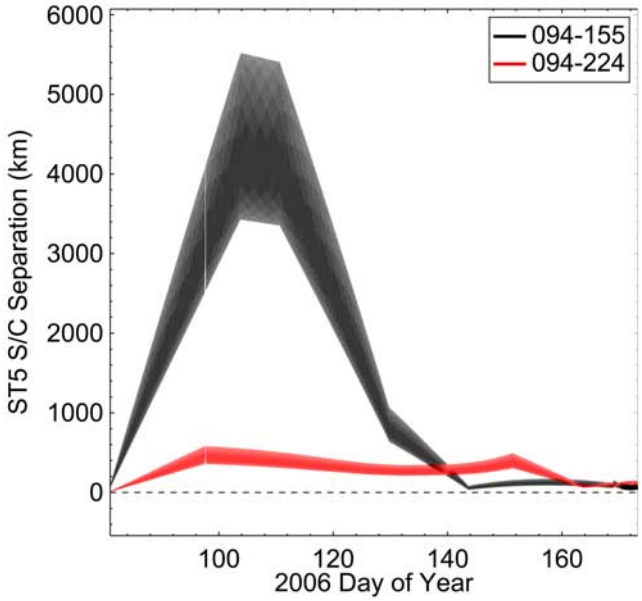

Figure 1. Plot of the along-track separation (in km) of the three ST5 spacecraft (s/c) during its 90-d mission.

tudes observed by Magsat. The other study, by *Erlandson and Anderson* [1996], used 14 months of electric field data from the Dynamics Explorer 2 satellite. Most events observed in this study were between the frequencies of 0.4 and 2.0 Hz and were observed in the dawn and noon sectors. The characteristics of Pc1 waves reported here are consistent with the findings of these earlier studies, but the availability of three spacecraft make it possible to provide increased information on their spatial-temporal characteristics. Because of the relatively quiet geomagnetic conditions during the 3 months of the ST5 mission, however, these characteristics are not necessarily typical of those throughout the solar cycle.

[5] Ground observations of ULF waves can show their temporal duration, but because of well-known horizontal ducting of these waves in the ionosphere [*Greifinger and Greifinger*, 1968; *Fujita and Tamao*, 1988; *Fujita*, 1988], these observations can provide only limited information about spatial location or extent. In contrast, single-satellite data can show spatial extent but cannot untangle spatial-temporal effects unless data from multiple ground sites are also available [e.g., *Engebretson et al.*, 2002]. Although even three closely spaced satellites are not adequate to fully deconvolve spatial and temporal properties, the observations reported here provide additional insights into the spatial characteristics of these waves and show the potential advantages of larger multiple-spacecraft missions. The ST5 mission also provides an additional low-altitude platform from which to observe temporal patterns of Pc1 waves during weak and moderate magnetic storms.

2. Observations

[6] In this study, Pc1 wave activity was visually identified in 5-min time series plots of magnetic field data displayed in GSE coordinates after subtraction of the International Geomagnetic Reference Field model vector magnetic field. Candidate events were marked for possible further study, which included the L value and the magnetic local time (MLT) at which the event occurred, the number of satellites observing the event, and the wave amplitude and duration. Fourier spectrograms of each event were prepared in order to determine wave frequency; these also served to discriminate short-lived packets of broadband noise, which were presumably associated with field-aligned currents rather than with EMIC waves. Because the spatial separation of the three spacecraft resulted in each crossing a specific L shell at different times (up to ~10 min earlier for ST155), wave events were designated primarily by L shell not UT. Events occurring in near magnetic conjugacy to the search coil magnetometer at Halley, Antarctica (−75.50° geographic latitude, 333.40° geographic longitude, L = 4.56, MLT of local noon equal to 1444 UT), were compared with simultaneous data from that station. Event occurrences at both ST5 and Halley were also compared to the *Dst* index to determine their timing relative to the occurrence of geomagnetic storms.

[7] Although the amplitude of spin tones in the satellite data was relatively low, it varied throughout each spacecraft's orbit; in particular, it was higher in the Northern Hemisphere because of the satellites' lower altitude there. The threshold for reliably identifying waves in ST094 and ST224 data was ~10 nT peak to peak (pp), so this became the amplitude threshold for event selection. Spin tone amplitude was higher in ST155 data, but events could be identified in data from the other two spacecraft and subsequently searched for in ST155 data. Analysis of the number of events observed by each spacecraft revealed no obvious sign of observational bias in the list of events observed at each satellite but would be expected to lead to an undercount of events observed only by this spacecraft.

[8] Table 1 lists the number of satellites observing each event, as well as the number of events with data missing from one or more satellites. Half (24) of the 48 events identified were observed by all three spacecraft. An additional three events were recorded by two spacecraft at times when no data were available from the third spacecraft, and one event was recorded by one spacecraft when no data were available from the other two spacecraft. Nearly half the events, however, were not observed by at least one spacecraft despite their close separation in time. Eleven events were seen by only two of the three, and five events were seen by only one of the three. In none of these cases could the absence of wave activity at a given spacecraft be attributed to obscuration by other activity, either natural or artificial.

[9] As noted in Figure 1, the spacecraft separation was largest during the first half of the mission (before day 136 on 16 May). Of the 11 wave events observed at only two (of three available) spacecraft, nine occurred before day 127, and six of these were observed at both ST094 and ST224 not at the more distant ST155 spacecraft. This pattern provides modest support for the hypothesis that the larger temporal separation of ST155 during the first half of the ST5 mission contributed to some of the lack of wave events at all three spacecraft and suggests either the existence of a <10 min time scale for the existence of some localized

Table 1. Number of ST5 Spacecraft Satellites Observing a Given Pc1–2 Wave Event[a]

	Number of Events
Events seen by three s/c	
Subtotal	24
Events seen by two s/c, one s/c missing	3
Events seen by two s/c	11
Subtotal	14
Events seen by one s/c, two s/c missing	1
Events seen by one s/c, one s/c missing	4
Events seen by one s/c	5
Subtotal	10
Total events	48

[a]Spacecraft denoted by s/c.

regions of Pc1 wave generation or a limited longitudinal scale of such wave regions, so that on average they can move out of a given local time plane within ~10 min.

3. Example Events

[10] In this section we show several observations of Pc1 waves made by the ST5 spacecraft. We begin with three examples showing the variation in observations of a single event by each spacecraft. We then present information about the only event observed on two legs of an orbit and conclude with two events observed both by ST5 and on the ground at Halley.

3.1. Examples From Three Spacecraft

[11] In this section we show three example wave events of the 48 identified in the 3-month data set, illustrating both the waveforms observed and the variation between the three spacecraft. Figure 2 shows 1-min line plots of GSE B_y component data for an ~1.2-Hz event observed near $L = 3.7$ near dusk in the Southern Hemisphere on 5 April 2006. Figure 2 (middle) shows waves of up to 15 nT pp and over 20-s duration observed by ST094, centered near 1928:30 UT. Figure 2 (bottom) shows waves of the same frequency and duration but with lower amplitude (~3 nT) that were observed a minute later when ST224 passed through the same region. Figure 2 (top) shows the signals observed by ST155 when it passed through this same region 7 min earlier; weak wave signals between 1921:35 and 1921:50 of 1–2 nT pp amplitude were near the background noise level. Although the waves observed by ST155 would most likely not have been identified had stronger waves not been evident in data from at least one other spacecraft, we have counted this event as appearing at all three spacecraft.

[12] Figure 3 shows a similar plot of a 1.6-Hz wave event observed near $L = 4$ near dawn in the Northern Hemisphere on 13 April 2006. Although the temporal duration (~6 s) is shorter than that of the event in Figure 2, the spacecraft traveled ~2.5 times farther in latitude during the 1-min span shown. The width in L, ~ 0.1, is thus similar. This event was again observed most clearly by ST094 and ST224, with amplitudes of 35 nT and 40 nT pp, respectively, while the ~6 nT pp signal at ST155 was only marginally visible above the spin-related background, which was larger at northern latitudes where the altitude is lower.

