Pc 1 Waves Generated by a Magnetospheric Compression During the Recovery Phase of a Geomagnetic Storm

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A multipoint ground-satellite observation of a Pc 1 wave event is used to investigate electromagnetic ion cyclotron (EMIC) wave generation during a magnetospheric compression. The event occurred on September 15, 1986, from approximately 0400 to 0900 UT. Viking satellite observations were acquired by the magnetic and electric field experiments from 0622 to 0637 UT near 60° invariant latitude, 1130 magnetic local time, and an altitude of 13,500 km. The ground magnetic field observations were acquired throughout the event using the Finnish ground-station chain (Rovaniemi, Ivalo, Kilpisjarvi) and Sondre Stromfjord, South Pole, McMurdo, and Siple. The event occurred during the recovery phase of a large geomagnetic storm, where D_{st} reached -180 nT. There was a transient increase in D_{st} during the recovery phase of the storm. The wave event was observed during this transient increase in D_{st}, which is interpreted as a signature of a magnetospheric compression. The correlation between the D_{st} index and EMIC waves is used to investigate the association between magnetospheric compressions during the recovery phase of a geomagnetic storm and EMIC wave generation. Viking satellite and Finnish ground-station observations are used to compare spectral amplitudes in the magnetosphere and on the ground and to estimate ionospheric attenuation of Pc 1 waves.

Introduction

Low-frequency fluctuations in the Pc 1 frequency range (0.2–5 Hz) observed on the ground are believed to be due to the electromagnetic ion cyclotron (EMIC) instability generated by temperature anisotropies of protons in the energy range from a few keV to a few hundred keV [Cornwall, 1965; Kennel and Petschek, 1966; Liemohn, 1967]. The EMIC instability was later confirmed as the source of Pc 1 pulsations using simultaneous wave and particle data recorded at geostationary orbit [Mauk and McPherron, 1980]. In a statistical study using 7500 hours of data acquired by the AMPTE/CCE satellite it was found that EMIC waves are generated near the magnetic equator at all local times from $L \sim 3.5$ to $L > 9$ [Anderson et al., 1992]. EMIC waves occur most often in the outer magnetosphere ($L > 7$) and in the magnetic local time (MLT) sector from 1200 to 1500 hours [Erlandson et al., 1990; Anderson et al., 1992].

The occurrence of some types of Pc 1 wave activity have been found to be associated with geomagnetic storms. This association, however, depends on the type or morphology of the waves (see Jacobs et al. [1964] and Fukunishi et al. [1981] for a discussion of Pc 1 wave classification) and the phase of the storm. For example, IPDP (intervals of pulsations of diminishing periods) tend to occur during the main phase of geomagnetic storms in the afternoon–evening sector [Heacock, 1971; Barfield and McPherron, 1972; Bossen et al., 1976]. Periodically structured Pc 1 pulsations tend to occur during the recovery phase of geomagnetic storms [Wentworth, 1964; Plyasova-Bakounina and Matveyeva, 1968; Heacock and Kivinen, 1972]. On the other hand, unstructured Pc 1 pulsations, dominant at high latitudes, do not appear to be associated with geomagnetic storms [Kuwashima et al., 1981].

The generation of Pc 1 waves has also been associated with sudden impulses and sudden storm commencements [Troitskaya, 1961; Teply and Wentworth, 1962; Heacock and Hessler, 1965; Saito and Matsushita, 1967]. Olson and Lee [1983] have shown that wave generation during a magnetospheric compression can be explained by the corresponding increase in proton temperature anisotropy; they also found that the maximum growth rate occurs near noon, just inside the magnetopause. A further test on the effect of compressions was performed by Anderson and Hamilton [1993], who found that 47% of sudden magnetic field increases greater than 10 nT in the 8 to 16 MLT sector at $L > 6$ resulted in EMIC wave generation. A number of studies have also investigated the spectral structure of Pc 1 waves during magnetospheric compressions [Troitskaya et al., 1968; Hirasawa, 1981; Kangas et al., 1986]. Kangas et al. [1986] found that the Pc 1 spectral structure could vary significantly from one event to the next. It was speculated that this variability is the result of the particular state of the magnetosphere at the time of the compression.

The purpose of this paper is to investigate the generation of Pc 1 waves by a magnetospheric compression that occurs during the recovery phase of a geomagnetic storm. The event is studied using multipoint ground-satellite and Viking satellite observations acquired on September 15, 1986.