[13] Figure 4 shows plots of an ~0.5-Hz wave event observed near $L = 9.6$ near dawn in the Northern Hemisphere on 10 June 2006. At this late stage in the ST5 mission, the separation between the three spacecraft was less than 200 km but with ST155 still in the lead. Waves of ~15 nT pp were visible for 5 to 10 s at all three spacecraft.

[14] These three wave events are typical of the entire ST5 data set in that the region of wave activity was quite narrow in latitudinal extent, consistent with earlier satellite studies by *Erlandson et al.* [1990], *Engebretson et al.* [2002], and *Yahnin et al.* [2007]. Of the 48 events, 22 had observed durations of <~15 s, 19 had durations between ~20 and ~30 s, and 6 had durations between 30 and 90 s. Each of these latter six occurred while the ST5 spacecraft were moving predominantly in azimuth (i.e., near the geographically northernmost or southernmost parts of their orbits).

3.2. A Temporally Extended Event

[15] The typically limited temporal extent of Pc1 wave events is suggested by the fact that only one event in the ST5 data set was observed on both legs of a high-latitude pass. During this event, on 19 April 2006 (day 109), 1.2-Hz waves were observed at $L \sim 3.7$ on both legs of a Northern Hemisphere pass. Table 2 provides information on the waves seen by each of the ST5 spacecraft, and Figure 5 shows the ground tracks for the three ST5 spacecraft from 0405 to 0430 UT on this day. The color-coded circles show the locations at which each satellite observed the waves. On its poleward pass, ST155 saw the event first at 0407 UT. The other two spacecraft, ST094 and ST224, observed waves during their poleward passes at 0417 UT and 0418 UT, respectively. ST155 again saw the event on the following equatorward pass, at 0417 UT, as did ST094 and ST224 at 0428 and 0429 UT, respectively. As Table 2 indicates, the event was of similar temporal duration during each of the six observations and occurred at nearly the same L shell but was observed at magnetic local times separated by ~5.5 h. The data also suggest some evolution of the wave region during this 22-min interval. First, the amplitude observed by ST155 at 0407 UT was somewhat weaker than that observed during any of the later passes. Second, the L value declined from 3.9 to 3.7 from 0407 to 0429 UT. Third, after ~0420 UT the apparent duration of the wave events (and by implication, their width in L) also decreased. The waves observed by ST224 at 0429 UT were split into two shorter intervals. The 7-s duration of the second of these events was like the event observed by ST094 at 0428 UT and was roughly half that observed during passes at both local times 10 min earlier.

[16] It is possible to interpret these observations of very similar waves on both legs of this orbit as signatures of one longitudinally extended event, consistent with earlier reports of EMIC waves extending up to 10 h at individual stations, and hence extending over large ranges of local time [*Fukunishi et al.*, 1981; *Engebretson et al.*, 2002]. This interpretation is supported by its occurrence 5 days after a magnetic storm (see Figure 10), with *Kp* having been at levels of 1 or lower for the previous 24 h (again, similar to the long-lasting quiet time events noted by *Engebretson et al.* [2002]). However, we cannot rule out the possibility that the waves observed on these two orbital legs are, in fact, separate and localized, as is suggested by observations of localized precipitation of energetic protons and multiband Pc1 events reviewed by *Yahnin and Yahnina* [2007].

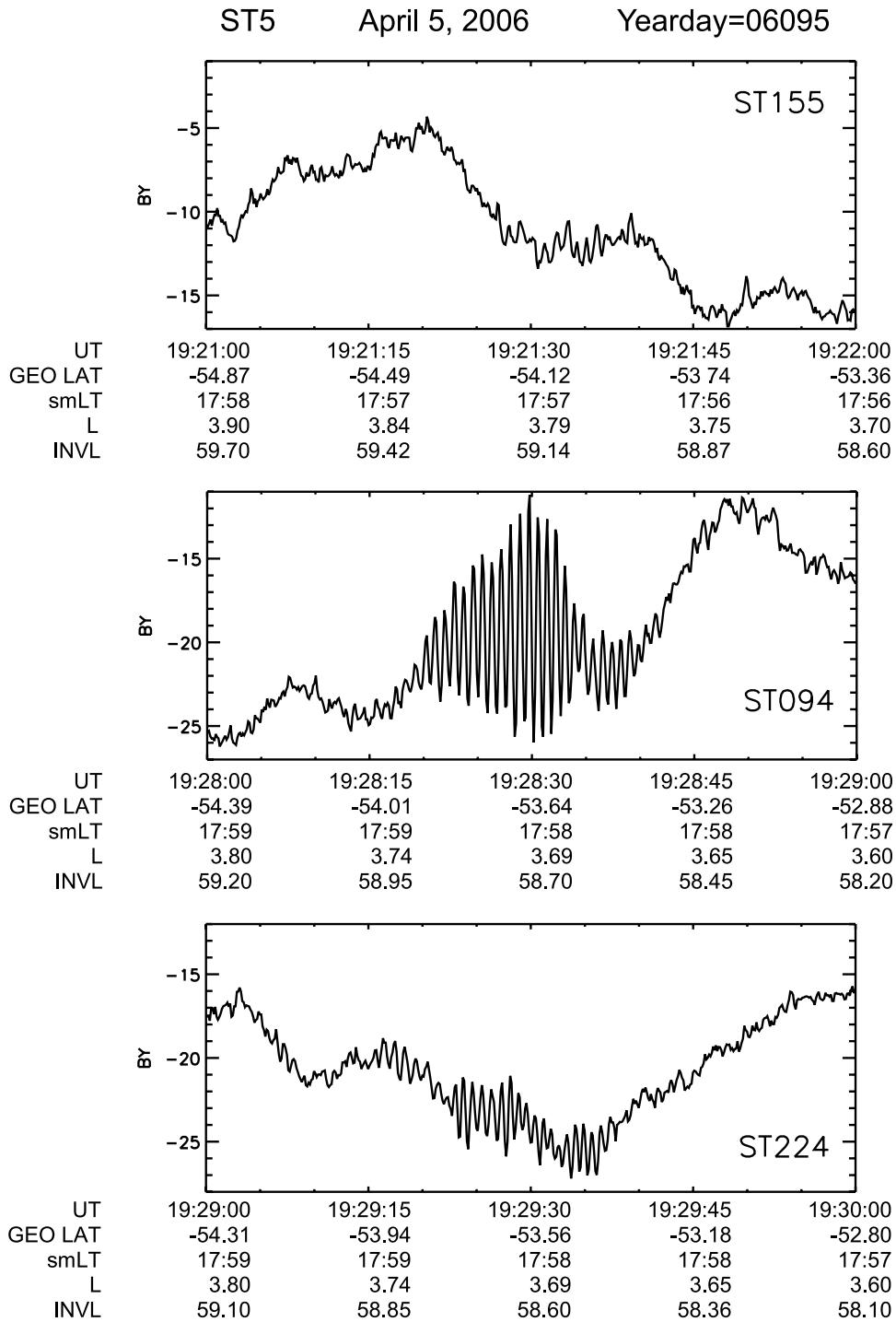

Figure 2. Plots of the GSE B_y component of magnetic field data from the three ST5 spacecraft during a Pc1 wave event in the Southern Hemisphere on 5 April 2006 (year/day 06095). The duration of each plot is 1 min. Below each plot universal time (UT), geographic latitude (GEO LAT), magnetic local time in the SM coordinate system (smLT), L shell (L), and invariant latitude (INVL) are indicated.

3.3. Ground-Satellite Conjunctions

[17] In this section we show two events observed by ST5 during passes near Halley. The first event was observed only by ST094; the second was observed by all three spacecraft.

[18] Figure 6 (top) shows the southern ground track of the magnetic field lines traversed by the three ST5 spacecraft from 2005 to 2015 UT on 6 May 2006. The yellow oval indicates the location at which waves were identified in ST094 data. Figure 6 (middle) shows the GSE B_y component of magnetic field data from the ST094 spacecraft from 2010 to 2012 UT, and Figure 6 (bottom) shows north-south component data from the search coil magnetometer at Halley during the same time interval. Both plots show 0.4-Hz waves which ended near 2011:15 UT. Neither ST224, which passed

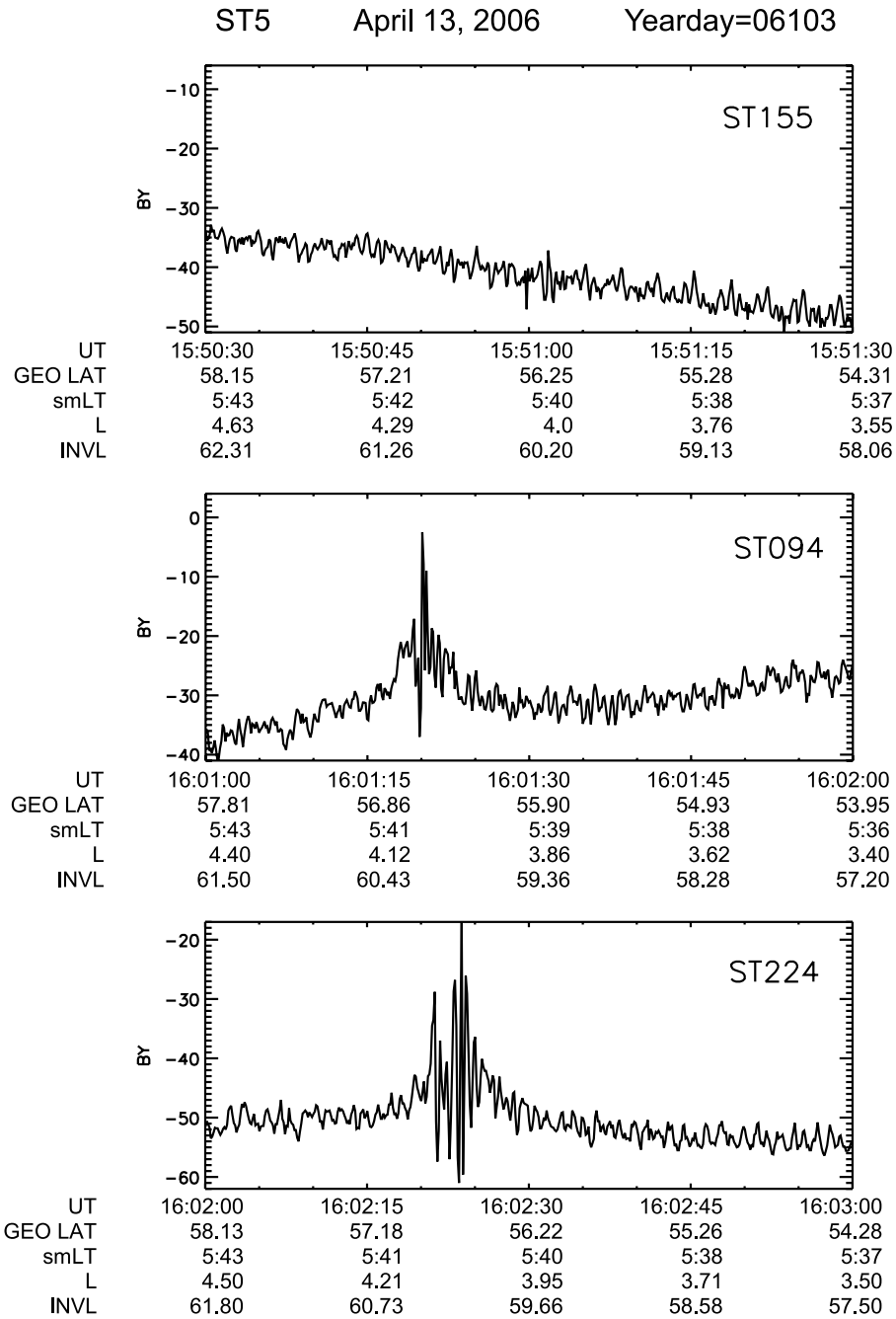

Figure 3. Plots of the GSE B_y component of magnetic field data from the three ST5 spacecraft during a Pc1 wave event in the Northern Hemisphere on 13 April 2006 (year/day 06103), as in Figure 2.

through the same region slightly over 1 min later, nor ST155, which passed 4 min earlier, saw any evidence of these waves (not shown). The ratio of wave amplitude at ST5 to amplitude on the ground was 95 ± 10. (The Halley instrument measures dB/dt, so search coil amplitudes were first converted to corresponding amplitudes of B.)

[19] Figure 7 is a similar display of wave events observed on 17 April 2006. Figure 7 (top) shows the conjugate (Southern Hemisphere) ground tracks of the magnetic field lines traversed by the three ST5 spacecraft during 4-min intervals of a Northern Hemisphere pass near 1800 UT on this day. As shown in Figure 7 (top), ST155 traversed the region from 1746 to 1750 UT, and ST094 and ST224 traversed the same region roughly 12 and 13 min later, respectively. Two bursts of waves were observed on each of the three spacecraft at the locations shown, and consistent with current ideas of EMIC wave generation, the frequency was higher at lower latitude. Figure 7 (middle) shows the GSE B_z component of magnetic field data from the ST224 spacecraft from 1759 to 1801 UT, and Figure 7 (bottom) shows north-south component data from the search coil magnetometer at Halley during the same time interval. The duration of 0.8-Hz wave activity at Halley was over an hour, while waves of similar frequency appeared at ST224 for