Instrumentation

Data used in this investigation were obtained from the magnetic and electric field experiments on the Viking satellite and from ground-station magnetometers. The field line projection to a 100-km altitude of the Viking satellite and location of ground stations used are shown in Figure 1. In that figure the locations of ground stations in the Southern Hemisphere have been mapped to their conjugate point in the Northern Hemisphere. The ground stations located in the Northern Hemisphere include Rovaniemi (ROV), Ivalo (IVA), Kilpisjarvi (KIL), and Sondre Stromfjord (SSF). The ground stations located in the Southern Hemisphere include Siple (SIP), South Pole (SP), and McMurdo (MCM). Search coil magnetometers were used on the ground and were sampled at a rate of 10 Hz (SSF, SIP, SP, and MCM) and at 5 Hz (ROV, IVA, and KIL). For reference, the location of $L = 4$ and 12 MLT (at 0630 UT) are indicated by the dashed lines in Figure 1.

The geographic and geomagnetic locations of the ground stations are listed in Table 1. The Finnish chain was at approximately 0900 MLT at a time of 0630 UT, resulting in a separation of 2.5 h in MLT with the Viking satellite.

Observations and Discussion

The wave event discussed in this paper occurred during the recovery phase of a geomagnetic storm. In addition, the event occurred during solar minimum at the boundary between solar cycles 21 and 22 when the sunspot number was 0. The D_{st} index during this storm is shown in Figure 2. The main phase of the geomagnetic storm occurred on September 12, 1986, and the recovery phase lasted for 3 to 4 days. At 0400 UT on

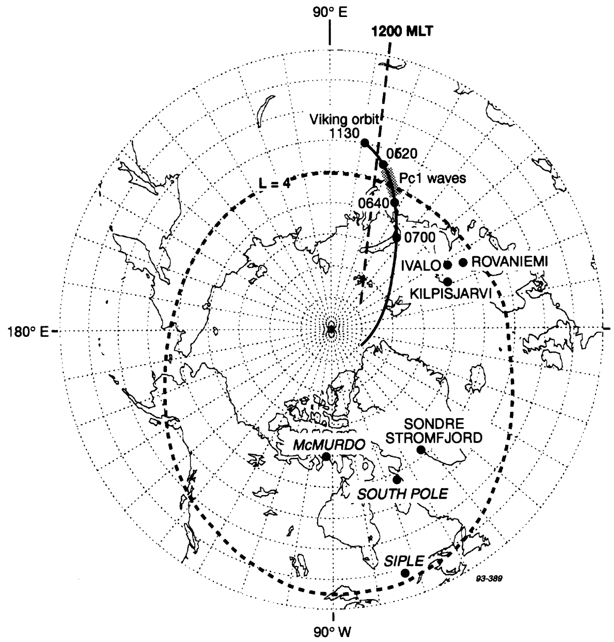

Fig. 1. Location of ground-based search coil magnetometers at 0630 UT and Viking's ionospheric footprint from 0620 to 0720 UT. The box along the Viking trajectory indicates the location of the wave event at Viking. The stations located in the Southern Hemisphere (Siple, South Pole, and McMurdo) have been projected to their conjugate point in the Northern Hemisphere and are shown in italics.

TABLE 1. Ground Station Geographic and Geomagnetic Locations

Station	Geographic latitude (deg)	Geographic longitude (deg)	Geomagnetic latitude (deg)	Geomagnetic longitude (deg)	L Value	MLT (h) 630 UT
Rovaniemi	66.8	25.9	63.2	107.4	4.8	9.00
Ivalo	68.7	27.3	65.0	209.9	5.5	9.18
Kilpisjarvi	69.0	20.9	65.7	105.3	6.0	8.87
S. Stromfjord	66.0	−52.0	73.5	40.5	13.3	4.55
Siple	−76.0	−83.0	−61.4	3.1	4.2	2.05
South Pole	−90.0	N/A	−74.2	18.6	14.7	3.08
McMurdo	−78.0	165.0	−80.6	−32.0	>15.0	23.72