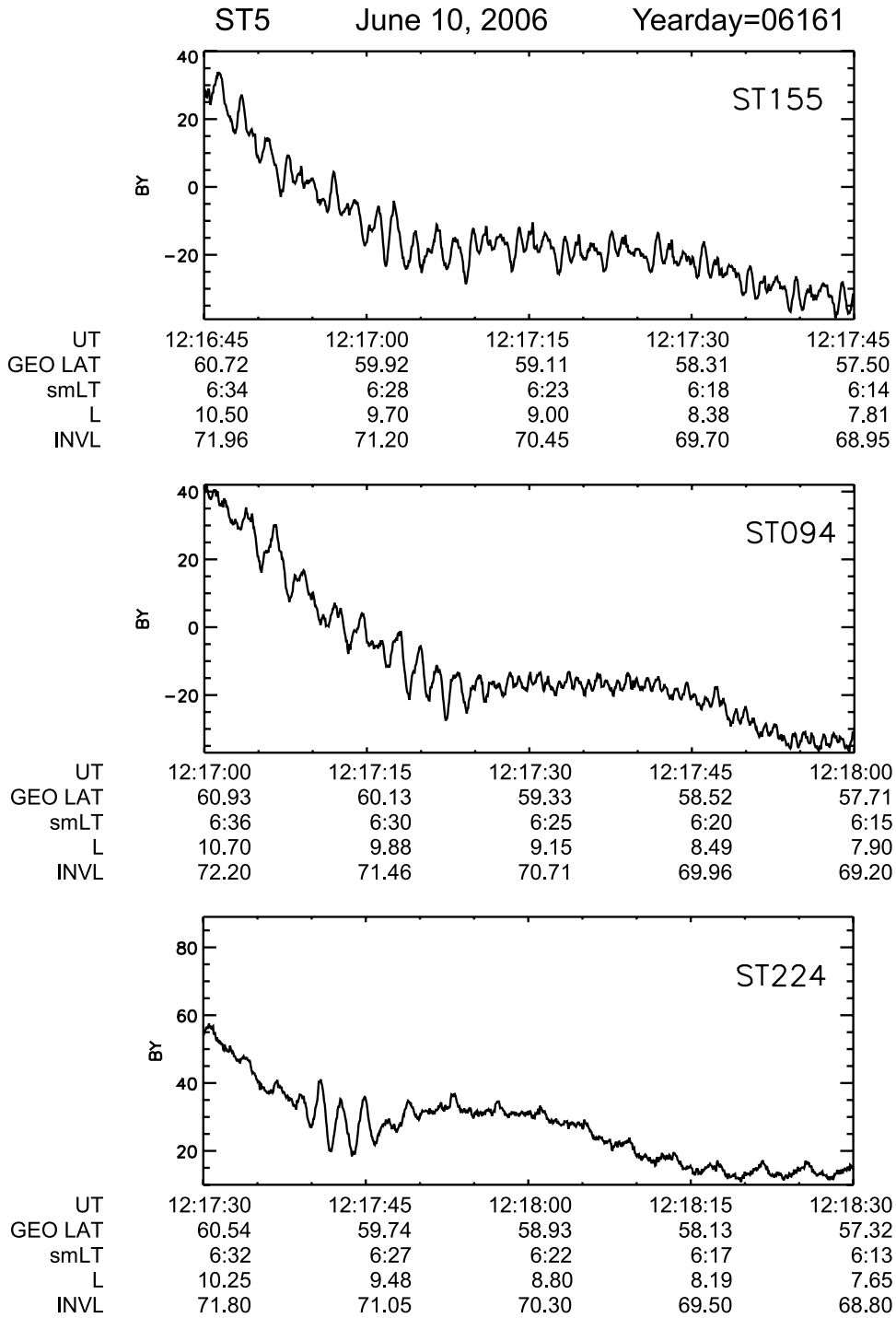

Figure 4. Plots of the GSE B_y component of magnetic field data from the three ST5 spacecraft during a Pc1 wave event in the Northern Hemisphere on 10 June 2006 (year/day 06161), as in Figure 2.

only ~10 s near $L = 6.1$. Similar wave activity appeared at the other two spacecraft for a similarly brief time interval at the same L shell 12 min earlier (ST155) and 1 min earlier (ST094), again near $L = 6.1$ (not shown). The ratio of wave amplitudes for this event was different for the three satellites, ranging from 18 to 47. Signals at the frequency of the second burst of wave activity (~0.5 Hz) appeared only weakly in logarithmically scaled Fourier spectrograms of Halley data and were unobservable in line plots. These weaker ground signatures are consistent with the larger distance in L between the location of the second burst and Halley ($L > 6.6$ to $L = 4.56$).

4. Occurrence Patterns

[20] Figure 8 shows the occurrence of Pc1 wave events in the ST5 data set as a function of MLT and L shell. Despite their roughly dawn-dusk orbit, the angular offset between

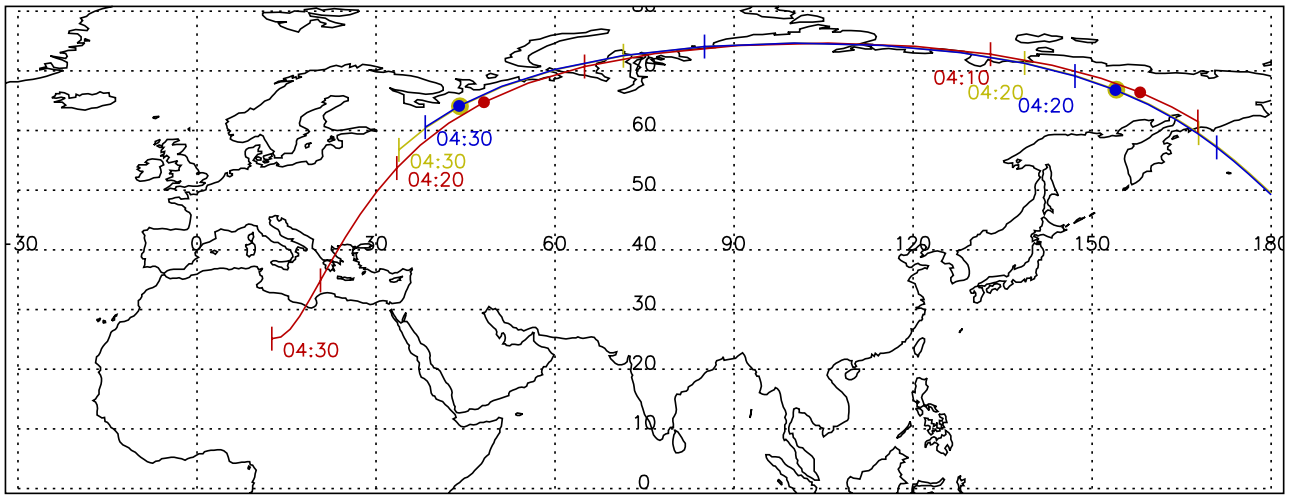

Figure 5. Northern Hemisphere ground track of the magnetic field lines traversed by the three ST5 spacecraft from 0405 to 0430 UT on 19 April 2006, based on data from the Satellite Situation Center Web utility, available at http://sscweb.gsfc.nasa.gov. The yellow, red, and blue traces refer to ST094, ST155, and ST224, respectively.

the Earth's geographic and geomagnetic poles allowed the ST5 spacecraft to cover essentially all magnetic local times at higher latitudes, although not with uniform coverage. Events shown in Figure 8 are also coded according to the number of satellites observing each event; little pattern is evident except for the tendency for daytime events (0600–1600 MLT) to be more likely to be observed by all three spacecraft.

[21] The observed dayside maximum in occurrence of wave events is consistent with that found in other studies, including those of *Anderson et al.* [1992], who used data from the equatorially orbiting CCE satellite of the Active Magnetospheric Particle Tracer Explorers program, and *Kim et al.* [2007], who used recent observations from a closely spaced latitudinal array of search coil magnetometers installed on Svalbard. This maximum can be attributed to the effects of both transient magnetospheric compressions [*Anderson and Hamilton*, 1993] and the effects of magnetospheric convection on sunward drifting plasma sheet and ring current plasmas [*Horne and Thorne*, 1993; *Engebretson et al.*, 2002].

[22] Only seven wave events occurred at $L < 4$, all but one of them 2–4 days after magnetic storms. Three of these events, including the one at lowest L (2.9), occurred on 19 April, 5 days after the most intense magnetic storm of this 3-month period. We speculate that the relative scarcity of low-L events reflects the generally magnetically quiet conditions during this 3-month period. Higher-latitude events (at $L > 9$) occurred in a broad local time range on the dayside as well as shortly before midnight.

[23] Figure 9 shows additional characteristics of the Pc1 waves observed. Figure 9 (top) shows the frequency distribution of observed events, from 0.2 (the minimum frequency included in our analysis) to 2.0 Hz, well below the 4.0-Hz Nyquist frequency. Most events had frequencies between 0.2 and 1.4 Hz. The distribution of frequencies observed by ST5 is qualitatively similar to that shown in Figure 8 of *Engebretson et al.* [2008], which grouped frequencies observed at Halley, Antarctica ($L = 4.56$), according to UT and day after magnetic storm onset. Figure 9 (middle) shows the distribution of wave frequencies as a function of amplitude (from 5 to 110 nT); these show no evident correlation. Note, however, that events with amplitudes below ~20 nT pp were difficult to identify at auroral zone latitudes and so are very likely to be undercounted. Figure 9 (bottom) shows observed frequency as a function of L shell. The data show a general tendency toward higher frequencies at lower L shells, as expected theoretically and observed, for example, by *Erlandson et al.* [1990] and *Anderson et al.* [1992]. The nearly constant distribution of frequencies above $L \sim 6$ is also consistent with the pattern observed by *Erlandson et al.* [1990], who noted that the frequency of high-L wave events was above the calculated equatorial helium gyrofrequency, while the frequency of low-L wave events was below it.

5. Localization in Latitude

[24] In section 3.1 we noted the narrow latitudinal extent of the Pc1 wave events observed by the ST5 spacecraft. Early ground-based observations of Pc1 waves suggesting peak occurrence near the plasmapause were consistent with the assumption that magnetospheric ion cyclotron waves are trapped within some waveguide, presumably at the plasmapause, in order to overcome wave refraction effects caused

Table 2. Parameters of the Pc1 Waves Observed by the Three ST5 Spacecraft Between 0407 and 0429 UT on 19 April 2006

Time (UT)	Spacecraft	Magnetic Local Time	L	Duration (s)	Peak-to-Peak Amplitude (nT)
0407:00	ST155	1351	3.9	<10	<4
0417:10	ST155	0824	3.8	15	12
0417:45	ST094	1355	3.8	15	15
0418:45	ST224	1355	3.8	12	12
0428:00	ST094	0826	3.7	7	15
0429:00	ST224	0826	3.7	14	10

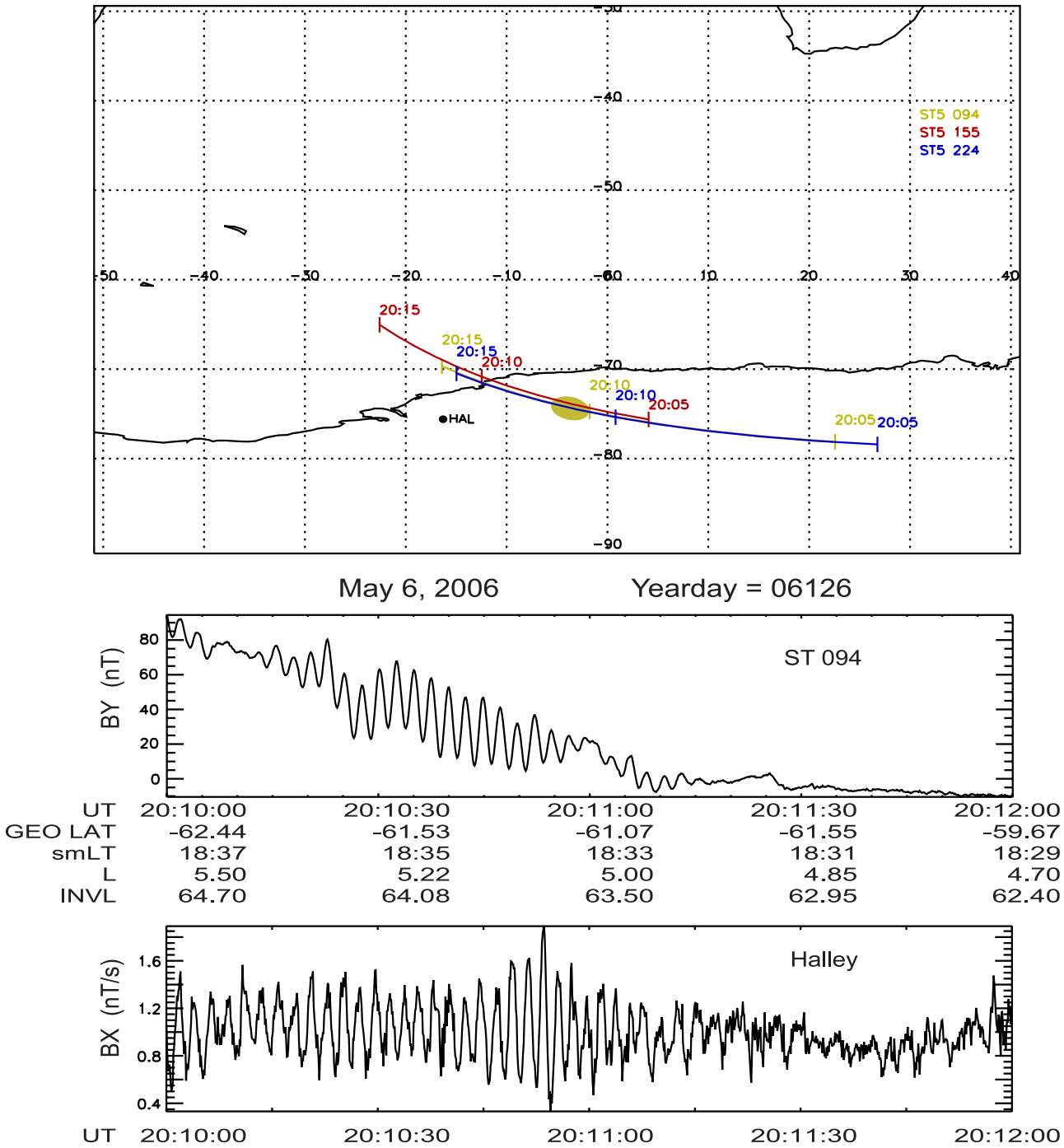

Figure 6. (top) Southern Hemisphere ground track of the magnetic field lines traversed by the three ST5 spacecraft from 2005 to 2015 UT on 6 May 2006, as in Figure 5. The interval during which ST094 observed Pc1 waves is indicated by the yellow ellipse. (middle) Plot of the GSE B_y component of magnetic field data from the ST094 spacecraft during a Pc1 wave event in the Southern Hemisphere from 2010 to 2012 UT on 6 May 2006 (year/day 06126), as in Figure 2. (bottom) North-south component of data from the search coil magnetometer at Halley, Antarctica, during the same time interval, 2010–2012 UT on 6 May 2006.

by field line curvature [*Kangas et al.*, 1998]. Even though many satellite studies have now shown that the plasmapause is not a preferred site for EMIC wave generation [e.g., *Erlandson et al.*, 1990; *Anderson et al.*, 1992; *Fraser and Nguyen*, 2001], the idea that these waves may be guided along narrowly defined density gradients is still theoretically attractive, is consistent with the growing realization that the radial density structure in the outer magnetosphere is by no means smooth and monotonic, and is qualitatively consistent with the observations here of wave events nar-