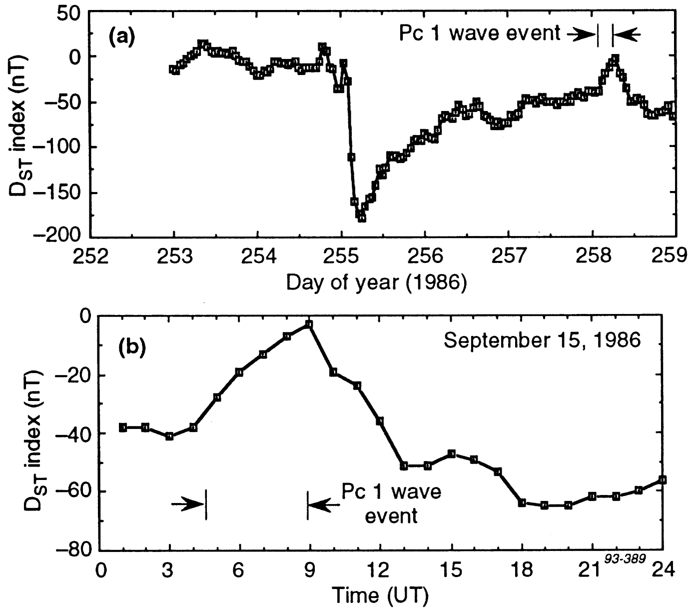

Fig. 2. D_{st} index (a) from September 9 to 16, 1986, and (b) on September 15, 1986.

September 15, 1986, an enhancement in D_{st} was observed. The D_{st} index increased for approximately 5 h until 0900 UT. The EMIC wave event discussed in this paper occurred during the positive slope in D_{st}.

The increase in D_{st} index from 0400 to 0900 UT is interpreted as resulting from an increase in solar wind dynamic pressure. The D_{st} index has been found to respond to solar wind dynamic pressure [Verzariu et al., 1972]. An empirical relationship between the D_{st} index and interplanetary conditions was investigated by Burton et al. [1975]. The observed increase in D_{st} from −38 to −2 nT would imply that the solar wind dynamic pressure increased by 5 nPa based on the empirical results of Burton et al. [1975]. Unfortunately, confirmation of a solar wind dynamic pressure increase is not possible since solar wind data are not available for this time period.

Pc 1 waves were recorded over a wide range of magnetic local times extending from the midnight sector around to the dawn and dayside sectors (Figures 3 and 4). Figure 3 contains a summary of magnetic field fluctuations in the MLT sector from 2200 to 0700 recorded at SSF, SIP, SP, and MCM from 0400 to 1000 UT. Figure 4 contains a summary of magnetic field fluctuations recorded at ROV from 0330 to 0930 UT in the 0630 to 1130 MLT sector. The waves at IVA and KIL (not shown) were lower in amplitude but had similar temporal and spectral structure. The largest wave amplitudes were recorded at SIP (L = 4.2) and ROV (L = 4.8), indicating that the source region is in this L-value range. The morphology of the waves at SIP and ROV were similar, even though the stations were separated by 7 h in MLT. The waves recorded at SIP were also very similar to those recorded at the high-latitude stations (SSF, SP, and MCM), although the waves at MCM were very low in amplitude. The similarity between Northern and Southern Hemisphere stations is also evident. The wave event begins near 0400 UT at ROV (0630 MLT) and near 0430 UT at SIP (2330 MLT) and SP (0030 MLT). The event ends abruptly at around 0900 UT at all stations.

Magnetic and electric field fluctuations were also recorded at Viking during this event and were used to identify the source field line of the Pc 1 waves. The magnetic field data are presented in eccentric dipole coordinates, where BN is positive north, BE is positive east, and BP (not shown) is along the magnetic field direction. The electric field component, E34, is in the spin plane of the satellite. The waves were recorded from 0622 to 0637 UT when Viking crossed L-shells from L = 3.7 to L = 4.5 (Figure 5). Waves were not observed by Viking outside these L-shells. The magnetic local time of Viking at this time was 1130 MLT. Magnetic field fluctuations recorded at ROV (L = 4.8), IVA (L = 5.5), and KIL (L = 6.0) are shown from 0622 to 0637 UT (Figure 6). The wave amplitude was found to decrease as a function of L-value or distance from the wave source field line (~L = 4). The identification of the source field line near L = 4 is also consistent with the decrease in amplitude as a function of L-value observed in stations located in the post-midnight sector (SIP, SP, SSF, and MCM) (Figure 3).

The combination of Viking at 1130 MLT, the Finnish chain at 0900 MLT, and the stations in the post-midnight sector (SIP, SP, SSF, and MCM) imply that the wave source region was not localized in local time near Viking (L = 4 and 1130 MLT) but was extended to the dawn (ROV, IVA, and KIL) and midnight sectors (SIP, SP, SSF, and MCM). This can be seen by noting that the distance between each of the three Finnish ground stations (ROV, IVA, and KIL) and Viking were nearly the same, ruling out a single localized source at Viking (Figure 1). The maximum in amplitude and the nearly constant wave frequency observed at Viking, ROV, and SIP suggest that the source region was probably near L = 4 for the duration of the event. The similarity between waves recorded at SIP (post-midnight sector) and ROV (pre-noon sector) suggests that the waves were generated over a wide range in magnetic local time.