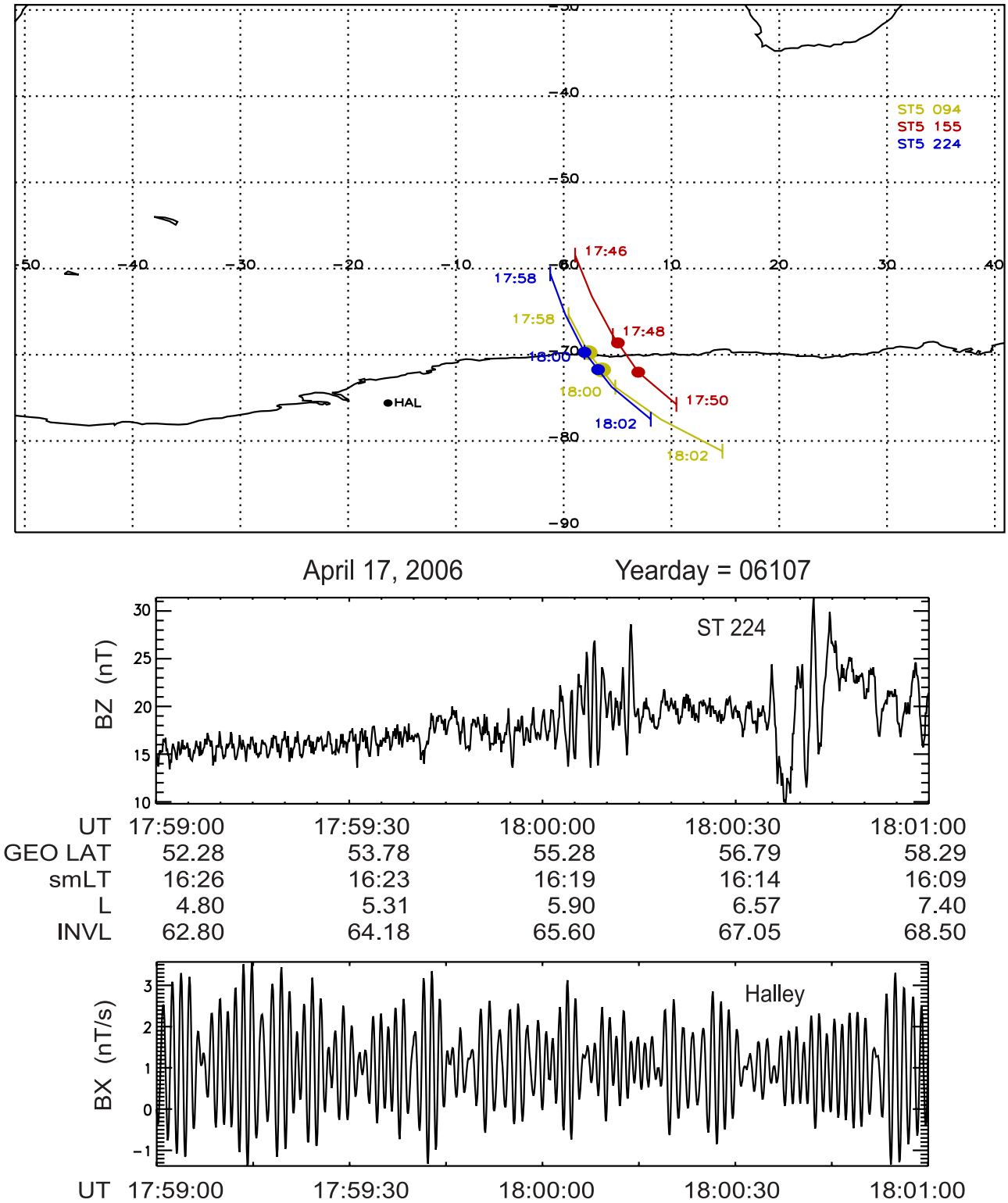

Figure 7. (top) Southern Hemisphere ground track of the magnetic field lines traversed by the three ST5 spacecraft during 4-min intervals near 1800 UT on 17 April 2006 (year/day 06107), as in Figure 5. The circles indicate times when waves were observed at each satellite. (middle) Plot of the GSE B_z component of magnetic field data from the ST224 spacecraft during a Pc1 wave event in the Northern Hemisphere from 1759 to 1801 UT on 17 April 2006, as in Figure 2. (bottom) North-south component of data from the search coil magnetometer at Halley, Antarctica, during the same time interval, 1759–1801 UT on 17 April 2006.

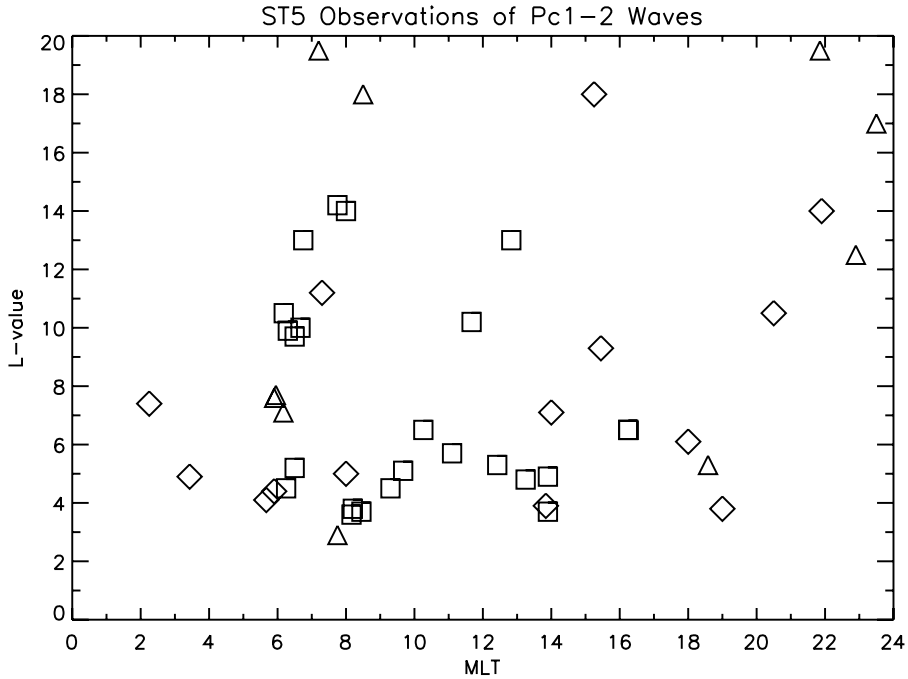

Figure 8. Plot of the occurrence of Pc1 wave events observed by ST5 satellites as a function of L value and magnetic local time. Squares, diamonds, and triangles indicate events observed by all three, two, and only one spacecraft, respectively. Two events for which $L > 20$ are plotted at $L = 19.5$.

rowly localized in latitude. Here we consider some conjectures stemming from this idea.

[25] Wave polarization is a sensitive indicator of the wave spatial structure. If a wave is indeed trapped in the radial direction in an open waveguide, so it can freely propagate in the azimuthal direction as $\exp(ik_y y)$, where k_y is the wave number in the azimuthal direction, then the relationship between transverse magnetic components can be inferred from the following simple consideration. Conversion of the satellite data into the field-aligned coordinate system has shown that all detected Pc1 signals are noncompressional ($b_{\|} \sim 0$). Therefore, one may write

$$\nabla \mathbf{b} \approx \nabla_{\perp} \mathbf{b}_{\perp} = \partial_x b_x + i k_y b_y = 0,$$

where b_x and b_y are the magnetic perturbation amplitudes in the north-south and azimuthal directions, respectively. If the structure of $b_x(x)$ is described by the fundamental waveguide eigenfunction, the above relationship predicts that the phase shift between b_x and b_y must be of opposite signs on different slopes (i.e., at $\partial_x b_x > 0$ and $\partial_x b_x < 0$) away from the amplitude maximum. Thus, the ellipse rotation is expected to be reversed on opposite sides of the amplitude maximum of a trapped waveguide mode.

[26] Examination of b_x-b_y hodograms of the 5 April 2005 wave event in a rotated field-aligned coordinate system (not shown) showed that the waves were purely transverse and that polarization was elliptical and counterclockwise before 1928:24 UT, then became nearly linear, and after that became elliptical and clockwise. A similar polarization rotation reversal of Pc1 waves detected by Magsat was noticed by *Iyemori and Hayashi* [1989]. This effect is a strong argument in favor of the importance of the waveguide mechanism in governing the radial spatial structure of Pc1 events. However, not all wave events observed by ST5 showed such polarization reversals. For example, no clear polarization shift was evident during the 13 April 2005 event.

[27] Waveguide trapping can be achieved via the combined action of a nonmonotonic V_A inhomogeneity and transverse dispersion. The dispersion of small-scale Alfven waves ($k_{\perp} > k_{\|}$) due to finite ion Larmor radius effects or electron inertia provides a wave localization with a very small transverse scale. The characteristic parameters (the proton Larmor radius and electron skin depth) can be estimated as $\rho_i[\mathrm{km}] = 4.6 \times 10^3 \sqrt{E[\mathrm{keV}]}/B[\mathrm{nT}]$ and $\lambda_e[\mathrm{km}] = 5.3/\sqrt{N[\mathrm{cm}^{-3}]}$ respectively, where E is the proton energy and N is the electron density. For the midlatitude magnetosphere with $L \sim 4$, $B \sim 490$ nT, and $N \sim 10^3$ cm^{-3}, one obtains for $\sim$10 keV protons $\rho_i \sim 30$ km. Projected onto the ionosphere, taking into account the mapping factor $\sqrt{L(L-1)}$, this gives a transverse scale of $\sim$8.5 km and even less for $\lambda_e \sim 0.17$ km. The short-lived events shown in Figures 2–4 have a width in invariant latitude of 0.3°–0.4° or $\sim$40 km. The estimates above suggest that the radial/latitudinal width of some Pc1 waves may be related to the radial width of the region unstable with respect to wave growth (a small multiple of a ring current ion's gyroradius) but not to electron inertia effects and that waveguide effects may play a role in maintaining their radially narrow character as they propagate earthward. However, the scale of the Pc1 event in Figure 6 is about an order of magnitude bigger than ρ_i, roughly 1° in invariant latitude or $\sim$110 km. Such a medium-scale ($k_{\perp} < k_{\|}$) Pc1 waveguide is supposedly formed because of finite frequency dispersion $\sim\omega/\Omega_i$. This dispersion is essential in the quasi-longitudinal