The Pc 1 waves recorded at ROV, IVA, and KIL were structured pearl pulsations with an average repetition period of 62 s (Figure 6). The waves recorded at SIP, SP, MCM, and SSF were also structured, although the structure was less defined than the ROV structure. The structure or repetition period is not as obvious in the Viking data. A repetition period of 60 s can been seen from 0622 to 0625 UT in the electric field (E34), although after 0625 UT the event appears to be unstructured. It can not be concluded, however, that pearl pulsations are features observed only on the ground, since clear examples have been observed using the Viking satellite [Erlandson et al., 1992]. The observations presented here indicate that conditions favorable for generating pearl pulsation structure may be localized in space and vary from one location to another.

The power spectra of the waves recorded at Viking were nearly identical to those recorded at ROV, IVA, and KIL (Fig-

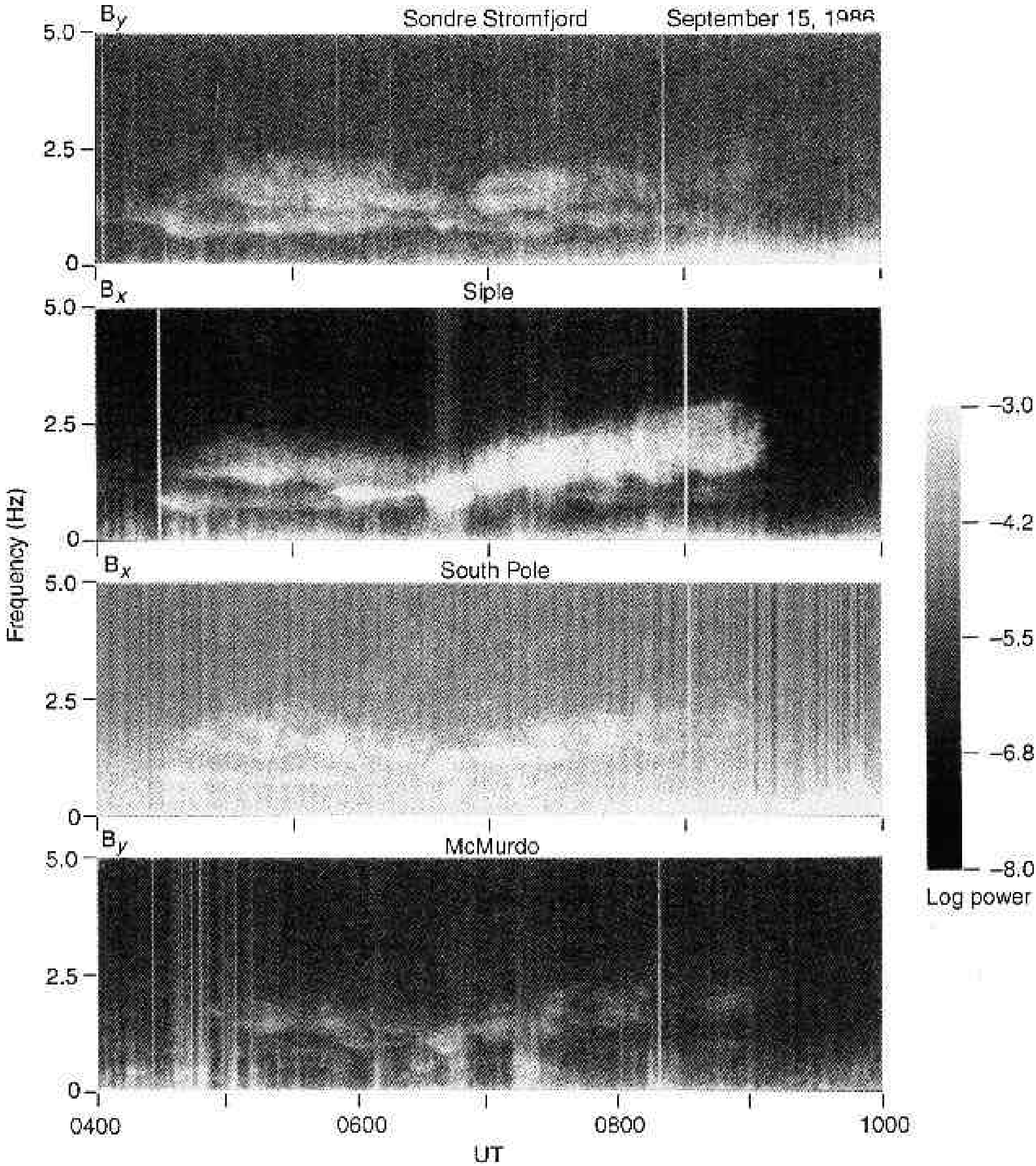

Fig. 3. Spectrograms of magnetic field fluctuations recorded at Sondre Stromfjord, Siple, South Pole, and McMurdo from 0400 to 1000 UT. The spectral power is in units of nT^2/Hz.