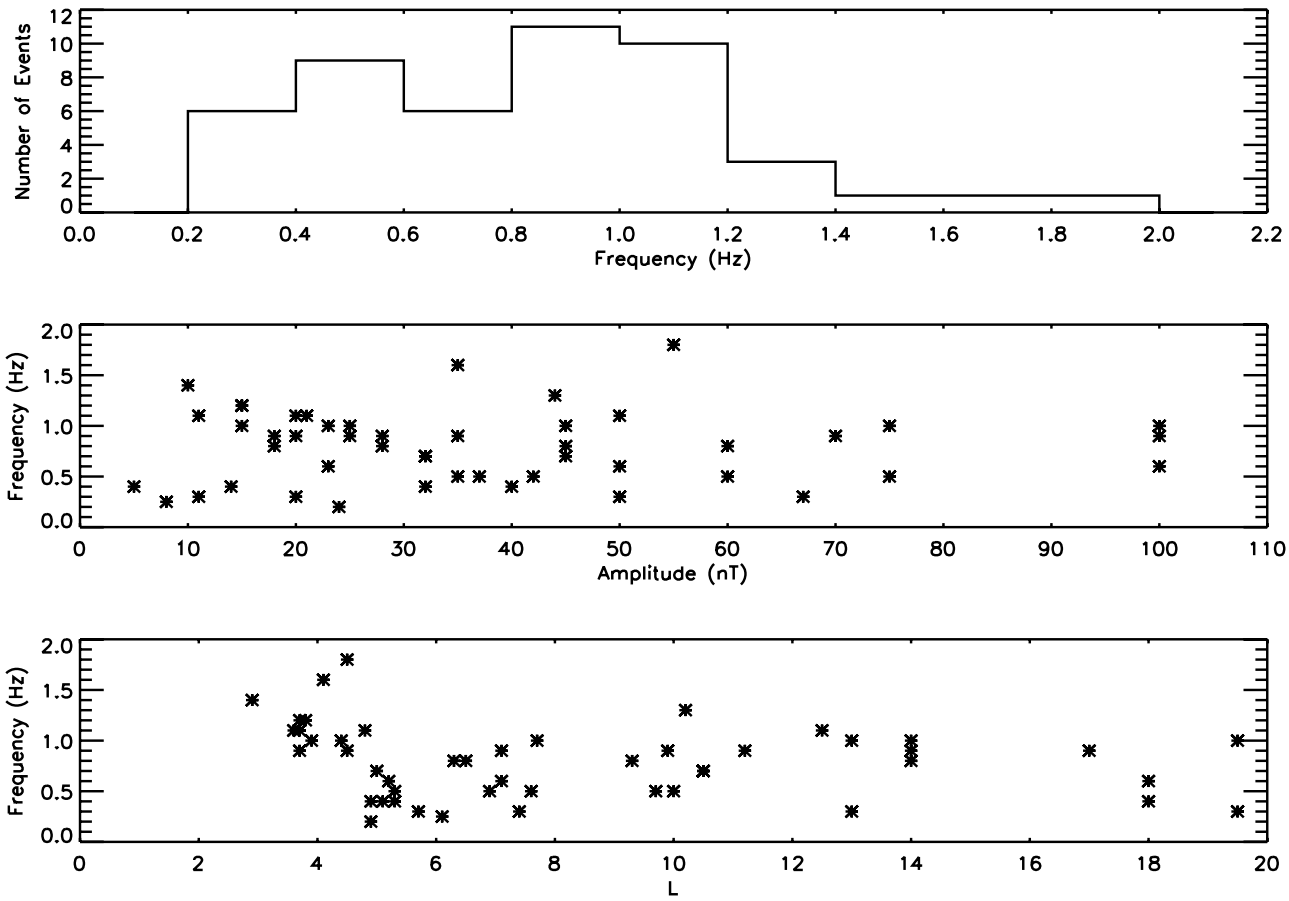

Figure 9. (top) Histogram of the frequency distribution (in Hz) of Pc1 wave events observed by the ST5 satellites. (middle) Scatterplot showing the distribution of wave frequency versus wave amplitude. (bottom) Scatterplot showing the distribution of wave frequency versus L shell. The two events at $L > 20$ are plotted at $L = 19.5$.

propagation regime, when $k_\perp \leq k_\parallel \sqrt{\omega/\Omega_i}$, and is negligible for the small-scale wave structure $k_\perp \gg k_\parallel$.

[28] The latitudinal scales of wave events reported here, ranging from ~40 to ~100 km, are again consistent with earlier observations. *Iyemori and Hayashi* [1989] observed wave regions <100 km, and latitudinal scales mapped into the ionosphere by *Erlandson et al.* [1990], based on Viking satellite observations near 3 R_E, ranged from 150 km for events to 35 km for individual bursts.

6. Relation to Magnetic Storms

[29] Pc1–2 wave activity has long been known to increase in the aftermath of geomagnetic storms (e.g., as reviewed by *Fraser et al.* [2006] and *Engebretson et al.* [2008]). Pc1–2 wave activity has also been suggested as a possible prompt loss mechanism for relativistic electrons during the main phase of such storms [*Thorne et al.*, 2005]. However, although the few published satellite studies of Pc1–2 waves during storms report their occurrence during both main and recovery phases, such waves are consistently absent in ground data during the main and early recovery phases [e.g., *Bräysy et al.*, 1998; *Engebretson et al.*, 2008].

[30] Although the 3-month duration of the ST5 mission did not include any major geomagnetic storms, it did include several minor and moderate ones. Figure 10 shows monthly plots of the hourly *Dst* index for April, May, and June 2006. Indicated below each panel are the number of Pc1 wave events observed by one or more ST5 spacecraft and the number of hours each day that intense Pc1 wave events were observed by the search coil magnetometer at Halley, Antarctica. The same criterion for intense wave events at Halley was used in a recent statistical study of such events in 2005 by *Engebretson et al.* [2008]; daily Fourier spectrograms of differenced search coil data were used to identify events with wave power $\geq 10^{-4}$ nT^2 Hz^3.

[31] The occurrence pattern shown in Figure 10 is typical of the patterns seen in earlier studies [*Wentworth*, 1964; *Engebretson et al.*, 2008; *Bortnik et al.*, 2008]; few, if any, events were observed during main and early recovery phases (e.g., 14–15 April), but an increasing number occurred during the middle and late recovery phases (e.g., 16–21 April). No wave events were observed either at ST5 or at Halley during the main phase day and first recovery day of the storms that began 9 April (minimum $Dst = -80$), 14 April (minimum $Dst = -111$), or 4 May (minimum $Dst = -62$). Although waves did appear at both ST5 and Halley during main phase storm days 5 April and 6 June, the event on 6 June occurred prior to main phase. Only the wave event on 5 April occurred late in the day, after storm