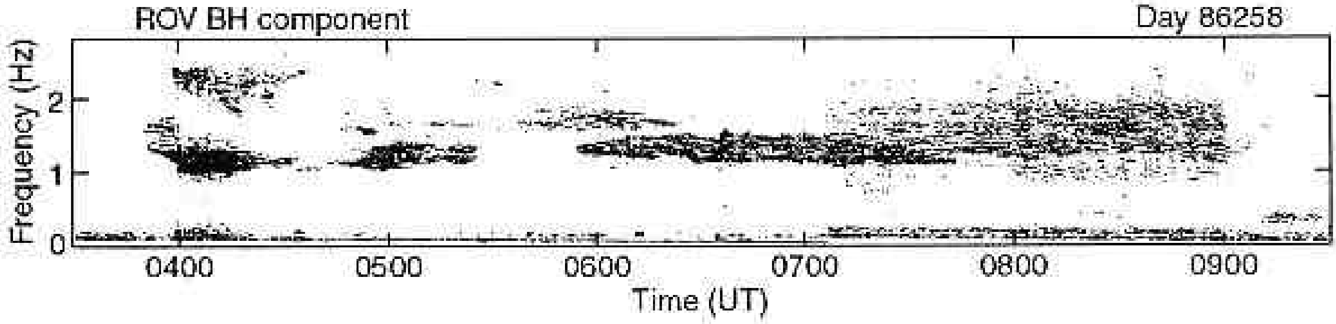

Fig. 4. Spectrogram of magnetic field fluctuations recorded at Rovaniemi (ROV) from 0330 to 0930 UT. The spectral power is in units of nT^2/Hz.

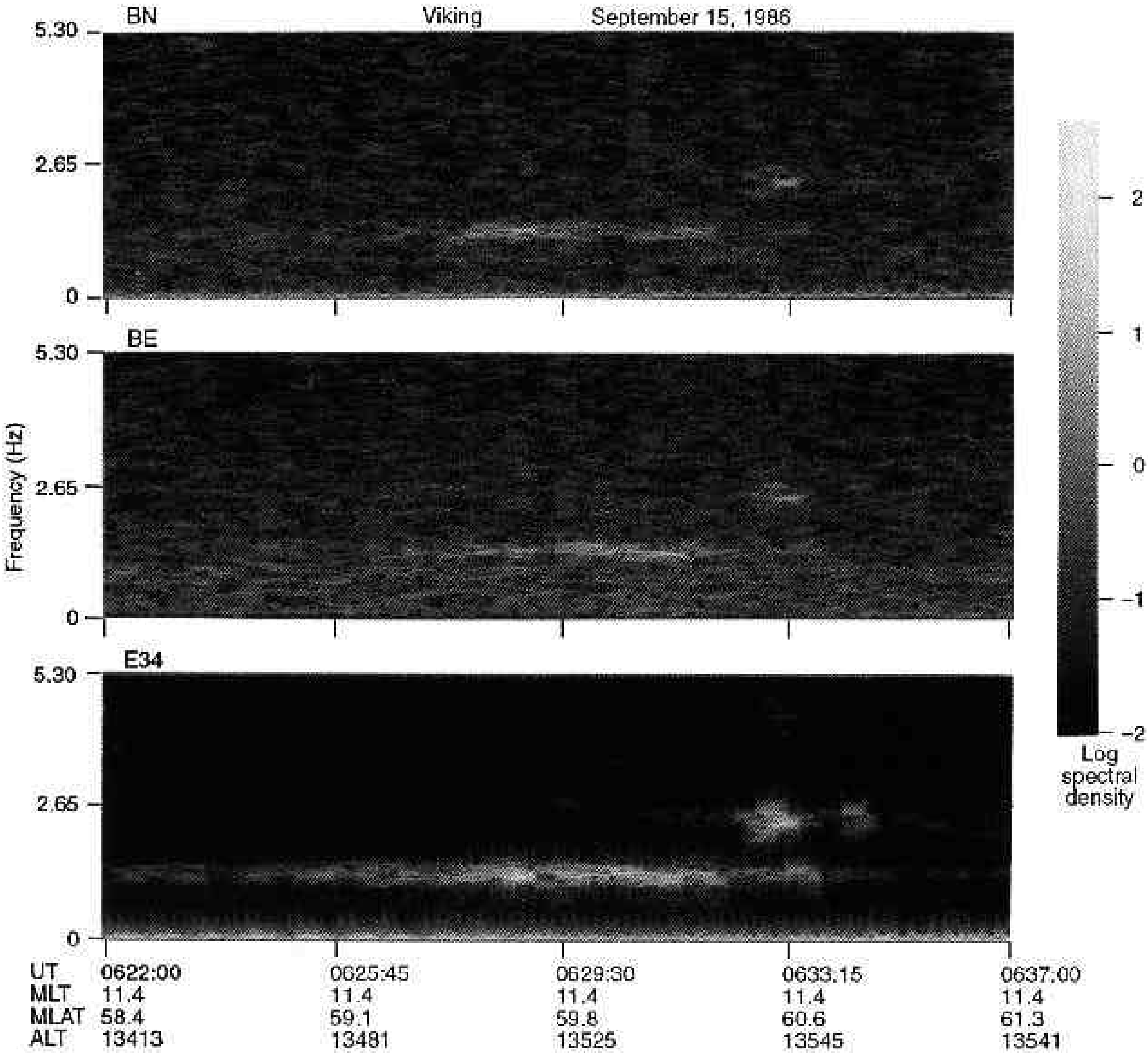

Fig. 5. Spectrograms of magnetic and electric field fluctuations in units of nT^2/Hz and $(mV/m)^2$/Hz, respectively. The data were acquired by Viking during orbit 1130 on September 15, 1986, from 0622 to 0637 UT.

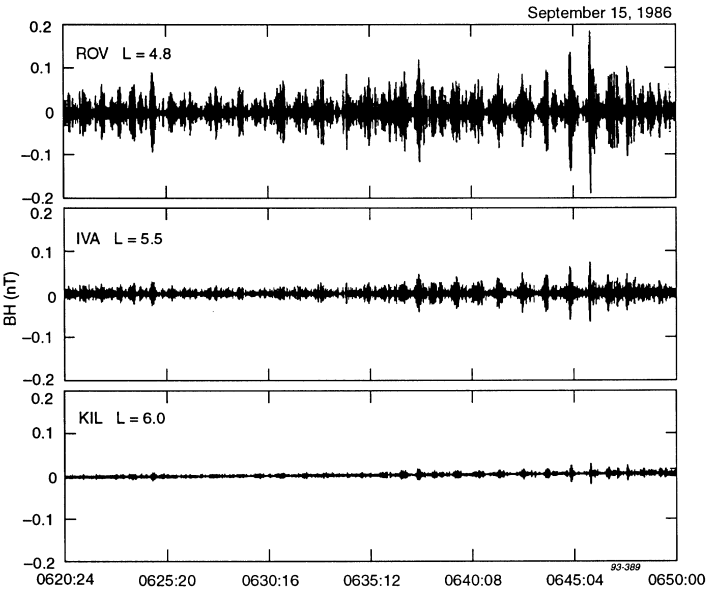

Fig. 6. Magnetic field fluctuations recorded at Rovaniemi (ROV), Ivalo (IVA), and Kilpisjarvi (KIL) on September 15, 1986, from 0620 to 0650 UT.

ure 7), even though the stations were separated from Viking by nearly 2.5 h in MLT (Figure 1). Fine structure in the power spectra was also very similar as seen in the spectral peaks at 1.3 and 1.45 Hz. The peak at 1.65 Hz observed at ROV would be expected to be below the Viking magnetometer noise level.

The observation of the wave amplitude as a function of L-value using Viking and the Finnish ground-station chain may be used to estimate the attenuation of waves in the ionosphere. The attenuation of waves in the ionosphere, as they propagate from the source region to higher latitudes based on the power spectral density at ROV, IVA, and KIL shown in Figure 7,

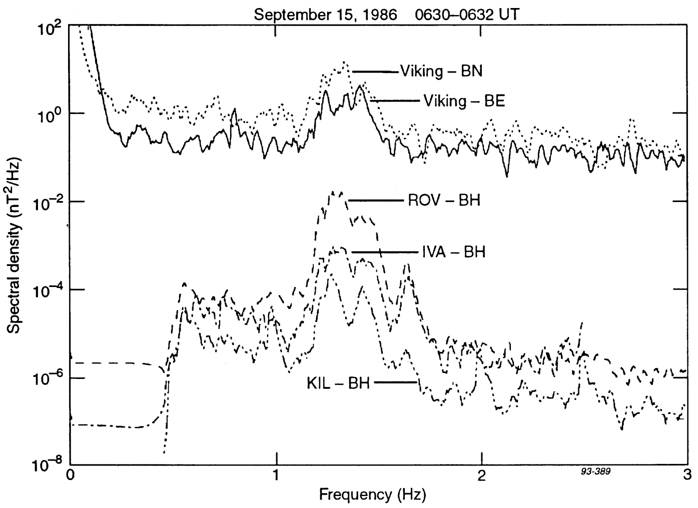

Fig. 7. Spectral comparison of Pc 1 waves recorded from 0630 to 0632 UT at Viking (BN is positive north and BE is positive east) and ROV, IVA, and KIL (BH is positive north).