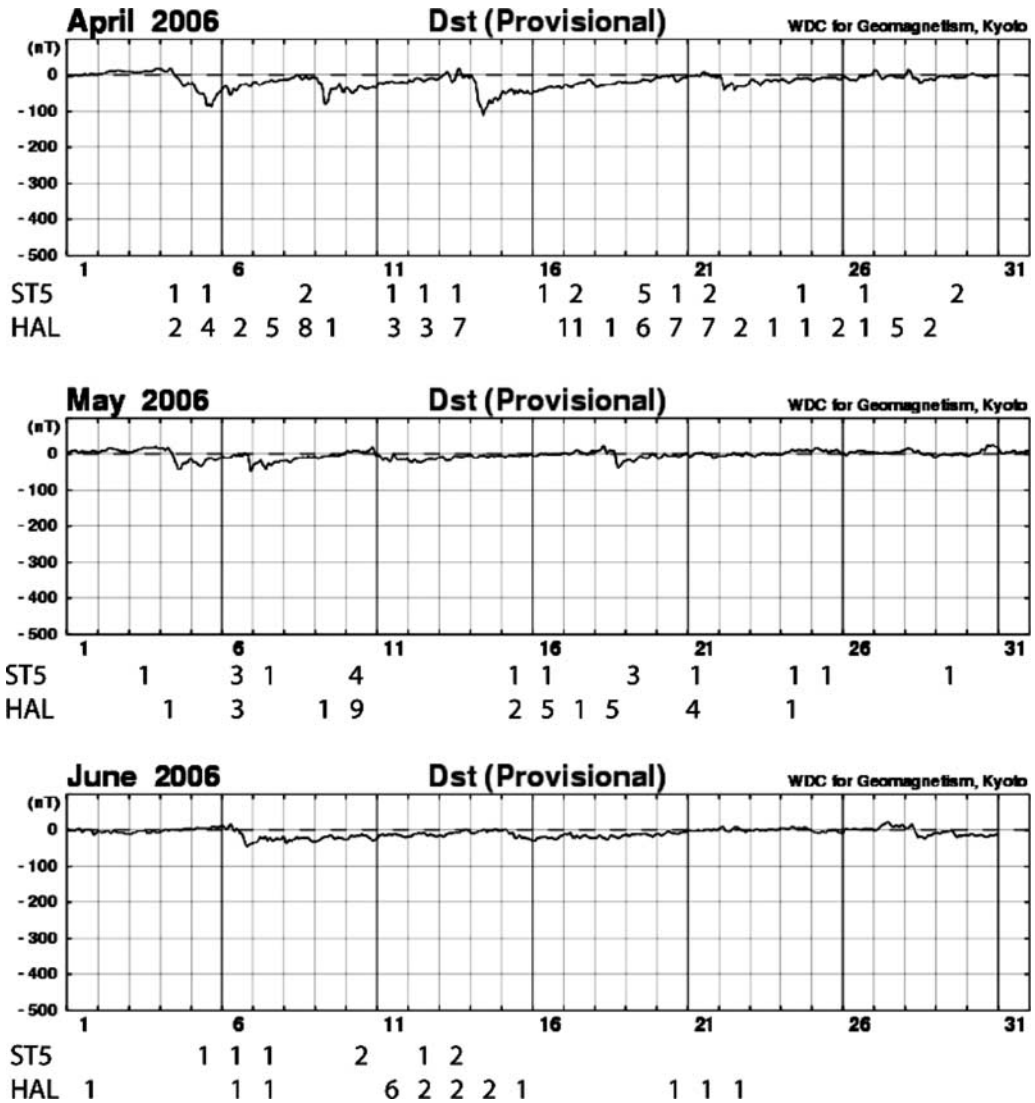

Figure 10. Plots of the provisional *Dst* index for April, May, and June 2006, with the number of Pc1 wave events observed by ST5 spacecraft and by the search coil magnetometer at Halley (HAL), Antarctica, indicated below each plot.

recovery (from a minimum *Dst* of −87) had begun, and it appeared both at ST5 and on the ground. In contrast, wave activity clearly maximized at Halley during the late recovery periods after several storms, both moderate and weak, and the activity at ST5 usually followed a similar pattern. Finally, examination of the distribution of events observed by one, two, or all three spacecraft revealed no clear dependence on magnetic storm phase or strength.

7. Discussion and Conclusions

[32] This survey of the complete data set from the ST5 mission has shown several characteristics of Pc1 wave events that are consistent with earlier studies using low-altitude satellites. The events in this data set are all highly localized in L shell (most with $\Delta L < 0.1$ or 0.2, with width corresponding to a few ion gyroradii, and some showing waveguide-like shifts in ellipticity); they are more common at dayside local times and during the recovery phase of geomagnetic storms, and their amplitudes, from 5 to over 100 nT, are from 1 to 2 orders of magnitude larger than corresponding amplitudes observed on the ground.

[33] This data set has also provided two new findings. First, only during about half of the observed events did waves appear at all three spacecraft. We interpret the relatively large number of events observed by only one or two spacecraft as indicative of the highly localized and often transient nature of regions in the magnetosphere (in time or space or both) that become unstable as a result of electromagnetic ion cyclotron instabilities. The relative absence of events at ST155, the most distant of the three spacecraft, suggests either the existence of a <10 min time scale for the existence of some localized regions of Pc1 wave generation or that these regions are very localized in longitude. The first interpretation is consistent with the EMIC wave classification study of *Fukunishi et al.* [1981], which included a category of local morning sector "dots" with durations of ∼10 min as observed on the

ground. The second interpretation is consistent with the study of proton "spots" observed in the Lyman alpha emission by the IMAGE spacecraft [*Frey et al.*, 2004], which detected longitudinally highly localized regions that, however, lasted from 1 to 4 h.

[34] However, in two of the events observed by only two spacecraft, the middle spacecraft (ST094) did not observe any waves. This suggests the reappearance of wave activity after a short-lived absence, consistent with the common observation in ground data of "pearl" pulsations (Pc1 events with periodic amplitude modulations with periodicities on the order of 30 s). It is still unknown, however, whether the "pearl" phenomenon is generated in the magnetosphere or in the ionosphere, and the two examples noted here (out of 11) are insufficient to justify further analysis.

[35] Although one might expect that wave emissions stimulated by transient magnetospheric compressions might result in observations by only one or two spacecraft, observations by three spacecraft were, in fact, most probable on the dayside, where the influence of compressions would be the greatest. As an alternative, we suggest that temporal and/or spatial variations in convecting ring current or plasma sheet ion populations that provide the source of free energy for these waves may be a more important cause for the limited temporal extent in our observations. Confirmation of this suggestion, however, will require data from multiple spacecraft also equipped with energetic ion detectors as well as comparison with a larger number of ground stations in order to further separate spatial and temporal variations of these waves.

[36] A second finding, which does not depend on the availability of three spacecraft, is the observation of essentially no difference between the pattern of occurrence of EMIC waves at ST5 and on the ground at subauroral latitudes (at Halley, Antarctica) as a function of geomagnetic storm phase, in that while numerous events were observed during the later recovery phase, only one event was observed during main phase during the several weak to moderate storm periods surveyed. This finding supplements the limited number of previous satellite studies of Pc1 waves during geomagnetic storms, which have reported activity during main phase as well as recovery phase. In particular, it provides a different picture than the study of *Bräysy et al.* [1998], which noted considerable main phase wave activity during a major storm with minimum *Dst* value of −169 nT in data from the Freja satellite, which like ST5 was in a low-altitude orbit, with apogee and perigee heights of 1750 and 600 km, respectively.

[37] A detailed examination of the study by *Erlandson and Ukhorskiy* [2001], which used ~10 years of data from the Dynamics Explorer 1 satellite for their statistical study of Pc1–2 events, may put these differing results into perspective. Their main phase statistics were dominated by one large storm (minimum *Dst* = −300 nT) which contributed 21 of the 22 main phase events they recorded. Waves were thus not present during the main phase of most storms in their large data set. Erlandson and Ukhorskiy also noted, however, that their study excluded data from $L < 3.5$, so their study might undercount main phase events during the largest storms.

[38] Other recent studies also suggest that Pc1–2 waves occur during the main phase of some but not all magnetic storms. *Engebretson et al.* [2007] observed intense, compressional Pc1–2 waves in the O^+ frequency band during the Halloween superstorm of October 2003 (with a minimum *Dst* value of −401 nT). In contrast, *Engebretson et al.* [2008] studied Pc1–2 waves at Halley and simultaneous bursts of precipitating ring current protons (a consequence of EMIC wave generation) observed by the four low-altitude POES satellites during two storms in 2005 and noted that neither were observed during the main or early recovery phase of these storms (with minimum *Dst* values of −216 and −76 nT). A more recent study by *Posch et al.* [2007] noted Pc1–2 waves on the ground at Halley and in observations from the Finnish chain during one of two moderate magnetic storms in late 2006. If there is any pattern in these studies, it is that Pc1–2 waves may occur during the main phase of some storms but not in many others, whereas they occur quite often during the recovery phase. Because these waves are expected to be highly effective in depleting energetic electrons from the outer radiation belt, further studies of the relative occurrence of these waves during the main phase of geomagnetic storms should become a high priority. However, insofar as these waves are also highly localized and evidently transient, a comprehensive understanding of their occurrence and role during magnetic storms must also await the simultaneous deployment of a larger fleet of spacecraft, preferably with energetic particle instruments as well as magnetometers.

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