was found to be approximately 0.06 dB/km. It is more complicated, however, to estimate the ionospheric attenuation between Viking (at $L = 4$) and the ground-station chain (ROV, IVA, and KIL). For example, some of the wave energy incident on the ionosphere is reflected and transmitted, representing a source of attenuation unrelated to the attenuation in the ionospheric duct. In addition, the wave amplitude at Viking's altitude (13,500 km) may not necessarily represent the amplitude of the wave at ionospheric altitudes. Ignoring these two effects, however, it is found using the data shown in Figure 7 that the average attenuation between Viking ($L = 4$) and the Finnish ground stations is 0.07 dB/km. These two estimates are very similar and are comparable to the predicted value of 0.06 dB/km from Fujita [1987], who investigated ionospheric attenuation of Pc 1 waves using the International Reference Ionosphere model. The fact that the attenuation estimates using Viking were similar to the estimates using only ground stations indicates that the increase in wave amplitude as the waves propagate to lower altitudes just happens to be compensated by the attenuation of the waves due to reflection and transmission in the ionosphere. A more detailed discussion of ionospheric attenuation, including any possible frequency dependence, will be the subject of an additional paper.

The spectrograms for SIP, SP, SSF, and MCM (Figure 3) have been expanded in Figure 8 to show the time sequence from 0610 to 0650 UT, which corresponds more closely to the time period of waves observed at Viking (see Figure 5). The time extent of the waves recorded at Viking is most likely determined by the spatial size of the source region (≈59–61° invariant latitude). The ground observations, on the other hand, show the long-term temporal profile of the waves. It was shown earlier that the wave spectra recorded at Viking and on the ground in the Finnish chain were very similar, with the primary difference being the wave amplitude. It was also shown that the wave morphology at SIP, SP, MCM, and SSF was very similar (Figure 3). A more detailed comparison indicates that the wave frequency recorded at Viking was 1.1 to 1.5 Hz, whereas the wave frequency at SIP was 0.95 to 1.25 Hz at 0628 UT. Minor frequency differences might be expected, however, based on the location of the plasmapause at different local times and differences in the energetic plasma at a given local time. The waves at SIP ($L = 4.2$) and SP ($L > 10$), which were located in the same MLT sector, were similar, although lower-frequency waves (0.5 Hz) were observed at around 0627 to 0630 UT from SP but not SIP. The lower-frequency waves observed at SP were also observed at MCM, another high-latitude station. The waves recorded at SP and SSF, stations at similar L-values but located in different hemispheres, were similar, with the primary difference being that the increase in wave amplitude after 0630 UT was observed at SP but not SSF. Differences between these two stations may be related to hemispherical differences or MLT differences between stations. This detailed comparison illustrates that although the wave morphology is similar on a long time scale (hours), significant differences may exist on shorter time scales (minutes). It may be that overall wave morphology is domi-

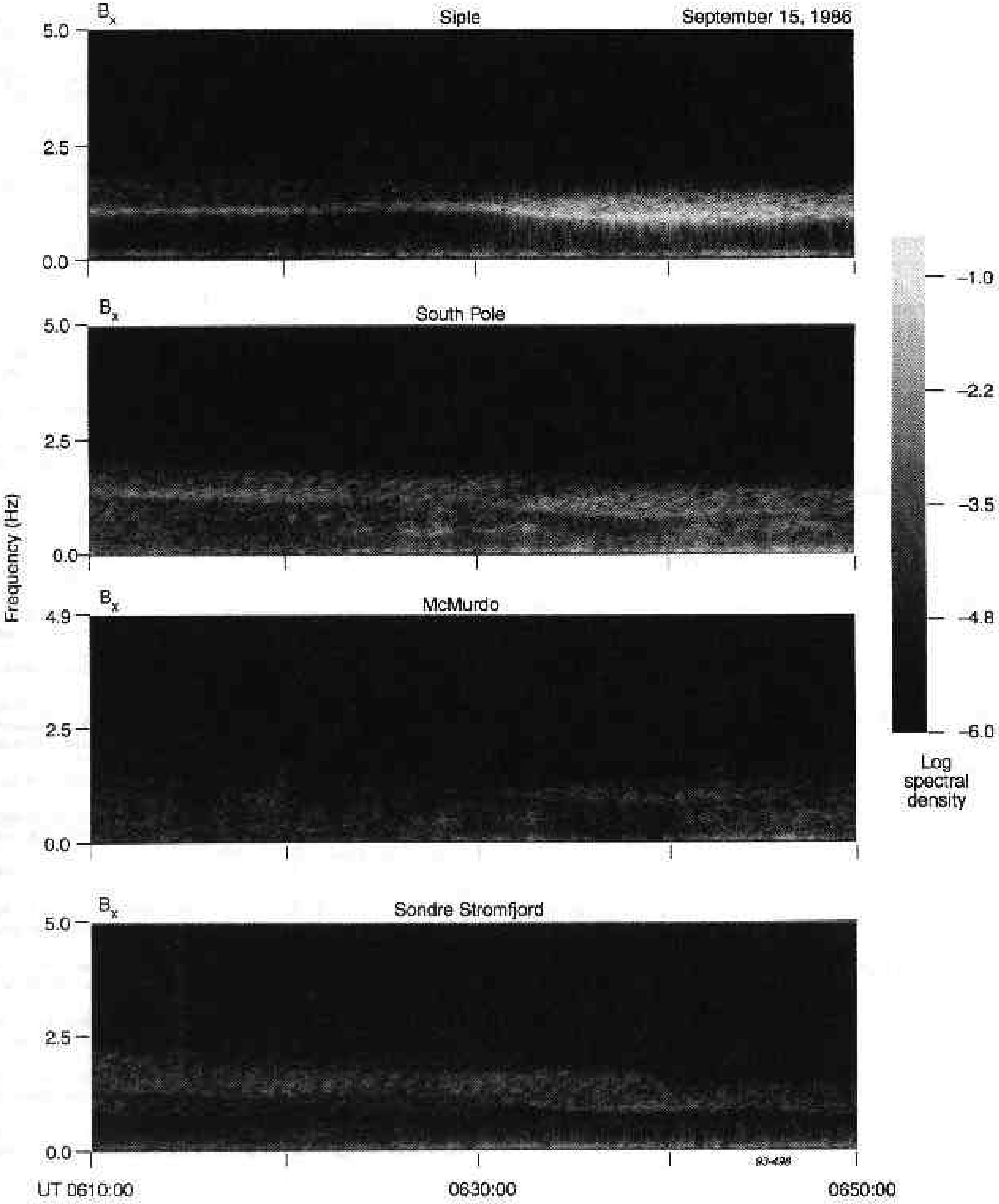

Fig. 8. Spectrograms of the magnetic field B_x component at Siple, South Pole, McMurdo, and Sondre Stromfjord in units of nT^2/Hz from 0610 to 0650 UT on September 15, 1986.

nated by large-scale magnetospheric dynamics, whereas on shorter time scales differences result from the particular particle distributions at a given local time.

Summary

The primary observations from this event are that the waves were excited during a magnetospheric compression as inferred from the D_{st} index. After the magnetosphere reached its maximum compressed state and began to relax, the waves were no longer observed. The wave event ended nearly simultaneously, both on the dayside and nightside. This observation was not necessarily expected since the magnetosphere would still be in a compressed state when the relaxation of the magnetic field began. During a compression, energetic ions that excite the waves are driven unstable through adiabatic acceleration [Olson and Lee, 1983]. The sudden end of the event, on a global scale, suggests that the energetic ions quickly become stabilized in the absence of a driving force such as a compression.

A second observation is that the event, most likely driven by a magnetospheric compression, occurred during the recovery phase of a storm. This observation suggests that the role of geomagnetic storms, in terms of Pc 1 wave generation, is to populate the magnetosphere with energetic ions. The magnetospheric compression, which occurred during the recovery phase of the storm, resulted in driving the energetic ions unstable to the EMIC instability. Therefore, the effect of a magnetospheric compression on EMIC wave generation strongly depends on the state of the 5- to 100-keV plasma in the ring current. This is consistent with the findings of Kangas et al. [1986], who suggested that the type of Pc 1 emissions during a sudden impulse reflect the state of the magnetosphere at the time of the sudden impulse. In the case study presented here, we suggest that the recovery phase of geomagnetic storms would be the most favorable condition for EMIC wave generation at low latitudes through magnetospheric compression as a result of the newly injected plasma provided during the storm.

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